PROCEEDINGS OF THE
42ND FORUM ON THE
GEOLOGY OF INDUSTRIAL MINERALS
May 7-13, 2006 – Asheville, North Carolina, USA

Information Circular 34

Edited by

Jeffrey C. Reid

North Carolina Geological Survey Section
Division of Land Resources
Department of Environment and Natural Resources

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Michael F. Easley, Governor

Department of Environment
and Natural Resources
William G. Ross Jr., Secretary

Raleigh, North Carolina
May 2006

FORWARD

The 42nd Forum on the Geology of Industrial Minerals was held in Asheville, North Carolina on May 7-13, 2006. The Forum was convened by the North Carolina Geological Survey, in collaboration with industry and the Minerals Research Laboratory of North Carolina State University. Forum attendees and authors were from 27 states, nine counties and five continents.

This report presents the technical papers and posters given at the Forum on May 8-10. Pre- and post-meeting field trips showcased the diversity of our State's industrial minerals – including a three day field trip, "Mountains to the Sea."

Asheville is an industrial minerals center – and a mountain vacation destination. North Carolina is a significant industrial minerals storehouse with significant production of feldspar, high-purity quartz, mica, phosphate, clay (bricks), glass sand, dimension stone, peat, olivine, gemstones, silica, and has significant heavy mineral reserves (ilmenite, rutile and zircon). North Carolina is the headquarters of Martin Marietta Aggregates and the Mideast Division of Vulcan Materials Co. – two of the largest U.S. aggregates producers.

The 45 technical papers covered a broad range of topics beginning with an overview of North Carolina's geology and industrial mineral resources. Other theme sessions focused on phosphate, crushed stone, sand and gravel, clay, dimension stone, brick, gemstones, barite, soda ash, feldspar, high-purity quartz, talc, mineral processing advances, refractories, databases, strategic minerals for the future, and education outreach – including North Carolina's earth / environmental high school graduation requirement – the first in the nation.

The 30 posters covered an equally diverse range of topics beginning with the state's main industrial mineral districts, permitting application processes, activities of the North Carolina Geological Survey, abrasives (garnet), glass sand, aggregates, gemstones (natural and synthetic), phosphate, reclamation, refractory minerals (pyrophyllite, andalusite), geographic information systems (GIS), Spruce Pine District, valuation, travertine, magnesite, kaolin, limestone and aggregates.

Of special note are the "Oral history of mining in western North Carolina," and the "History of the Minerals Research Laboratory of North Carolina State University." These two contributions provide important historical perspectives of the mineral industry in North Carolina.

It is our hope that these 42nd Forum proceedings will be a long standing resource on industrial minerals in North Carolina and elsewhere, and one that will improve public understanding of the importance of minerals to society – "If its not grown, it has to be mined."

Jeffrey C. Reid
Co-Chair and Editor

Timothy W. (Tyler) Clark
General Chair

23 April 2006
Raleigh, North Carolina

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1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio
11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario, Canada
20th	1984	Baltimore, Maryland
21st	1985	Tucson, Arizona
22nd	1986	Little Rock, Arkansas
23rd	1987	North Aurora, Illinois
24th	1988	Greenville, South Carolina
25th	1989	Portland, Oregon
26th	1990	Charlottesville, Virginia
27th	1991	Banff, Alberta, Canada
28th	1992	Martinsburg, West Virginia
29th	1993	Long Beach, California
30th	1994	Fredericton, New Brunswick/Halifax, Nova Scotia, Canada
31st	1995	El Paso, Texas
32nd	1996	Laramie, Wyoming
33rd	1997	Quebec City, Quebec, Canada
34th	1998	Norman, Oklahoma
35th	1999	Salt Lake City, Utah
36th	2000	Bath, England
37th	2001	Victoria, British Columbia, Canada
38th	2002	St. Louis, Missouri
39th	2003	Reno/Sparks, Nevada
40th	2004	Bloomington, Indiana
41st	2005	Istanbul, Turkey
42nd	2006	Asheville, North Carolina

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(Editor's note: Posters are either in MS PowerPoint or Adobe Acrobat .pdf format. A link is provided at the bottom of each poster abstract along with an approximate file size.).

Papers from oral presentations

The geology of North Carolina – or how the heck did all these rocks get to where they are today?

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ABSTRACT

The rocks of North Carolina have experienced a long and varied history over the last 2 billion years. North Carolina rocks contain evidence of at least two Wilson cycles (mountain building, rifting, and passive margins) associated with both the Rodinia and Pangea supercontinents. Currently the oldest known rocks in North Carolina are nearly 2 billion years old, but these numbers keep increasing with continued research.

The first Wilson cycle was related to the supercontinent Rodinia. Sediment shed off the North American craton was metamorphosed during the Grenville orogeny to form the metamorphic rocks of the Elk Park Massif around 1.2 billion years ago. These rocks were then accreted to Laurentia during formation of the supercontinent Rodinia. The Grenville orogeny created igneous and metamorphic rocks that are now the basement rocks of North Carolina's Blue Ridge province. Many hundreds of millions of years later (750-550 Ma), Rodinia began rifting apart, creating sedimentary basins and igneous rocks of the Mount Rogers and Grandfather Mountain Formations. The final breakup of Rodinia opened the Iapetus Ocean and deposited passive margin sediments along the edge of Laurentia.

While the first Wilson cycle was ending, the second had already begun on the other side of the Iapetus Ocean. Around 650-550 Ma, subduction in the Iapetus Ocean off the edge of Gondwana created a series of volcanic island arcs. This was a period of abundant igneous and sedimentary activity, including emplacement of granitoids, as well as the formation of important gold and pyrophyllite deposits. Throughout much of the Paleozoic Era (475-250 Ma), a series of three tectonic orogenies caused the accretion of the volcanic islands arcs to Laurentia, culminating with the closure of the Iapetus Ocean and the formation of the supercontinent Pangea. This was a period of intense metamorphism and deformation, thrust faulting, and emplacement of granitoids and pegmatites. During the Mesozoic Era, Pangea rifted apart, creating Late Triassic sedimentary basins and Early Jurassic diabase dikes. Since that time to present, North Carolina has been in a passive margin environment producing a variety of sedimentary units along the Atlantic margin.

The 2 billion years of geologic activity recorded in North Carolina's rocks provide merely a glimpse into the varied past. However limited our view, our understanding of these events has critical importance in understanding the important mineral resources to be found. Only through a thorough investigation of past geologic events will we make the best use and stewardship of our limited natural resources.

Clark, Timothy W., 2006, The geology of North Carolina – or how the heck did all these rocks get to where they are today?, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Early geologists organized the rocks of the North Carolina into "belts," (e.g., Carolina slate belt, Charlotte belt, Blue Ridge belt, etc.). This method of nomenclature grouped rocks of a similar age and origin into belts of varying sizes striking roughly northeast-southwest, parallel to the trend of the Appalachian Mountains. While this terminology proved useful in grouping together similar rocks, the emergence of the theory of plate tectonics allowed researchers to view North Carolina's geologic belts in a new light and much of the belt terminology became obsolete. Many of these belts now have different names and are called "terranes" in recognition of the fact that they originated as parts of other continents and were later added onto North America.

In the most general sense, North Carolina can be divided into four main zones (Figure 1):

1.) Cumberland zone: native metamorphic "basement" formed during the assembly and subsequent rifting of the supercontinent Rodinia;

2.) Piedmont zone: medium- to high-grade metamorphic terranes of unknown origin, (possible Laurentian island arc);

3.) Carolina terrane: low - to medium- grade metavolcanic and metasedimentary terranes (volcanic island arc terrane formed off Gondwanian coast);

4.) Atlantic Coastal Plain: passive margin sediments shed off North America from Jurassic Period to present.

During the past 2 billion years, these terranes have been created and deformed in a complicated series of tectonic events: 1) the continental collision that formed the supercontinent Rodinia; 2) continental rifting that formed the Iapetus Ocean; 3) a series of three crustal collisions that formed the supercontinent Pangea; 4) continental rifting that formed the Atlantic Ocean; and finally 5) passive margin development that formed the Atlantic Coastal Plain. These events consolidated multiple crustal terranes of varying ages that originated in different parts of the world.

THE ASSEMBLING OF RODINIA

The oldest rocks discovered in North Carolina are about 2.2 to 1.8 billion years old and occur near Roan Mountain in the western Blue Ridge close to the North Carolina/Tennessee state line. They are interpreted to represent meta-igneous and metasedimentary rocks of the North American craton. Outcrops of these Early Proterozoic rocks are scarce and are interspersed throughout younger Grenville-age rocks, which are discussed below. Little is known about the contact relation between the Early Proterozoic rocks and the younger rocks surrounding them, but research continues to unravel the complicated history of North Carolina's oldest rocks.

The next major group of North Carolina rocks formed nearly 1 billion years later during the Grenville orogeny, which occurred in the Middle Proterozoic, from about 1,200-900 million years ago. During this time, a block of continental crust known as the Grenville province collided with the North American craton (Laurentia), one of many collisions of crustal blocks that coalesced into a single supercontinent called Rodinia. Grenville-age rocks in North Carolina include meta-igneous and metasedimentary, biotite and biotite-hornblende gneiss and granitic gneiss (Merschat and others, 2006). Most Grenville-age rocks in North Carolina occur in the northwestern portion of the state along the Tennessee border (Figure 2).

THE RIFTING OF RODINIA

Following the Grenville orogeny, from about 750 million years ago until about 680 million years ago, Rodinia began to rift apart. The continental crust stretched and thinned, creating a series of deep marine rift valleys that filled with sediment. The thinning crust also allowed upwelling bimodal magmatism to cut across older crystalline rocks, as well as newly forming sedimentary units (Figure 3).

The initial rifting of Rodinia failed and did not produce an ocean as evidenced by the lack of 750-680 million year old beach or marine sediments. However, rifting resumed about 620 million years ago and a second pulse of bimodal magmatism began. Finally, the supercontinent of Rodinia broke apart, creating the Iapetus Ocean between the continents of Laurentia, which would much later become North America, and Gondwana, which would become South America and Africa.

THE ASSEMBLING OF PANGEA

The Piedmont Zone

Following the final rifting of Rodinia around 600 million years ago, there is little in the geologic record for western North Carolina for the next 100 million years. Then, about 500 million years ago, new subduction zones formed in the Iapetus Ocean, and Laurentia and Gondwana started moving back toward each other. Offshore between Laurentia and Gondwana was a crustal block that most likely had rifted away from Laurentia during the break up of Rodinia 100 million years earlier. Subduction of oceanic crust of the Iapetus Ocean under this crustal block converted it into a volcanic island arc. Continued subduction created an accretionary wedge of ocean-floor sediments and basaltic oceanic crust as the gap closed between the crustal block and the Laurentian mainland.

Eventually, sometime between 475-350 million years ago, the crustal block and its accretionary wedge collided with Laurentia during the Taconic and/or Acadian orogeny. There is much controversy today between geologists as to the actual timing of this event and further research is needed. In North Carolina, the crustal block and its accretionary wedge were thrust up and over the edge of Laurentia along a series of low-angle thrust faults. This accreted crust is now referred to as the Piedmont zone (Figure 4).

The Carolinia Volcanic Island Arc – Home to North Carolina Gold Country

Prior to the Piedmont zone's accretion to Laurentia, another important event was occurring on the other side of the Iapetus Ocean along the margin of Gondwana. Here could be found a series of crustal blocks similar to those of the Piedmont zone originally offshore from Laurentia. These blocks may have also been rift fragments related to the break up of Rodinia. As subduction began offshore of Gondwana, these crustal blocks became active as volcanic island arcs between about 600-500 million years ago. During the Early Paleozoic many of these crustal blocks or terranes began assembling in a larger crustal block, sometimes referred to as the Carolinia volcanic island arc.

As subduction in the Iapetus Ocean continued during the middle Paleozoic, the gap between Gondwana and Laurentia began to close. Geologists are not exactly sure how or where, but sometime between 450 and 350 million years ago, the Carolinia volcanic island arc hit Laurentia prior the final collision between Laurentia and Gondwana. This event, known as the Acadian orogeny, is well documented in the northern Appalachians (New England and Canada). There is less obvious evidence of the Acadian orogeny in North Carolina, and the subject is highly controversial between geologists researching the region.

The Carolinia volcanic island arc was variably deformed and metamorphosed prior to and during accretion. Today the exposed remnants of the island arc make up make the Carolina Zone (Figure 4). The Carolina Zone rocks can be divided into two broad categories; those that are made of primarily volcanic and sedimentary rocks and have only experienced low-grade metamorphism and those that include more plutonic igneous rocks and have experienced intense deformation and metamorphism. Both categories of the Carolina Zone experienced sulfide mineralization due to the volcanic activity, and the Carolina zone is where most of the 19th century gold mining took place. In fact, the Reed gold mine, now a state historic site, is the location of one of the first documented discoveries of gold in North America.

The collision of the Carolina zone created localized metamorphic rocks between about 400 and 360 million years old in the western portion of the state, such as the alaskite bodies that are important sources of mica, feldspar, and ultra-high purity quartz. The collision also created some minor granitic rocks and pegmatites in central and western North Carolina that are of an Acadian age. From a mineral resource perspective, these include the dimension stone resources of the Concord, Salisbury and Mount Airy plutons as well as the emerald-bearing Spruce Pine pegmatites (Figure 5).

The Alleghanian Orogeny: Laurentia and Gondwana Collide

The final culmination in the assembly of the supercontinent Pangea occurred when Gondwana itself collided with Laurentia about 330 million years ago, closing the Iapetus Ocean permanently. Evidence for this huge continental collision, known as the Alleghanian Orogeny, can be found all along the Appalachian mountains from Alabama to the maritime provinces of Canada. This event created large, stacked thrust faults and associated folding, as the older rocks of the Laurentian basement were pushed up and over younger sedimentary rocks. After the initial thrusting, several strike-slip faults developed across the state, juxtaposing different rock types of the various zones and terranes against one another. Finally, the Alleghanian Orogeny created a suite of post-orogenic granitoids in the central and eastern part of North Carolina that are important sources for crushed stone (Figure 6). The Alleghanian orogeny was the last major mountain-building event to occur in North Carolina and culminated with the final assembly of the supercontinent Pangea near the end of the Paleozoic Era.

THE RIFTING OF PANGEA

Beginning in the Triassic Period, about 220 million years ago, Pangea began rifting. As happened when Rodinia started to break up 750 million years ago, the crust stretched and thinned, creating a series of rift basins up and down what is now the east coast of North America, as well as the west coast of Africa. These rift basins filled with sediment shed from the surrounding rocks and therefore have high degrees of variation depending on their sediment source. Some of the basins continued growing and coalesced to eventually form the Atlantic Ocean. Other basins further away from the newly forming Atlantic Ocean stopped growing, and today are exposed on either side of the Atlantic Ocean in North America, Africa and Europe.

North Carolina has two major Triassic basins: the Deep River basin and the Dan River basin (Figure 7). The Deep River basin was historically a major local producer of coal in the 1800s and early 1900s. Today the Deep River basin produces abundant clay for the production of bricks.

FORMATION OF THE NORTH CAROLINA COASTAL PLAIN

Since the middle Mesozoic Era, there has been little to no tectonic activity in North Carolina. Erosion has slowly been eating away at the Appalachian Mountains and depositing the detritus along the Coastal Plain. As sea level has risen and fallen over millions of years, a wide variety of Coastal Plain deposits have formed. During the Jurassic Period, marine sediments were deposited far out on the continental shelf (now under the Atlantic Ocean). About 90 million years ago, during the Cretaceous period, sea level was near its highest level and deposited several types of sediment far inland in North Carolina, perhaps as high as 600 feet above the current sea level. These deposits include the shallow marine Cape Fear Formation, the deltaic Middendorf Formation, the lagoonal Black Creek Formation and the shallow marine Pee Dee Formation (Figure 8).

Large fluctuations in sea level continued throughout the Cenozoic Era, slowly eroding, reworking and redepositing older Coastal Plain sediments. During the Eocene Epoch, reef deposits in shallow seas lead to the formation of the limestones of the Castle Hayne and River Bend Formations (Figure 9). These limestones are important sources of crushed stone in the aggregate-poor eastern portion of the state. The phosphate-rich Pungo River Formation was laid down during the Miocene Epoch. Similar Miocene-age phosphate deposits occur in Florida as well. When combined, North Carolina and Florida account for about 95% of the world's production of phosphate. Lesser-important peat deposits formed during the Pliocene. High stands of sea level created a series of wave-cut benches delineated by a discontinuous series of scarps as sea level slowly dropped. The youngest and most prominent of these is the Pleistocene Suffolk Scarp, which separates the dissected Inner Coastal Plain from the nearly flat Outer Coastal Plain. Pleistocene and Holocene wave action along the Outer Coastal Plain margin led to the development of the fragile system of sandy barrier islands that provide numerous tourist activities today.

SUMMARY

The rocks of North Carolina have experienced a long and varied history. During the past 2 billion years, the state has experience five main geologic events: 1) the formation of the supercontinent Rodinia; 2) continental rifting that formed the Iapetus Ocean; 3) a series of three crustal collisions that formed the supercontinent Pangea; 4) continental rifting that formed the Atlantic Ocean; and finally 5) passive margin development that formed the Atlantic Coastal Plain. This complicated series of events consolidated multiple crustal terranes of varying ages that originated from different parts of the world, giving North Carolina the wide variety of geology and mineral resources that we see today.

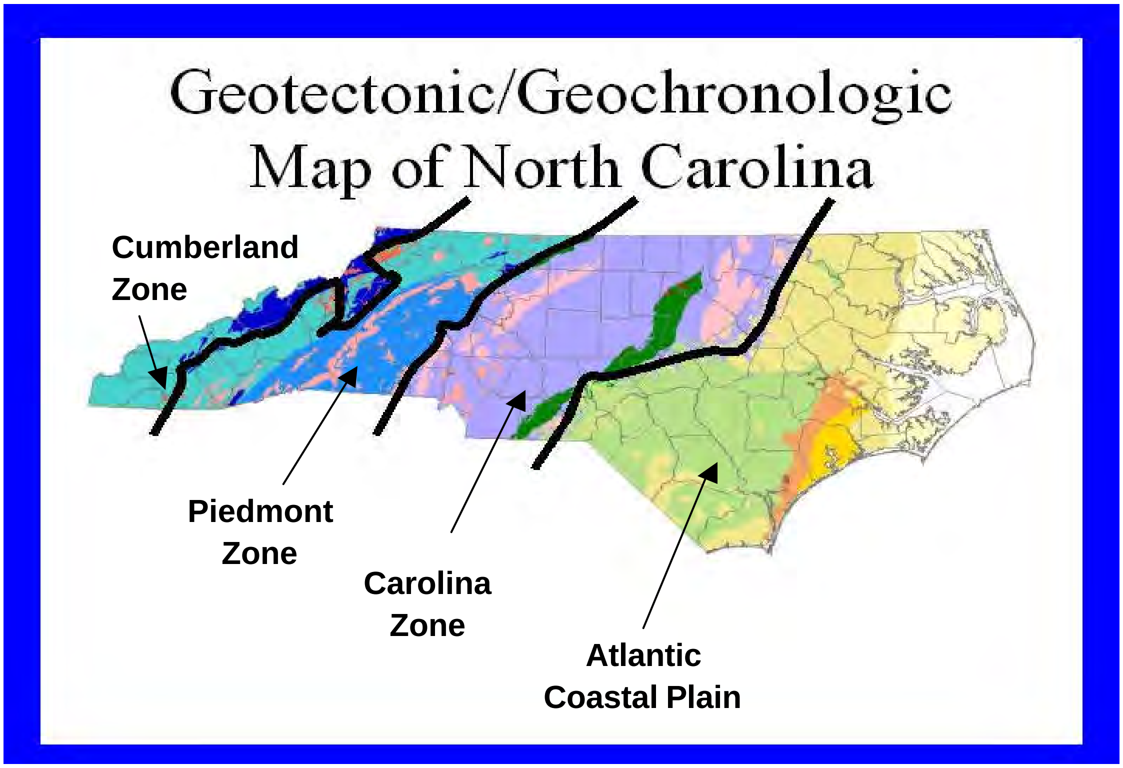
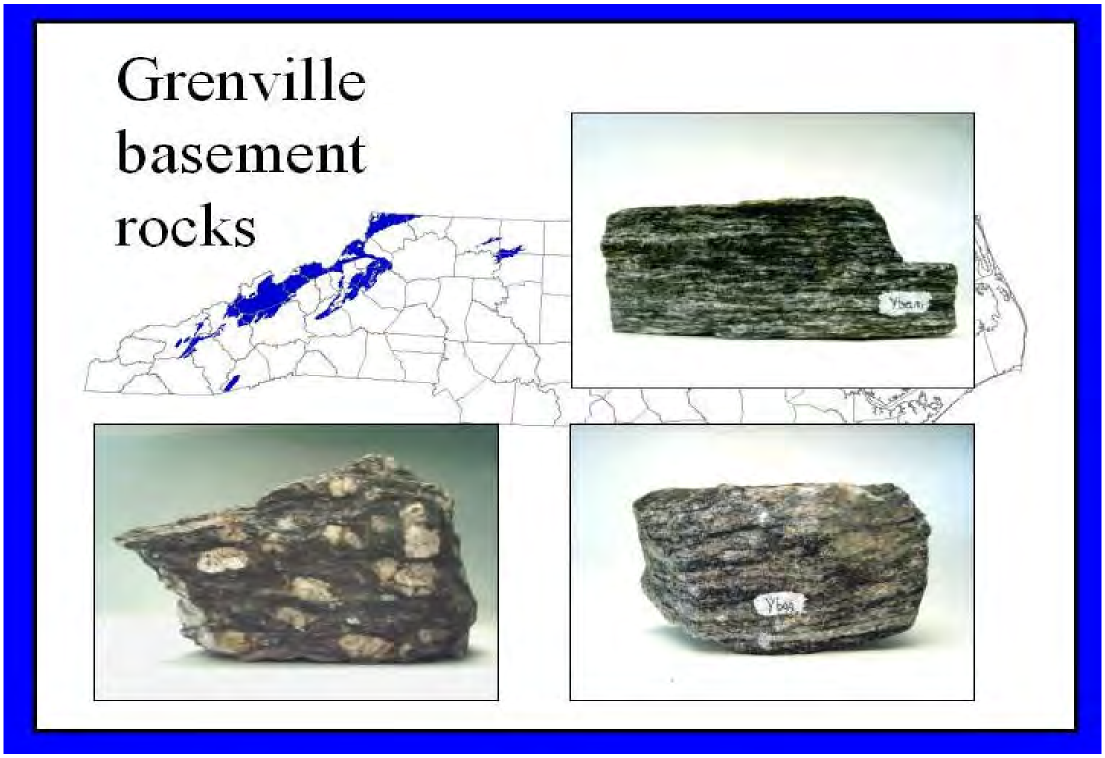
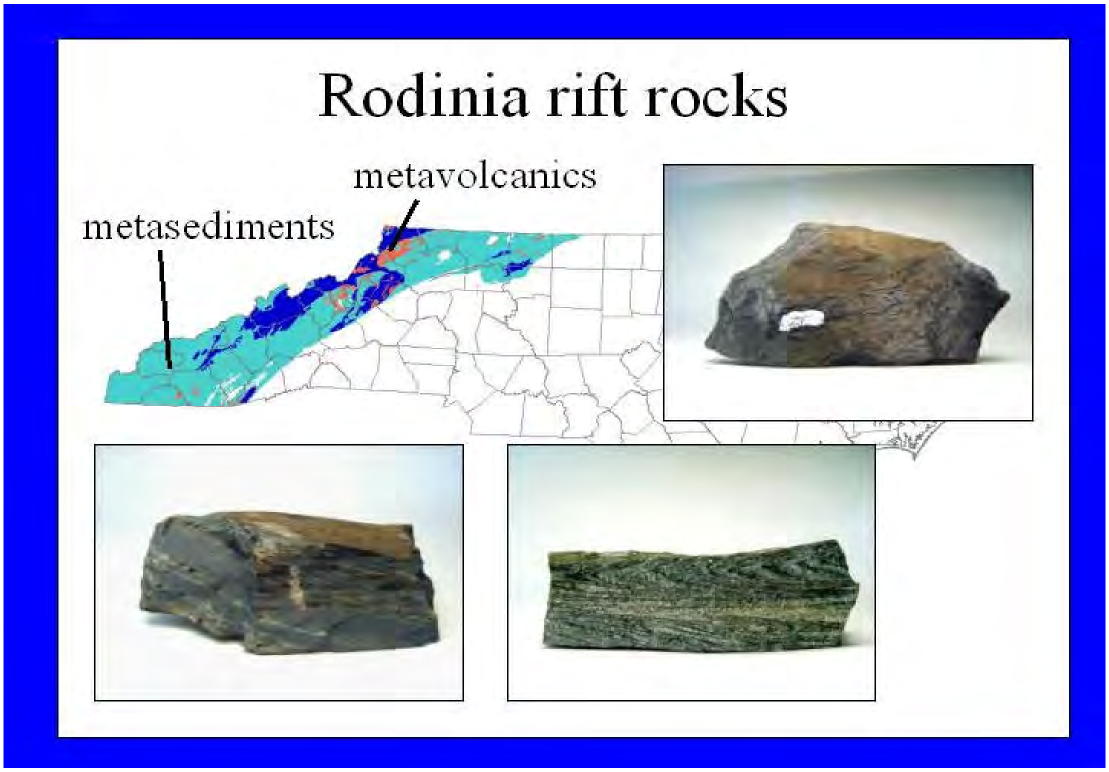


FIGURE 1 Geotectonic/Geochronologic map showing the four main geologic division of North Carolina.



Grenville basement rocks

FIGURE 2 Locations and examples of Grenville basement rocks in North Carolina.



Rodinia rift rocks

FIGURE 3 Locations and examples of Rodinia rift-related rocks in North Carolina.

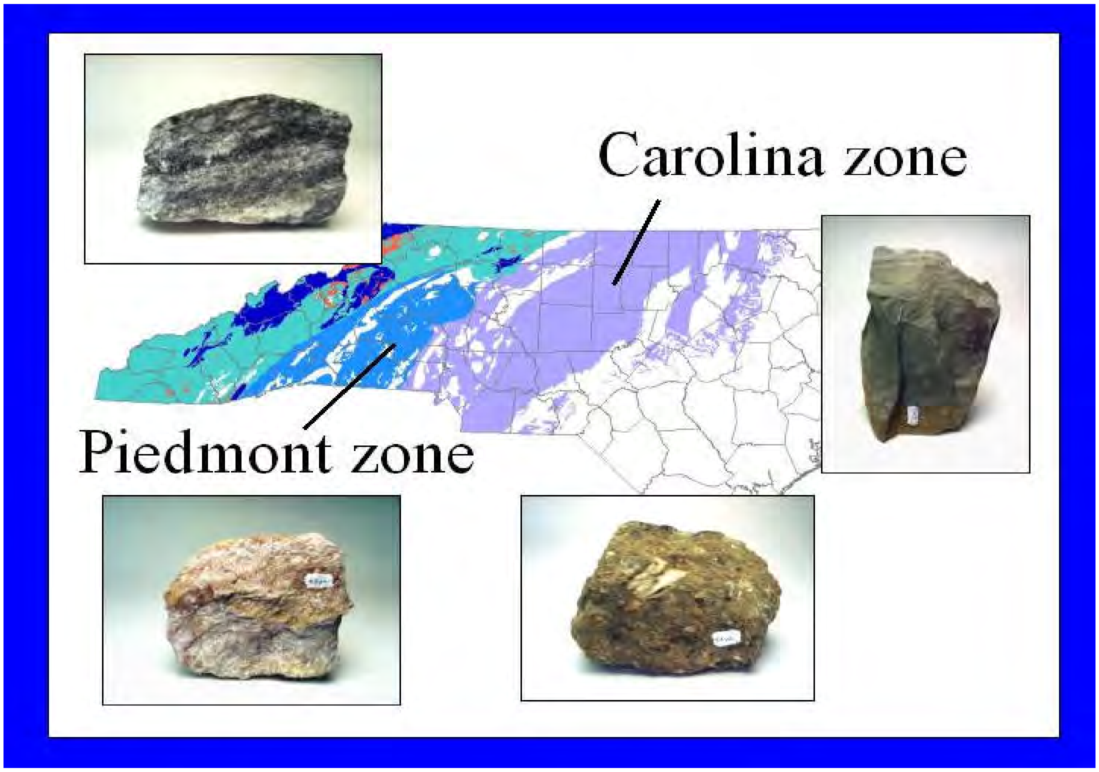
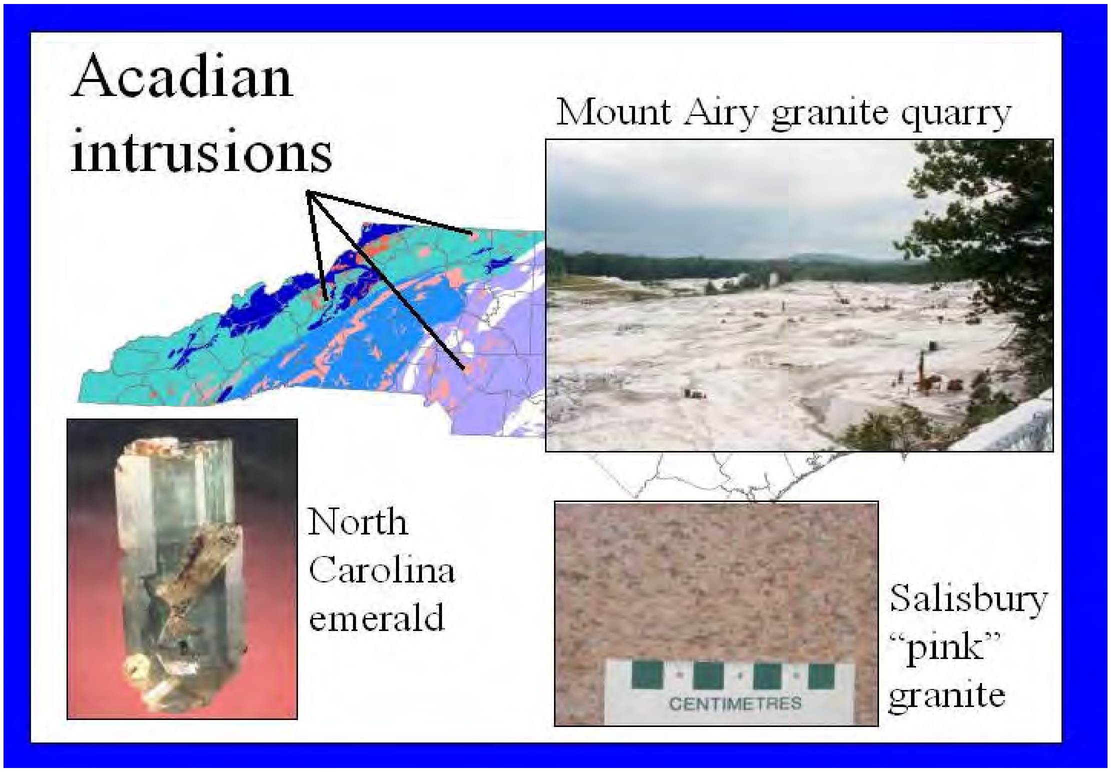


FIGURE 4 Locations and examples of Piedmont and Carolina zone rocks in North Carolina.



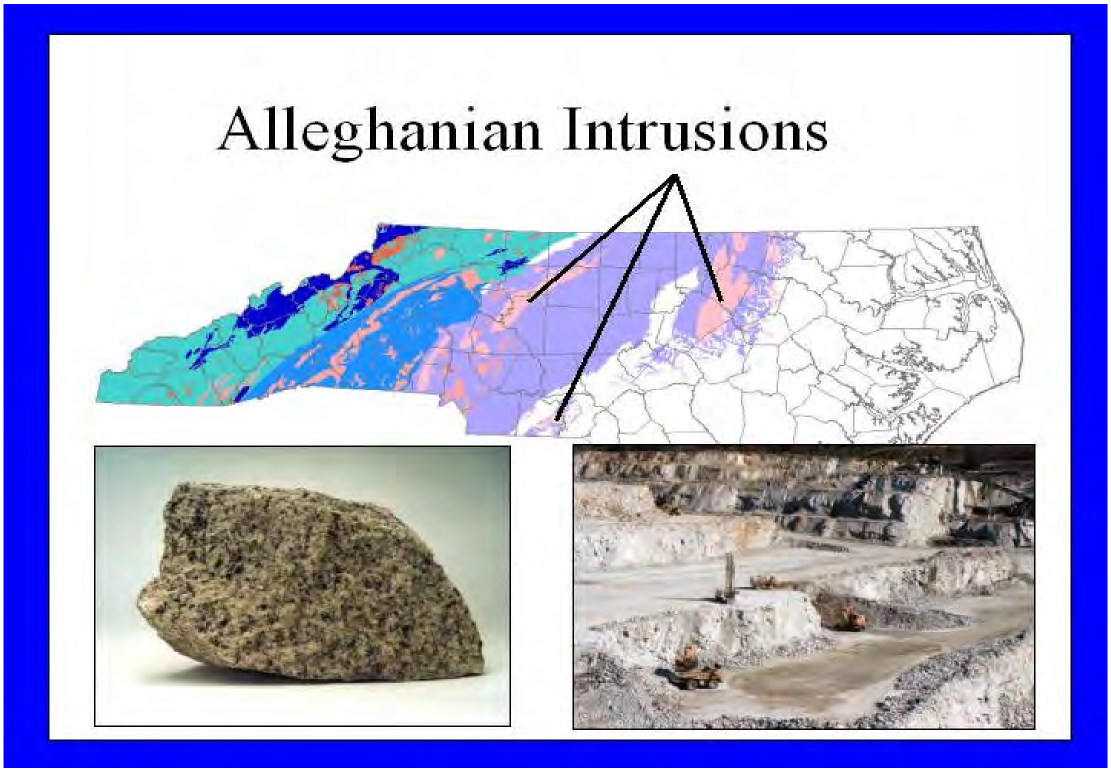
Acadian intrusions

Mount Airy granite quarry

North Carolina emerald

Salisbury "pink" granite

FIGURE 5 Locations and examples of Acadian-age intrusive rocks in North Carolina.



Alleghanian Intrusions

FIGURE 6 Locations and examples of Alleghanian intrusive rocks in North Carolina.

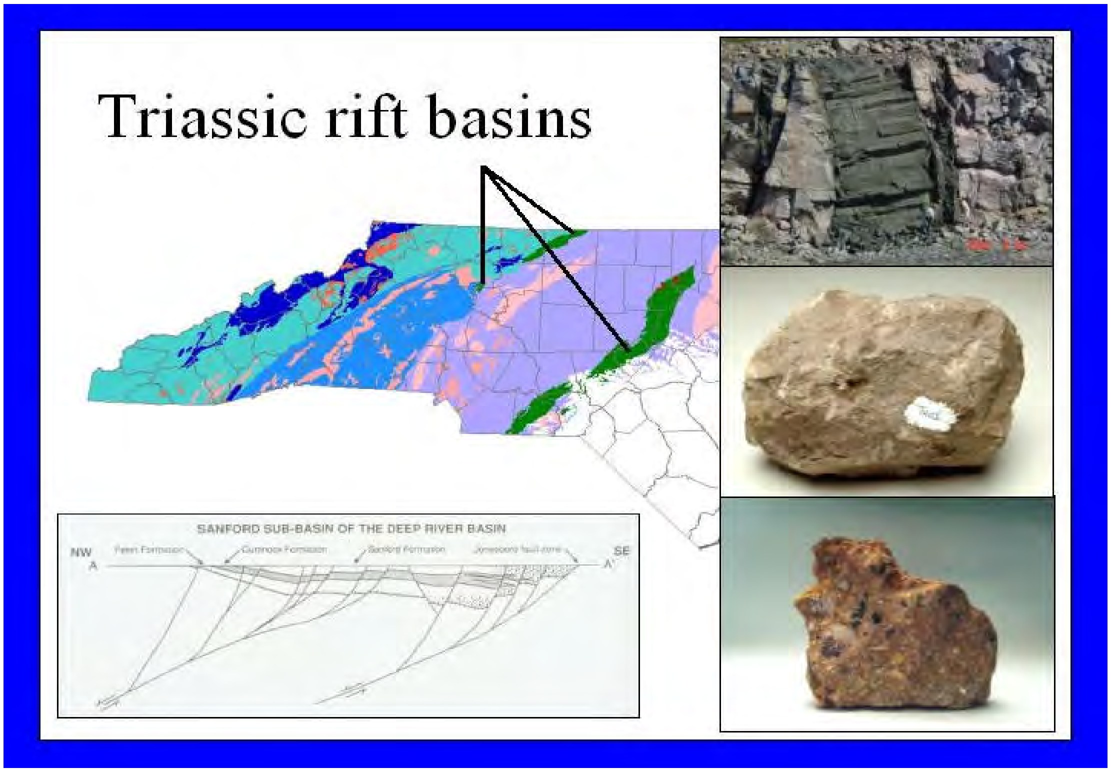
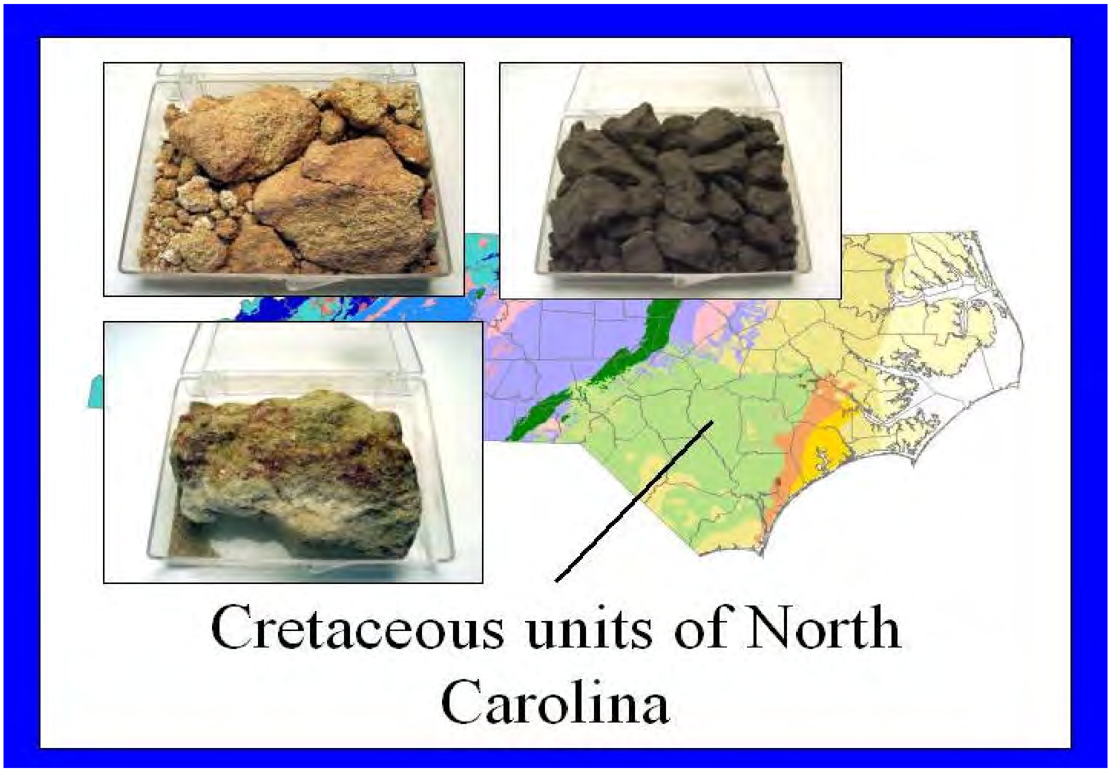


FIGURE 7 Locations and examples of Triassic rocks in North Carolina.



Cretaceous units of North Carolina

FIGURE 8 Locations and examples of Cretaceous units in North Carolina.

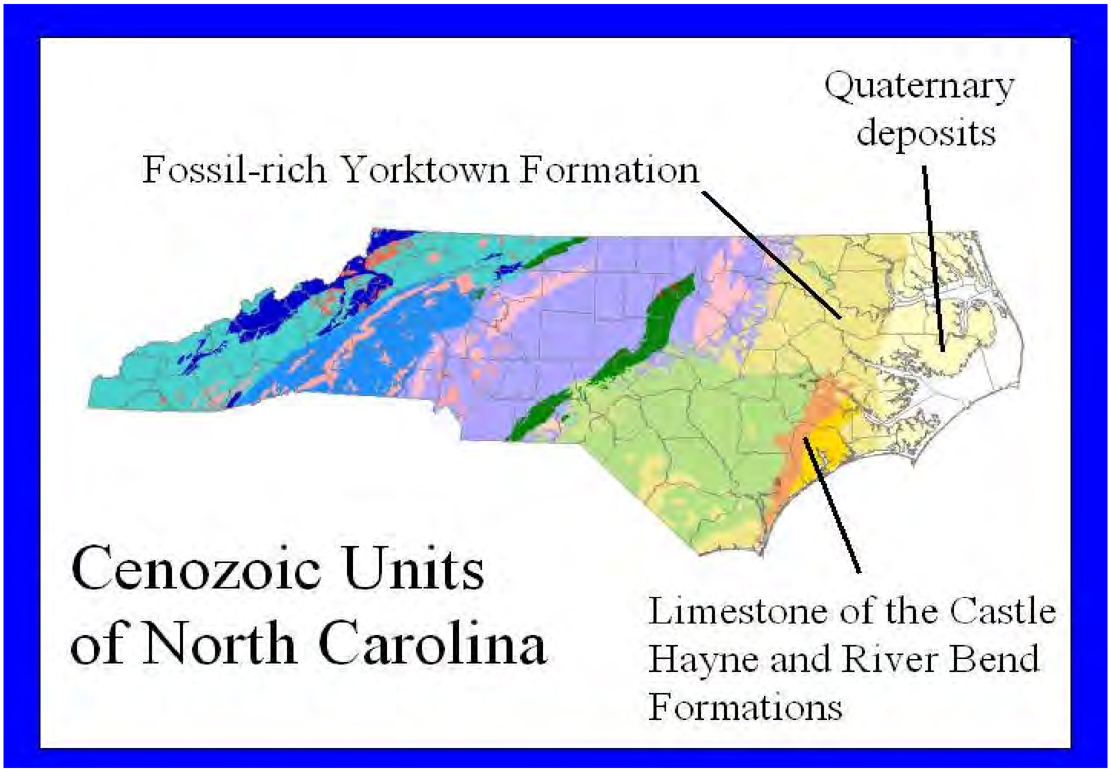


FIGURE 9 Locations and examples of Cenozoic units in North Carolina.

North Carolina: An industrial mineral storehouse

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ABSTRACT

North Carolina, USA, an industrial minerals storehouse, produced $846 million in 2005 (not including ultrapure quartz and synthetic gemstones). Estimated total mineral production is ~$1 billion—about 5% of North Carolina's annual state budget. All mining is from 785 permitted active mines that cover 112,857 permitted acres, or only ~0.37% of the state's ~48,000 square miles of land area. This is about $7,400 per permitted acre. Per capita mineral production is about $100 per year. The overall direct and indirect economic impact of mining is about $11.3 billion annually.

The North Carolina Mining Act of 1971, requires anyone affecting one acre or more of land for the purpose of mining must obtain an approved complete mining permit. The application must include information concerning the mining operation, a detailed mine map, and a final reclamation plan for the restoration of all affected land.

Crushed stone remained North Carolina's leading nonfuel raw mineral resource accounting for about 70% of the State's total value of nonfuel raw mineral production. Other major commodities include phosphate rock, construction sand and gravel, industrial sand and gravel, feldspar, dimension stone, common clays and mica.

North Carolina generally leads the nation in the quantities of feldspar (60% of the United States' consumption), common clays, mica, olivine, and pyrophyllite produced; the latter two were produced in only one other state and North Carolina. About 90% of the world's high purity quartz is mined and processed in western North Carolina for the electronic industry. Significant quantities of construction sand and gravel and dimension stone were produced in the state. Metal production in the State, especially that of primary aluminum and raw steel, resulted from the processing of recycled materials or raw materials received from other domestic and foreign sources.

The Minerals Research Laboratory (MRL) of North Carolina State University is a world class mineral processing facility and works with domestic and international private industry. MRL also collaborates with the North Carolina Geological Survey on state-sponsored mineral resource projects.

North Carolina offers good ocean ports for international commerce, inland ports, rail and road systems, international airport cargo hubs and economic development zones. The ocean ports of Morehead City and Wilmington may become hubs for ocean delivered aggregates from elsewhere on the US East Coast or even from Canada – the Morehead City port is already an important mineral export facility. Several industries provide value added for industrial and metallic minerals including specialty steel production, fiberglass insulation and fiber optic production.

(continued)

This state mineral resource overview provides information and data resources available for the “New Stone Age” – a time of renewed interest and focus on industrial minerals, aggregates, domestic and international infrastructure development, and national security.

Reid, Jeffrey C., 2006, North Carolina: An industrial mineral storehouse, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey**.**

INTRODUCTION

This report provides a brief overview of the industrial minerals in North Carolina and resources to assist mineral exploration and development. North Carolina produced $846 million in 2005 (not including ultrapure quartz and synthetic gemstones). Estimated total mineral production is ~$1 billion—about 5% of North Carolina's state budget. The overall direct and indirect economic impact of mining in North Carolina is about $11.3 billion annually (National Mining Association, 2006).

Industrial minerals are mined throughout North Carolina in the Mountain, Piedmont and Coastal Plain provinces. Figure 1 shows the major mining districts exclusive of crushed stone, sand and gravel. Sand and gravel are mined in about half the counties – mostly in the eastern part of North Carolina. A variety of igneous and metamorphic rocks are quarried in many Mountain and Piedmont counties for the production of crushed stone and dimension stone. The Coastal Plain has a few limestone quarries which produce crushed stone and agricultural limestone. Figure 2 shows important industrial mineral mining districts in North Carolina in relation to generalized geologic units of North Carolina.

INDUSTRIAL MINERALS

Clay

Common clays suitable for the manufacture of brick and tile products are found throughout the Coastal Plain, Piedmont and Mountain provinces. These clays provide raw materials for the manufacture of bricks. North Carolina is annually the nation's leader in brick production. In Lee and Moore counties, clays are mined from Triassic sediments. Mines in the central Piedmont obtain clays from weathered slate belt rocks. In addition to face brick, other major clay uses are for lightweight aggregate, cement, common brick, sewer pipe, and to a lesser extent, structural drain tile and glazed tile. Allen and Likes (1980) and Broadhurst (1950) provided a summary of the clay and shale resources of the Piedmont.

Kaolin is recovered as a byproduct of mica-beneficiation in Avery and Cleveland counties. Most of it is used in the manufacture of white-colored brick. There is an accelerated trend to automation using robots in brick plants in North Carolina and throughout the brick industry. Several new brick-making plants have been built and these are fully automated.

Crushed Stone

For many years, crushed stone has been the leading mineral commodity by value and tonnage in North Carolina. Crushed stone accounts for almost two-thirds of the total mineral production value in the state. Leading counties in the production of crushed stone are Wake, Mecklenburg, Guilford, Forsyth and Buncombe. An overview of crushed stone resources, production history and examples of crushed stone can be viewed on the North Carolina Geological Survey virtual crushed stone tour at:

http://www.geology.enr.state.nc.us/NAE%20aggregates%20Internet%20NRC%20with%20USGS%20sheet/Aggregate%20overview%20new.htm.

Granite and other crystalline rocks in the Piedmont and Blue Ridge geologic belts provide the principal sources of crushed stone in North Carolina. Small amounts of construction sand are obtained from granitic saprolites in the Piedmont. Other quarries are located in the dense fine-grained rocks of the Carolina Slate belt. Dolomite crystalline limestones and marble are quarried, in limited amounts, in the Piedmont and Mountain regions. Shell limestone from the Castle Hayne and River Bend formations and Rocky Point Member of the Peedee Formation are the primary sources of crushed stone in the Coastal Plain.

Dimension Stone

Dimension stone in North Carolina is produced from granite, argillite, quartzite, marble and sandstone Councill (1954a,b), and Carpenter (1983, 2001). An overview of building stone resource, production history, examples of dimension stone and suggested references for additional information mentioned in this section can be viewed on the North Carolina Geological Survey virtual dimension stone tour at:

http://www.geology.enr.state.nc.us/03072002buildingstones/NC%20building%20stones/Building%20stones/Dimension%20stone%20overview.htm

The North Carolina Granite Corporation operates one of the largest granite dimension stone quarries in the world at Mt. Airy in Surry County. A finishing plant is located on site. The Mount Airy ‘granite,’ a light-colored biotite granitoid (monzogranite) (Dietrich, 1961), is used as street curbing, ashlar for masonry walls, rubble, rip-rap, monuments and sawed slabs for buildings. Dimension granite is also quarried in Rowan County from light-colored gray to pink granite of the Salisbury pluton. The granite is used for foundations, street curbing, paving and monuments.

Dimension stone blocks are also shipped overseas for cutting and finishing; some finished material is returned to the United States for sale. North Carolina’s building stones face many buildings in the United States and overseas.

Dark bluish-gray argillite (Mudstone Member of the Cid Formation) is quarried by Jacobs Creek Stone Company from slate belt rocks in Montgomery and Davidson counties, North Carolina. This stone’s smooth, natural cleavage allows it to be used extensively in flooring, stair treads, borders and window sills.

A variety of rocks, such as metasandstone, quartzite, phyllite, amphibolite and other metamorphic rocks and mylonites are quarried in the Blue Ridge and Piedmont for dimension stone uses and marketed as flagstone. Their fissility is enhanced by mylonitization in many cases. Rounded river rock is also sold as part of the general flagstone market. Many of the flagstone products are sold under diverse trade names. Marble was quarried near Murphy as market conditions dictate in years past.

Sand and Gravel

Sand and gravel used for construction purposes are mined in about half the countries in North Carolina. The Sandhills region in Anson, Moore, Lee, Harnett and Richmond counties is the principle producing area. Much of the sand is obtained from the Pinehurst Formation. Gravel is mined from the overlying terrace gravels. Material from the area is shipped to many parts of the state and to South Carolina. In western North Carolina, Buncombe County is the largest producer of sand and gravel. Most sand is used for concrete aggregates, asphaltic concrete and fill.

Industrial sand is mined primarily in Anson and Richmond counties in the Sandhills region. Additional tonnages are also obtained during feldspar and lithium beneficiation in the Spruce Pine and Kings Mountain areas. Most of the sand is used in the container and flat-glass industries and also for ferrosilicon, filtration, sandblasting and traction industries.

North Carolina Geological Survey staff geologists in cooperation with many state, federal and university parties have undertaken sand resource studies in state coastal waters in recent years. Reports of investigations include seismic, side-scan, vibracore, grain size and mineralogy studies.

Feldspar

Feldspar was first mined in North Carolina in 1911 in the Spruce Pine district, the main feldspar-producing district in North America. Original mining was from pegmatite bodies but current mining is from alaskite, a very coarse-grained, light-colored, feldspar-quartz-muscovite rock. Composition of the rock averages about 40 percent plagioclase (soda-spar), 25 percent quartz, 20 percent microcline (potash-spar), and 15 percent muscovite. The alaskite is processed using a three-stage acid circuit flotation (Wiener and Merschat, 1990). Production is from mines in Mitchell County, but a company in the Kings Mountain area recovers a feldspar-silica concentrate during mica beneficiation.

The main uses of feldspar are in whiteware, tile and glass fiber insulation. Feldspar is used both in the body of the ware and in the glaze of ceramics. Example publications of the North Carolina Geological Survey are Speer (1996), Parker (1952), Olson (1952), Cameron (1951), and Bundy and Carpenter, 1969). Carpenter and other (1995) provided field and laboratory data on potassic- and sodic feldspar in saprolite as glass raw materials.

Mica

Mica mining began on a large scale in western North Carolina about 1868. Selected reports include Ballew (1992) that provide a listing of mica mines located in the Blue Ridge of North Carolina. These extensive mineral commodity files of mica mines provide considerable detail about each of several hundred mica mines and prospects, and in many cases geologic maps. During World War II these files were "Confidential" because of the war effort. Duplicate files, with small differences, are maintained in the North Carolina Geological Survey's Swannanoa and Raleigh offices:

- http://www.geology.enr.state.nc.us/Mineral%20resources/Asheville_commodityfiles.html

- http://www.geology.enr.state.nc.us/Mineral%20resources/Archdale_commodityfiles.html

Other selected reports include Carpenter and others (1995), Kesler and Olson (1942), Olson and others (1968) and Lesure, (1968).

The area is the most important producer of mica in the United States. Sheet mica was the principal product for many years, but other materials have eliminated many of the uses for sheet mica. Consequently, North Carolina has not produced significant amounts of sheet mica since about 1962. Flake or “scrap” mica is still produced in large quantities. Primary sources are alaskite and granite.

North Carolina annually leads the nation in the production of flake “scrap” mica, accounting for about 60 percent of the total production. Primary production is from Mitchell County in the Spruce Pine district, and in Cleveland County in the Kings Mountain district. Mica is also produced as a co-product of feldspar, silica and kaolin mining.

Both wet- and dry-ground products are produced. Dry-ground mica is used primarily in the manufacture of gypsum plasterboard joint cement, wallboard, and well-drilling muds. Wet-ground mica is used in cosmetics, paint and plastic manufacture.

High-purity quartz and glass sand

The Spruce Pine District in western North Carolina is the only producer of high-purity quartz in the world (Brobst, 1962; Kessler and Olson, 1942; Olson, 1944; Parker, 1946, 1952; Swanson, 2006; Tappen and others, 2006; Millington and others, 2006; Glover 2006). In fact 90% of the world’s high purity quartz is mined and processed in western North Carolina for the electronic industry. Aboriginals mined in the Blue Ridge Mountains during the Woodland period – a neglected aspect of North Carolina prehistory (Margolin, 2006).

Mensah-Biney and Reid (2006), reported on field and laboratory study of Iota grade quartz from stockwork quartz veins associated with pyrophyllite in Montgomery County, North Carolina.

Glass sand is mined on the Inner Coastal Plain. (Mensah-Biney and others, 2005, 2006) report laboratory investigations on sand samples from the Pinehurst Formation in Richmond County, North Carolina. Laboratory beneficiation methods were successful in producing a glass sand product using split-spoon samples of six drill cores, 0.0- to 60.0 feet deep within approximately 2,800 acres underlain by the Pinehurst Formation.. Indicated reserves by drilling are approximately 36.8 million short tons. The Pinehurst Formation is currently being investigated as a potential frac sand by the Minerals Research Laboratory and the North Carolina Geological Survey).

Wiener and others (1990) reported geologic and mineral-dressing data to evaluate the upper part of the Cambrian-age Chilhowee Group rocks in northern McDowell County, North Carolina, as a source of high-silica material. Previous investigations demonstrated that quartzites of the upper Chilhowee in this area are a potential silica resource (Broadhurst, 1954). Mineral-dressing data show the silica concentrate is coarse enough for plate glass and container glass. With additional grinding the remainder of the concentrate would probably meet most market specifications for fine-ground silica.

Quartz is also produced from the Kings Mountain District.

Lithium (spodumene)

Although first recognized as early as 1906, the economic significance of the spodumene-bearing pegmatites of the Kings Mountain district was not realized until 1942. Today, this relatively small area in Cleveland and Gaston counties contains ore reserves and probable reserves of 70 million short tons of 20 percent spodumene or 1.5 percent Li_2O. This represents than 80 percent of known lithium (spodumene) reserves. Broadhurst (1956) summarized the occurrence of lithium in North Carolina.

The lithium-bearing pegmatites crop out along a 1-mile-wide zone on the west flank of the Kings Mountain Shear zone that separates high-grade metamorphic rocks of the Inner Piedmont on the west from lower grade metamorphic rocks of the Kings Mountain belt on the east. The pegmatites contain approximately 20 percent spodumene, 32 percent quartz, 27 percent albite, 14 percent microcline and 6 percent muscovite. The pegmatite zone was originally referred to as the tin-spodumene belt because cassiterite occurs in some pegmatites in this zone.

Lithium (spodumene) mineral production ceased with the 1998 closure of the FMC Corp. mine south of Cherryville. The overburden is currently being processed for aggregate. FMC's Lithium Division produced a full range of downstream compounds, lithium metal, and organic lithium compounds at its facilities in Bessemer City, North Carolina (Ober, 2004). Lithium is also used in the manufacture of ceramics, glass, greases, TV glass and batteries.

Olivine

Olivine occurs as isolated dunite bodies in the Blue Ridge. Two main districts, the Webster-Balsam district in Jackson County and the Spruce Pine district in Yancey and Mitchell counties, have produced most of the olivine (Parker, 1952; Hunter, 1941). The deposits contain 50 to 90 percent olivine. Vermiculite and anthophyllite asbestos also occur in the same rocks as the olivine and have been mined in the past (Conrad and others, 1963; Murdock and Hunter, 1946). North Carolina leads the nation in olivine production, although production is presently limited to the Daybook Mine in Avery County and another as economic conditions dictate near Burnsville in Yancey County.

Olivine, a magnesium silicate, is a refractory and is chiefly used as a molding sand in the foundry industry. Olivine is being studied for use in heat-storage blocks for heat-storage furnaces and as a silicosis-free alternative to quartz in sand blasting.

Olivine production as a fluxing agent has declined in recent years because of a decline in steel production and more significantly because of increased competition from olivine imports.

Phosphate

Florida and North Carolina accounted for more than 85% of total domestic output; the remainder was produced in Idaho and Utah (USGS, 2006). In the late 1950s, a phosphate deposit was found beneath a large portion of Beaufort County in the Miocene Pungo River Formation (Miller, 1987; Kimrey, 1965). Subsequent exploration delineated a minable ore body that contained about 2 billion tons of phosphate ore.

Phosphate is produced by PCS (Potash Corporation of Saskatchewan), from the large open-pit Lee Creek mine located near Aurora in Beaufort County. PCS is the largest single integrated phosphate mine in the country. The major portion of the output from this mine is used in nearby chemical facilities to produce phosphoric acid, triple superphosphate and diammonium phosphate.

Deposits of phosphorite also occur off North Carolina's coast in the northeast Onslow Bay district and the Frying Pan Shoals district (Riggs and v.d.P. Ames, 1992;

Snyder and others, 1993; Crowson and others, 1994). The lower part of the Pliocene Yorktown Formation contains phosphorite in the Aurora phosphate district and represents a potential resource. Further exploration may lead to production from these deposits.

Pyrophyllite, Talc and Andalusite (Refractory minerals)

Pyrophyllite, a high alumina mineral, in North Carolina occurs exclusively within hydrothermally altered felsic volcanic rocks of the Carolina Slate Belt (Broadhurst and Councill, 1953; Stuckey, 1928; Pratt, 1900). The Piedmont, composed of metavolcanic centers and intervening metasedimentary rocks intruded by subvolcanic centers, has been extensively prospected in the past for gold and massive sulphide deposits.

The mineral was first mined commercially in North Carolina in 1855 and has been mined almost continuously since that time. Pyrophyllite is mined near Robbins and Glendon in Moore County and at Hillsborough in Orange County. Major pyrophyllite uses are in the refractory, ceramic, paint, insecticide industries and as joint compound filler. The Orange County deposit contains andalusite in addition to pyrophyllite. Other pyrophyllite deposits in the Slate Belt have been mined and prospected and may provide additional reserves.

Resco announced the installation and start up of a new kiln at its Greensboro, North Carolina plant in March 2005. The kiln is of roller hearth design; concurrently Resco reported upgrades to auxiliary drying equipment to enhance capabilities. The physical properties by the new kiln meet those produced by the periodic kilns according to Resco's quality assurance studies (Block Talk, 2005). A variety of colors and surface textures produced using the new kiln.

Talc deposits are associated with the white, siliceous, dolomitic Murphy Marble in Cherokee and Swain counties. These deposits were mined as early as 1859 but are currently inactive.

Roofing granules

Luck Stone mines andesitic metavolcanic rock from the Central Carolina Slate Belt. The mine produces a green-colored andesite utilized on site by 3M's Pittsboro plant for the production of roofing shingle granules. Roofing granule production started in 2002 using crushed metavolcanics rocks. 3M uses the latest technology to provide colors to the andesite used in its roofing granules. A unique aspect of the operation is that Luck Stone has one entire circuit of their plant dedicated solely to providing material to 3M which is the plant's largest single customer (3M press release of August 12, 2002). The crushed stone is coated using a proprietary process and used in composite shingles. The Luck Stone plant also blends volcanic tuffs with other volcanic types for aggregate use.

Garnet and other abrasives

Significant reserves of garnet occur in western North Carolina (Mensah-Biney and Reid, 2004). Collaborative investigations between the North Carolina Geological Survey and the North Carolina State University's Mineral Research Laboratory are in progress of investigating the potential of garnets from an ecolgite as an abrasive.

Pratt and Lewis (1905) provided a comprehensive report on the geology, mineralogy, petrology, prospecting and milling of corundum and the peridotites of western North Carolina and includes discussion of emery deposits. Lewis (1896) provided preliminary information on corundum and peridotites of western North Carolina.

Heavy Minerals

Deposits of heavy minerals, including ilmenite, rutile, and zircon have been discovered in the upper Coastal Plain of North Carolina and Virginia (Carpenter and Carpenter, 1991) and elsewhere (Williams, 1964). Total reserves are estimated at 25 million short tons of heavy minerals. In North Carolina, the deposits are located in Wilson, Nash and Halifax counties. Deposits near Roanoke Rapids and in the Aurelian Springs and Bailey areas have been considered for development. The National Uranium Resource Evaluation (NURE) geochemical data was useful in delineating these deposits (Reid, 1991, 1993; Carpenter and Reid, 1993a-1993hh).

Gemstones, natural

North Carolina has long been famous for the variety of precious and semi-precious stones found in the Piedmont and Mountain regions of the state (Kunz, 1907; Wilson,1962; Conley, 1958). Several dozen commercially operated collection localities are open to the public. Amateur collectors search for emeralds, rubies, sapphires, hiddenite, garnet, and other semi-precious stones. North Carolina ranks first in the east in the mining and marketing of gemstones and minerals specimens.

The main gem-collecting counties are Alexander (emeralds and hiddenite), Macon (rubies, sapphires, and garnets), and Mitchell (emeralds and aquamarine). Commercial gem mining for emerald occurs in Alexander County, North Carolina, associated with pegmatites of early- to mid-Paleozoic age intrusions.

Gemstones, synthetic

Charles & Colvard manufactures moissanite, a synthetic gemstone rivaling aspects of diamond, in Morrisville, North Carolina. Raw material, silicon carbide, is received from two sources. Once formed into ingots the material is graded, cut into individual preforms using computer controlled machinery and faceted in the Far East. The faceted stones are returned to Morrisville, North Carolina, for grading and placed into inventory for customers. Retail chains reported to carry moissanite include Lord & Taylor, Marshall Fields and J.C. Penny among others.

Other Non-metallic Minerals

Additional minerals may eventually be discovered in economic quantities in North Carolina. Monazite, a mineral that contains rare earth elements, was once mined in the western Piedmont, and occurrences are also known in the eastern Piedmont (Nitze, 1895; Mertie, 1975; Overstreet, 1968,1971). Monazite, ilmenite, and rutile may also occur with other heavy minerals offshore.

The source of 13 diamonds (Kunz, 1907) found in North Carolina during the mid to late 1800s has not been determined. Earlier exploration models are reported to have been kimberlites; a lamproites exploration model has been proposed (Reid and others

1991). Lamproites in the Charlotte (Mecklenburg County) area may provide clues to the source of these diamonds and for diamond prospecting in other areas of the Piedmont. The geologic map by Goldsmith and others (1988) shows several localities.

Other non-metallic minerals include sillimanite (Hash and Van Horn, 1951; Hunter and White, 1946), barite (Van Horn and others, 1949), talc (Van Horn 1948), halloysite (Hunter and Hash, 1949), vermiculite (Murdock and Hunter, 1946), anthophyllite asbestos (Conrad and others, 1963), residual kaolin (Parker, 1946) and crystalline limestones in the Piedmont and mountains (Conrad, 1960).

Synthetic gypsum

The Clean Air Act of 2002 required utility companies burning high-sulfur coal and releasing sulfur dioxide into the atmosphere to reduce their sulfur dioxide emissions. As a result, utility companies have formed partnerships with wallboard companies to convert byproduct sulfur into synthetic gypsum, which can be used in the manufacture of wallboard. In the past, synthetic gypsum would have been sent to landfills as a combustion byproduct from the burning of coal. North Carolina's two major electric utilities, Progress Energy, Inc. and Duke Energy Corp., announced plans to sell byproduct gypsum rather than sending it to a landfill. High-volume gypsum wall board plants will be built adjacent to coal-fired utility power plants.

Mineral Fuels

Mineral fuels provide the primary sources of energy currently consumed in the world. They include coal, petroleum, natural gas, and uranium. North Carolina is deficient in the mineral fuels and must import these resources from outside sources in order to meet its energy requirement.

Coal

Only one area in North Carolina is known to contain coal beds of potential commercial importance (Reinemund, 1955). This area is the Deep River coalfield that lies along the Deep River in Chatham, Moore and Lee counties. The coalfield is in the Deep River Triassic Basin and occupies a zone about 35 miles long and 5- to 10 miles wide. Its center lies about 10 miles northwest of Sanford, North Carolina.

The medium volatile bituminous coal occurs in beds in the Cumnock Formation. It is associated with shales, siltstones, and sandstones. Coal beds in the Cumnock Formation range from a few inches to 48 inches thick.

Coal was mined intermittently in the past with a production of 1,070,000 short tons. Most of this production came from the Cumnock and Carolina mines and all but a few hundred tons came from the Cumnock coal bed. Of the estimated 110,337,000 short tons of steam and coking coal reserve, only half is recoverable and is in the Cumnock coal bed (Reinemund, 1955). However, because of the presence of faulting in the area, less than half of this coal might be mined. In order to recover a large quantity of coal from this area, much subsurface structural geologic mapping and drilling must be done to determine the locations of faulted coal seams.

Peat

Fuel-grade peat deposits cover about 677,000 acres in Coastal North Carolina (Ingram,1987). Total reserves are about 500 million tons of moisture-free peat. These deposits formed in the past 10,000 years in swamps or pocosins, Carolina bays, and river flood plains. Most of the peat occurs at the surface with no overburden. The peat ranges from 1- to 15 feet thick and averages 4.5 feet thick. Production, to date, has been for use in agricultural products such as soil conditioners and potting soil. Other uses of peat include as a heat source, a feedstock for synthetic compounds, a waste treatment material, and as filter material.

Petroleum and Natural Gas

Approximately 125 exploratory oil and gas wells have been drilled in North Carolina since the first one was drilled in 1925. Most have been in the outer Coastal Plain. Traces of oil and gas have been detected in a few wells but there are no producing wells.

Several areas in North Carolina have been considered to have potential to produce oil and gas. The main area is the outer Coastal Plain where there have been a limited number of oil and gas test wells – some of which have penetrated basement rocks (Lawrence and Hoffman, 1993). It contains a relatively thick pile of sedimentary rocks including some excellent trap or reservoir rocks, but source rocks may not be present.

Seismic surveys in the Blue Ridge suggest that sedimentary rocks are deep beneath the crystalline rocks. These sediments may be similar to oil- and gas-bearing sediments in the Valley and Ridge Province. Detailed studies have been conducted to verify the seismic surveys.

The Triassic basins have received attention from oil and gas exploration companies during recent years. Excellent source rocks are present, but the sandstones are not permeable. Fine-grained material fills pore spaces between the sand grains, preventing the migration of hydrocarbons. The Cumnock and Gulf coal beds have been studied for possible *in situ* methane gas generation (Hoffman and Buetel, 1991; Reid and Milici, in preparation).

Mobil Oil Corporation and other interests proposed to drill for natural gas on the Atlantic shelf off the North Carolina coast in federal waters ranging from 2,100- to 2,700 feet deep in an area known as the Manteo Unit Exploration (Minerals Management Service, 1998 – http://www.gomr.mms.gov/homepg/regulate/environ/studies/1998/98-0024.pdf; http://www.gomr.mms.gov/homepg/offshore/atlocs/manteo.html). However, following a protracted period of State opposition, the Federal government canceled offshore leases and repurchased many of the leases.

Uranium Minerals

A number of the uranium-bearing minerals occur as minor constituents in the pegmatites of North Carolina and in other rocks (Councill, 1955). These pegmatites are principally in the Spruce Pine district and adjacent areas. Radioactive minerals have been found in schists and underlying granitic rocks in northern Burke, Mitchell, Avery and adjacent counties. However, it is not likely that any of these occurrences is large enough to be of commercial value. Trace amounts of uniformly distributed uranium are associated with the phosphate deposits in Beaufort County. The NURE stream sediment geochemistry data show uranium distribution in monazite minerals, heavy mineral deposits in the mineral zircon in the Fall Zone and elsewhere in North Carolina (Reid, 1991, 1993; Carpenter and Reid, 1993a-1993hh).

In 1982, Marline Uranium Corporation announced the discovery of a 30-million-ton uranium ore body in Pittsylvania County, Virginia. The ore body was in augen gneiss adjacent to the Chatham Fault, along the west side on the Danville Triassic basin. Because of a drop in uranium ore prices and local opposition to the project, these deposits were not developed. Similar rocks farther south in Rockingham County, North Carolina, were also explored.

METALLIC MINERALS

Metallic minerals are associated principally with the igneous and metamorphic rocks of the Piedmont and Blue Ridge geologic belts. Ores of chromium, copper, gold, silver, iron, lead, zinc, manganese, molybdenum, nickel, tin, titanium, and tungsten all occur in either the Piedmont or Mountain provinces.

Although of little importance in the state's mining industry today, gold, copper, iron and tungsten were produced in the past. During the 1950s, the Hamme Mine in Vance County was the largest tungsten mine in the U. S. The mine was reopened as the Tungsten Queen Mine for a short time about 1970 but closed in the fall of 1971 because of declining tungsten prices. Considerable reserves of tungsten ore remain.

North Carolina was the nation's leading gold producer prior to the 1849 discoveries in California. Because of its geologic similarity to important metal mining districts in Canada, the Carolina Slate Belt has been an area of extensive exploration. It is considered a good site for the discovery of base metal deposits (copper, lead and zinc). Use of heap-leaching methods to recover gold from low-grade ore revived interest several years ago in the Slate Belt. The previous development of four mines in South Carolina had encouraged exploration in similar geologic settings in North Carolina in years past.

MINERAL PRODUCTION, PERMITTING AND PRODUCTION ON U.S. FOREST SERVICE LANDS

Mineral production on U.S. Forest Service lands consists of crushed stone and flagstone. Periodically there has been exploration interest in metallic minerals – especially gold on U.S. Forest Service lands. Mineral production on U.S. Forest Service lands has been modest and mostly from aggregate production. Recently flagstone extraction has selectively occurred. Mineral production statistics on U.S. Forest Service lands are not included with state statistics, nor does the state have permitting jurisdiction on federal lands. A minerals staff officer is posted in Asheville, North Carolina, handles permits and mineral inquiries. The general telephone number is 828.257.4200. The mailing address is National Forests in North Carolina, PO Box 2750, Asheville, NC 28802.

RESOURCES FOR MINERAL EXPLORATION AND MINING IN NORTH CAROLINA

Geologic maps

Geologic and topographic maps for North Carolina are being collected, scanned, georeferenced, and preserved in a collaboration between the North Carolina Geological Survey (NCGS) and North Carolina State University (NCSU) Libraries. The legacy geologic and topographic maps have no digital counterparts and paper copies are scarcely accessible. Geologic and historic maps are in high demand, and are critical for earth science instruction and research. Many of these geologic maps are accompanied by mineral resource summaries. Geologic maps, especially in the western part of North Carolina list heavy minerals panned from streams in map areas.

As of December 2005, the inventory consists of 113 U.S. Geological Survey geologic maps, 100 North Carolina Geological Survey geologic maps, 36 maps from theses and dissertations, and 165 legacy 15-minute topographic maps, all of which are backed up on multiple secure servers. Data are planned for dissemination through the North Carolina Department of Environment and Natural Resources and NCSU Libraries, and contributed to NCOneMap, the National Geologic Map Database and the National Geologic Map Image Library (Essic, Reid, Morris and Ramakrishnan, 2006).

Geochemical data

The North Carolina National Uranium Resource Evaluation (NURE) database consists of stream-sediment samples, groundwater samples, and stream-water analyses. All data are geospatially located by latitude and longitude. Maps for these analytes can be viewed on line at http://www.geology.enr.state.nc.us/NUREgeochem/geochem2.htm.

The statewide database consists of 6,744 stream sediment sites, 5,778 groundwater sample sites, and 295 stream-water sites. Neutron activation analyses were provided for U, Br, Cl, F, Mn, Na, Al, V, Dy in groundwater and stream water, and for U, Th, Hf, Ce, Fe, Mn, Na, Sc, Ti, V, Al, Dy, Eu, La. Sm, Yb, and Lu in stream sediments. Supplemental analyses by other techniques were reported on U (extractable), Ag, As, Ba, Be, Ca, Co, Cr, Cu, K, Li, Mg, Mo, Nb, Ni, P, Pb, Se, Sn, Sr, W, Y, and Zn for 4,619 stream sediment samples. A small subset of 334 stream sediment samples was analyzed for gold (Reid, 1991, 1993; Carpenter and Reid, 1993a-1993hh).

Airborne geophysical data

The US Geological Survey, in cooperation with the North Carolina Geological Survey, has statewide coverage of airborne geophysical maps. Many of the paper copies (not listed here for brevity) are available for purchase from the North Carolina Geological Survey. Interested parties should conduct a search of available geophysical data on the US Geological Survey's Library Internet site http://library.usgs.gov/.

Minerals Research Laboratory – Reports of Investigation

A searchable list of specially prepared mineral beneficiation reports prepared by the Minerals Research Laboratory (MRL) or North Carolina State University is at http://www.geology.enr.state.nc.us/Mineral%20resources/MRL.html

These reports bridge exploration, bench-scale, and pilot plant beneficiation studies to assist the minerals industry and also provide a wealth of information on North Carolina's mineral resources. The MRL's main focus is beneficiation studies of industrial minerals. MRL is located at 180 Coxe Ave., Asheville, North Carolina. Their telephone number is 828.251.6155. Their Internet site is: http://www.engr.ncsu.edu/mrl.

Annual state mineral chapters

These reports, in Adobe Acrobat^R .pdf format, provide annual overviews of mineral industry activities in North Carolina published by the U.S. Geological Survey in cooperation with the North Carolina Geological Survey. These are located at http://minerals.usgs.gov/minerals/pubs/state/.

Publications of the North Carolina Geological Survey

Additional information about the geology and mineral resources of North Carolina is available at the North Carolina Geological Survey's Internet site: http://www.geology.enr.state.nc.us.

A growing number of North Carolina Geological Survey geologic maps, reports and base data are digital. Many are in geographic information system (GIS) format. Reid and Medina (2005) released 182 digital raster graphic (DRG) 1:24,000-scale topographic maps of North Carolina that were revised between 1999 and December 2005 through a collaborative program between the North Carolina Geological Survey and the U.S. Geological Survey. Each map is a .tif image and is accompanied by a world file and federally compliant metadata.

Theses and Dissertations

The North Carolina Geological Survey maintains a large collection of theses and dissertations. The holdings and physical location of individual theses or dissertations are at http://www.geology.enr.state.nc.us/bibliogr.htm#Theses%20and%20dissertations.

Permitted mine inventory

The North Carolina Mining Act of 1971, requires anyone affecting one acre or more of land for the purpose of mining must obtain a mining permit. Obtaining a mining permit requires the submittal and approval of a complete mining permit application. The application must include information concerning the mining operation, a detailed mine map, and a final reclamation plan for the restoration of all affected land (Williams and others, 2006).

A list of permitted active and inactive mines in North Carolina is maintained at:

http://www.geology.enr.state.nc.us/Permitted_mines_20041130/Permitted_mines_North_Carolina_Geological_Survey.htm

Links are provided to regulatory staff, the Mining Act, Administrative Rules, the North Carolina Mining Commission, staff and forms.

Digital data

Digital data in geographic information system (GIS) is available at the state, local and federal level for North Carolina. For example many counties have their tax mapping system based on GIS. For the mineral explorationist this means that property parcels accompanied by very current orthoimagery is available. Statewide LiDAR coverage and traditional digital elevation models are available for the entire state. The North Carolina Center for Geographic Information and Analysis (CGIA) maintains a digital data clearing house and a corporate geographic database (http://www.cgia.state.nc.us/).

Carolina Geological Society – Field trip Guidebooks

The Carolina Geological Society (CGS) has an extensive collection of annual field trip guidebooks on line at http://www.carolinageologicalsociety.org/. The first available title is for 1952. The Carolina Geological Society's 50th Anniversary Volume (Horton and Zullo, 1991) provides a general overview of regional geology and other mineral deposits.

Ports

With the volume of international trade expected to double by 2020, forward-looking businesses and industries can get ahead of the curve by taking advantage of the services offered by the North Carolina State Ports Authority. North Carolina's Ports of Wilmington and Morehead City, plus inland terminals in Charlotte and in the Piedmont Triad at Greensboro, are "ready, willing and able" to serve as alternatives to ports in neighboring states for competitive access to the global markets. Owned and operated by the Ports Authority, North Carolina's port system combines modern facilities and abundant capacity with the commitment to excel in service to our customers (North Carolina Ports, 2006; http://www.ncports.com).

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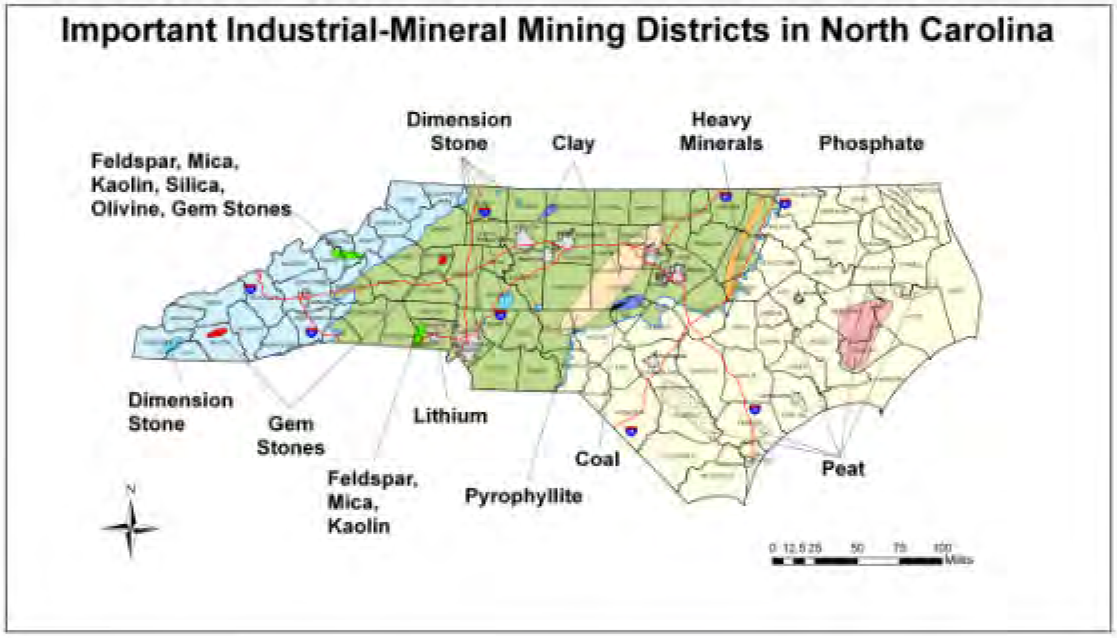

FIGURE 1. Important industrial mineral mining districts in North Carolina. The three main physiographic provinces are from the mountains (blue), Piedmont (green) and coastal plain (yellow).

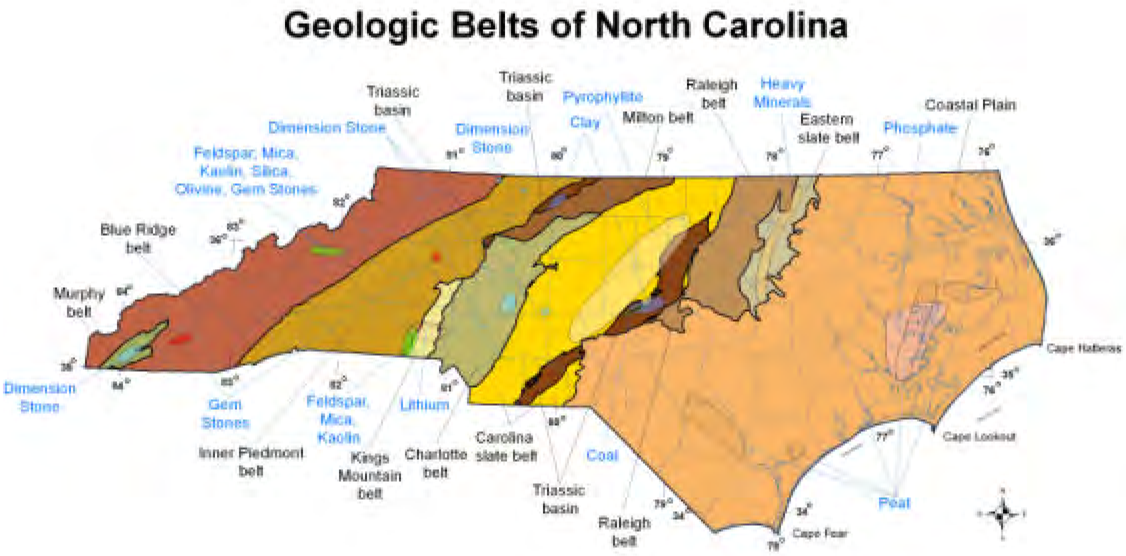

FIGURE 2. Important industrial mineral mining districts in North Carolina in relation to generalized geologic units of North Carolina. The named litho-tectonic features shown on this map are those from an inset map of the 'Geologic Map of North Carolina, 1985).

Controlling groundwater at PCS Phosphate mining operations – Aurora, Beaufort County, North Carolina

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ABSTRACT

PCS Phosphate and its predecessors have mined and processed phosphate ore at the Aurora Phosphate Mine in Aurora, North Carolina since 1965. The mine is located in the central coastal plain where the average surface elevation near the mining operations is approximately twelve feet above sea level. The mining sequence includes the removal of forty feet of unconsolidated overburden by using bucket wheel excavators followed by the removal of seventy-five feet of overburden and thirty-five feet of phosphate ore by large walking draglines. Controlling the influx of groundwater into the open surface mine is required in order to maintain safe, dry mining conditions to accommodate the extraction of the phosphate ore to depths that can exceed one hundred fifty feet below sea level.

PCS Phosphate controls groundwater ahead of the mine excavation by using wellpoints and shallow wells in the unconfined aquifer near the surface (Shallow Aquifer System). Typical withdrawals are approximately one million gallons per day. The ore deposit is underlain by a regionally extensive confined aquifer that exerts a significant pressure surface above the level of the ore excavation (Castle Hayne Aquifer System). A series of large diameter wells around the perimeter of the mine are utilized to depressurize the confined aquifer. Typical withdrawals are approximately sixty million gallons per day.

Groundwater withdrawals at the mine are regulated by the North Carolina Department of Environment and Natural Resources (NCDENR). Two water withdrawal permits are granted by the NCDENR for the purposes of controlling groundwater for mining operations. Impacts from the aquifer dewatering and depressurization are monitored as a condition of these permits.

Hydrologic monitoring includes the collection and analysis of groundwater data. The collection of the data began prior to mining and is ongoing. Groundwater withdrawals, groundwater levels, and water quality data are monitored. Additional hydrologic data are obtained from the United States Geological Survey (USGS). The groundwater monitoring system consists of a network of approximately two hundred twenty-five water level and water quality monitoring wells used to obtain data from the Shallow Aquifer System and the Castle Hayne Aquifer System.

Gilmore, I.K., 2006, Controlling groundwater at PCS Phosphate mining operations – Aurora, Beaufort County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

BACKGROUND

PCS Phosphate, formerly Texasgulf, Inc. (TGI), began phosphate exploration in eastern North Carolina (Figure 1) in 1958 and began acquiring land in 1961. In 1964, the company commenced construction of a mine, mill and mineral processing complex. The mill facilities included a washer, float plant, calciners, grinder, storage silos, and wet rock storage areas. The mineral processing facilities included plants to manufacture sulfuric and phosphoric acids, and solid fertilizer. The complex has undergone substantial expansion and modernization since 1965, including the addition of a 40-megawatt cogeneration facility, a purified acid plant and material storage facilities at the North Carolina State Ports Authority in Morehead City.

In 1985, the Aurora facility became the first phosphate mining and mineral-processing complex in the world to construct a by-product blending facility that combines mill clays and gypsum. The resulting gypsum/clay blend provides a sound reclamation base that consolidates rapidly, demonstrates soil characteristics, and supports a variety of grasses and trees. This unique solution to the material storage requirement enhances land reclamation timing and eliminates the need to consume new lands for separate clay and gypsum storage.

In 1985, TGI merged with North Carolina Phosphate Corporation (NCPC), a competitor preparing to mine from a 4,000-acre tract adjacent to the TGI complex. During 1987, TGI presented a modified mining plan to regulatory agencies which incorporated the more economical Bucket-Wheel Excavation System developed by NCPC, phased-out the dredges, and meshed the timing and logistics of mine progression, waste material storage, and land reclamation to the advance of the mining operation east into the NCPC tract. The Bucket-Wheel Excavation System began implementation in 1989. In April 1995, The Phosphate Division of TGI was purchased by Potash Corporation of Saskatchewan (PCS) and the mining operations resumed under the name of PCS Phosphate. With the permitted mining area comprising about 12,800 acres, a total of approximately 1,400 acres have been reclaimed and released from the mine permit. The mine location is shown on Figure 2.

The mining technique initiated in 1965 consisted of utilizing two draglines to remove the overburden and ore to depths of 100 to 140 feet below land surface (bls) or to elevations of 90 to 130 feet below mean sea level (msl). In 1977, the technique changed to utilize hydraulic dredges to excavate the overburden to a depth of about 30 to 40 feet bls. Once the first stage of overburden removal was completed, the dredge water was removed and the mine block allowed to dry for about 6 months before the draglines were moved into the excavation. The remaining overburden and the ore were then excavated by the draglines. In 1990, mining operations phased out the hydraulic dredges and began to utilize bucket-wheel excavators to excavate the upper section of the overburden. Utilization of draglines to remove the remaining overburden and the ore continued. Due to the depth of the ore, approximately 100 to 140 feet bls, and the high potentiometric surface of the Castle Hayne aquifer, it has been necessary to depressurize the artesian head in the upper Castle Hayne unit to maintain the dry-pit mining conditions.

Until 1988, dewatering of the overburden was not required. However, as the mine moved south and east it encountered a shallow water bearing formation termed the Channel Sand unit. This unit hindered mining operations due to the seepage into the pit and resulted in unstable and unsafe high-wall conditions. A dewatering system consisting of a series of shallow wells was constructed in the Channel Sand. In 1990, when the dredges were replaced with the bucket-wheel excavators, it became necessary to construct a dewatering system for the top section of the overburden. The bucket-wheel excavators are hampered when working the mine face without dewatering due to the seepage of groundwater at the face. The system consists of shallow-well points constructed in advance of the excavation. In years 2000 and 2001, it became necessary to implement contract dredging of the overburden to remove problematic soils and allow for the timely relocation of the bucket-wheel excavation system to a new mine development block.

In 2001 the Capacity Use water withdrawal permit was renewed for depressurizing pumpage for the mining operations and utility well operation. In November 2000 the bucket-wheel excavation system was relocated to the new (NCPC) mine development block. In March 2001 the first dragline was relocated to the new mine development block. The last remaining dragline was relocated into the new block in January 2003. The current permitted boundary allows for the mine advance to continue into the year 2011. The active mine face is advancing northeast towards the Pamlico River. The proposed future mine plan advances east and eventually turn back to the southwest. This proposed east and southwest advance is currently in the permitting process.

Hydrogeological experts have studied the Aurora Phosphate Mine and the effects of depressurizing the Castle Hayne aquifer system for over 40 years. Numerous reports prepared for and by PCS Phosphate and the State of North Carolina. The most significant of these reports are Hydrogeology and Effects of Pumping from Castle Hayne Aquifer System, Beaufort County, North Carolina (Joint Study Report, 1971) and Potential Effects of Pumping from the Castle Hayne Aquifer for Expanded Phosphate Mining in Beaufort County, North Carolina (Peek and Nelson, 1976). The Joint Study Report was prepared by a team of experts assembled by the State and evaluated the pumping effects on water levels and chloride concentration due to mine depressurizing. The report evaluated pumpage at 52 mgd from TGI, 80 mgd combined for TGI and NCPC, and 107 mgd combined from TGI, NCPC and an additional mine. The second report, North Carolina Water Resource Bulletin No. 11 (Peek and Nelson, 1976), was prepared by the State to evaluate the combined effects of the TGI and NCPC mines operating simultaneously. This report projected pumping effects on water levels and chloride concentration due to TGI pumping 33 mgd and NCPC pumping 45 mgd for a total of 78 mgd. A second pumping scenario evaluated by the State was for TGI pumping 64 mgd and NCPC pumping 45 mgd for total of 109 mgd. The third pumping scenario evaluated was for TGI pumping at a rate of 64 mgd and NCPC pumping at 54 mgd for total of 118 mgd.

HYDROGEOLOGY

General Stratigraphy and Structure

As reported in the Joint Study Report, the Coastal Plain of North Carolina is underlain by a "wedge" of stratified sedimentary rocks. From a thin veneer along the western boundary of the Coastal Plain, the wedge of sediments thickens seaward to about 10,000 feet at Cape Hatteras, the easternmost point on the Outer Banks. The sediments lie unconformably on a basement of igneous and metamorphic rocks of the Precambrian or early Paleozoic age, similar or equivalent to the rocks of the Piedmont region of the state.

The basement floor slopes generally southeastward at a gradient of 35 feet per mile (ft/mile) over much of the region, but the gradient is much steeper in the eastern part of the Coastal Plain.

The sedimentary rocks are subdivided into geologic formations or stratigraphic units that can be identified by their lithology, by their position in the sedimentary sequence and by the fossils they contain. These units range in geologic age from recent to early Cretaceous or possibly older. In general, the units have a northeastern strike and dip southeastward at a gradient of about 20 ft/mile.

In the Beaufort County area, the thickness of the sedimentary rock ranges from about 1,200 feet in the west to about 4,500 feet in the east. The sediments consist of clay, silt, sand, shells, limestone and combinations of these lithologies. Most of the sedimentary section contains residual seawater directed at the upper several hundred feet of sediments.

Stratigraphic and Hydrogeologic Subdivisions

The sedimentary rocks and unconsolidated sediments of the Beaufort County area are subdivided into hydrogeologic units (Joint Study Report, 1971) based principally on differences or apparent differences in permeability and hydrologic characteristics. These hydrogeologic units and descriptions are shown in Figure 3 along with the stratigraphic subdivisions based on geologic age as determined by paleontological criteria and stratigraphic position. The figure was modified to include better delineation of the post-Pliocene units. The stratigraphic units have been described and discussed in detail by many geologists in previous reports. The hydrogeologic units consist of subdivisions of stratigraphic units in some cases, and in others they overlap formational boundaries as indicated in the figure, however, the hydrogeologic units coincide generally with the stratigraphic units. Establishment and correlation of the hydrogeologic units was based on existing geologic and paleontological logs, electric and gamma geophysical logs, examination of core samples, and drillers' logs. Figure 1 shows the location and cross-section of the hydrogeologic systems through the area of the Aurora Phosphate Mine. PCS operations have been primarily concerned with the hydrogeologic units that lie above the Black Creek Formation of Cretaceous age. The hydrogeologic units in Figure 3 are summarized below.

Peedee Hydrogeologic Unit - Throughout most of the Beaufort County area, the Peedee unit consists of thin-bedded, glauconitic, silty sands and dark-gray, micaceous clays. The top of the Peedee unit is about 580 feet below msl in the area of the mine and is considered to be the basal confining unit of the hydrologic system between the Castle Hayne aquifer system and deeper aquifers of Cretaceous age.

Castle Hayne Aquifer System - The Castle Hayne aquifer system is the most productive aquifer system in North Carolina. In the study area, it includes: the Castle Hayne limestone of Eocene age, the predominant component; the Beaufort formation of the Paleocene age; and, in some parts of the area, sands that occur in the uppermost part of the Peedee unit. The Castle Hayne limestone lies unconformably on the Beaufort formation. It is predominantly a gray, white and tan shell limestone, grading downward into a denser, sandy shell limestone with interbedded calcareous sands. The Beaufort formation consists principally of silty sands with thin beds of limestone. The total thickness of the aquifer system ranges from about 140 feet to more than 640 feet, and the average thickness is about 350 feet in Beaufort County. In the vicinity of the mine, the aquifer system is about 370 feet thick (Figure 3). Analysis of the hydrogeologic character of the aquifer system included a review of published records, examination of geophysical and geologic logs, examination of cuttings and cores from deep wells and evaluation of other pertinent well information. On the basis of this analysis, the Castle Hayne aquifer system was subdivided into three hydrogeologic units representing three zones of significantly different hydrologic character and permeability, but a single hydraulic system. These units are the Beaufort unit, the lower Castle Hayne unit and the upper Castle Hayne unit.

The Beaufort hydrogeologic unit generally consists of a coarse to fine glauconite and quartz sand, silty and clayey sand, and some thin beds of limestone. The top of the unit ranges from about 35 feet to more than 850 feet below msl in Beaufort County, and occurs at an elevation of about 480 feet below msl at the mine. The transmissivity of the Beaufort unit is estimated to be about 2,000 to 7,000 gallons per day per foot (gpd/ft) (Joint Study Report, 1971).

The lower Castle Hayne Hydrogeologic unit consists of sandy shell limestone, dense sandy limestone, and mostly fine to medium glauconitic and calcareous sand. In Beaufort County, the top of the unit ranges from about 40 feet to more than 540 feet below msl. In the area of the mine, the unit is approximately 190 feet thick and the top of the unit occurs at about 220 feet below msl. The estimated range in transmissivity for this unit in the Beaufort County vicinity is about 10,000 to 35,000 gpd/ft (Joint Study Report, 1971).

The upper Castle Hayne unit is a porous and permeable interclast limestone and is the primary water-bearing unit of the aquifer system. The depth of the unit ranges from near mean sea level in the western part of the county to more than 380 feet below msl in the eastern part. In the area of the mine, the unit is about 130 feet thick and the top occurs at an elevation of about 140 feet below msl. The range of transmissivity of the upper Castle Hayne unit is about 90,000 to 350,000 gpd/ft in the Beaufort County area (Joint Study Report, 1971) with an average of about 250,000gpd/ft. Leakance values ranged from $2.3\text{x}10^{-5}$ gallons per day per cubic foot (gpd/ft^3) to 5.5 to 10^{-5} gpd/ft^3 and averaged 4.22 10^{-5} gpd/ft^3. Pumpage at PCS is from the upper Castle Hayne unit. At the top of the upper Castle Hayne unit is a stratigraphic unit that has been termed the lean ore. The unit consists of predominantly phosphatic fine-grained sandstone cemented with dolomite and a silty clay member. The top of the lean ore is approximately 140 feet bls or at an elevation of about 130 feet below msl in the current mining area but deepens to about 180 feet bls in the vicinity of the northeast mine advance.

Pungo River Hydrogeologic Unit - The Pungo River hydrogeologic unit consists predominantly of phosphate and quartz sands interbedded with sandy, silty clay, limestone and dolomite layers. Because of the low permeability of the beds of sandy and silty clay, limestone and dolomite, the unit as a whole is an effective confining layer above the Castle Hayne aquifer system. In the area of the mine, the unit is about 80 feet thick and the top occurs at an elevation of about 80 feet below msl.

The Yorktown Hydrogeologic Unit - The Yorktown unit consists largely of marine clay and silt interbedded with generally lenticular beds of sand, shells and shell limestone or marl. The top of the unit commonly represents the first substantial clay unit encountered below the surface, except in the southwestern part of the area where clays are absent. In the area of the mine, the unit is about 50 feet thick and occurs at an elevation of 20 feet below msl.

Post-Pliocene Hydrogeologic Unit - The post-Pliocene hydrogeologic unit consists primarily of the surficial sand, but includes some beds of shell, sand and some silt and silty clay. The thickness of the unit ranges from several inches to about 70 feet, but for the most part is about 20 feet and forms a system of two unconsolidated aquifers separated by semi-confining units. They have been divided into Croatan and post-Croatan aquifers and collectively are designated the Shallow-Aquifer System. The Channel Sand and Shell Bed are the most prolific members of the Shallow-Aquifer System.

Aquifer testing has been performed in the Channel Sand unit to determine the hydraulic properties. Transmissivity values in the Channel Sand unit averaged about 16,500 gpd/ft, while storativity averaged 5.4×10^{-4}, permeability averaged 662 gpd/ft^2, and leakance averaged 2.3×10^{-3} gpd/ft^3. The transmissivity of the Shell Bed is generally estimated to be a few thousand gpd/ft. Limited hydraulic data are available for the post-Croatan aquifer, however, laboratory vertical permeability values for samples collected during previous studies (Ardaman, 1989) ranged from to 0.02 gpd/ft^2 to 467 gpd/ft^2. Horizontal permeabilities would be higher by as much as an order of magnitude or more.

DESCRIPTION OF CURRENT MINING OPERATION

Presently, the mine utilizes a three-tier system of depressurizing/dewatering wells to maintain dry-pit conditions. In addition, a system of ditches and sumps are utilized to remove nuisance water. Due to the depth to the top of the ore, which is about 100 feet bls in the current mining area, it is necessary to remove the overburden in two stages. Bucket-wheel excavators are utilized to remove the overburden to about 30 to 40 feet bls. The Shell Bed, sometimes referred to as the boulder bed, forms the mine bench from which the draglines operate. Draglines are utilized to remove the remaining overburden to a depth of about 100 feet where the top of the ore body occurs. The ore is then excavated to a depth of about 135 to 140 feet bls and placed into a slurry pit where it is pumped to the processing plant. Figure 4 shows a schematic of the bucket-wheel excavators-dragline mining method.

Post-Croatan Aquifer Dewatering

In order for the bucket-wheel excavators to operate, it is necessary to control seepage into the mine block from the face of the excavation. This is accomplished through a combination of well points and ditching. The well points are 2-inches in diameter and approximately 30 feet deep. They are spaced at intervals of about 15 to 30 feet along the face of the excavation. They withdraw water from the post-Croatan aquifer unit of the Shallow-Aquifer System. Normally about 200 well points are operated concurrently. The well points are manifold to large capacity vacuum pumps from which the extracted water is discharged to the outfall canal. A totalizing flow meter is located at each discharge point for the system.

Croatan Aquifer Dewatering System

Withdrawals from the Croatan aquifer unit of the Shallow-Aquifer System occur primarily from the Channel Sand unit. The wells are constructed outside of the mine block to prevent seepage water from entering the excavated mine block. Occasionally, wells and well points are constructed on the mine bench (Shell Bed) to dewater the Channel Sand unit in order to stabilize the unit during overburden removal and mining of the ore by the draglines. Currently, approximately 10 Channel Sand unit pumping wells are in service.

The Channel Sand unit wells located outside of the mine block are constructed of 6-inch diameter PVC casing that extends to a depth of typically 40 feet bls depending on their position in the Channel Sand unit. A 6-inch diameter PVC screen extends from the bottom of the well casing to the bottom of the Channel Sand unit. The well screens are gravel packed to within several feet of land surface. The remaining annulus is sealed with bentonite and grout.

The pumping equipment consists of 4-inch nominal diameter, 5-horsepower submersible pumps set a few feet from the bottom of the well. A 1-inch diameter discharge pipe transports the water to the outfall canals. Totalizing flow meters are installed on each well.

Typically, seepage water is intercepted from the Channel Sand unit by a series of 22-foot deep trenches located on the mine bench between the bucket-wheel excavator and dragline operating faces. These trenches are utilized to control nuisance water from seeping beneath the dragline operating bench and into the open mine pit. The trenches are spaced approximately every 800 feet apart on the mine bench. The water is discharged to the mine bench perimeter ditch system where it flows to a sump. It is then pumped to the outfall canals from the mine bench sump. Figure 5 shows a schematic of the shallow aquifer systems tiered dewatering system.

Depressurizing System

The depressurizing systems are utilized to decrease the artesian pressure in the upper Castle Hayne unit to prevent the upward flow of water from this unit into the mine pit that would affect safe mining operations. The wells are typically 20-inches in diameter and approximately 270 to 280 feet deep. Twenty-inch diameter casing extends from a few feet above land surface to a depths of about 170 to180 feet bls. Water is pumped at a rate of about 3,000 gallons per minute (gpm) from each well to the canal system. The pumping equipment consists of fourteen 200-horsepower submersible pumps. The wells are equipped with flow measurement devices and are monitored daily.

Over the years, depressurizing wells that are no longer needed have been capped, abandoned by grouting, converted to water supply wells or are utilized as monitoring wells. Typically 13 to 17 depressurization wells are utilized at any one time around the perimeter of the mine advance, depending on depressurization requirements. The locations of the active depressurizing wells are shown on Figure 2.

Water Supply System

The water supply wells (utility wells) are dispersed throughout the northern portion of the plant site and western portion of the mine area. Primarily, they supply water for plant processing operational needs. The wells vary in diameter and depth and in some instances; former depressurizing wells are utilized as utility wells. The water supply wells vary from 8 to 20-inches in diameter and range from 200 to 300 feet deep.

REGULATORY CONTROL

Ground-water withdrawals from the Castle Hayne aquifer system at the mine are regulated by the North Carolina Department of Environmental Natural Resources (NCDENR). The NCDENR's Division of Water Resources (DWR) issues water use permits and monitors ground-water withdrawals, while the Division of Water Quality monitors ground-water quality. Capacity Use area Permit No. CU1003 was renewed in December 2001 and is scheduled to expire on December 31, 2011. Capacity Use Area Permit No. CU1007, which regulates withdrawals of up to 8.0 mgd from the Shallow-Aquifer System, was renewed in July 2001 and is scheduled to expire on July 31, 2011. Hydrologic conditions are monitored continuously by PCS Phosphate and reported to the NCDENR monthly.

GROUND-WATER WITHDRAWALS

During 2005, ground-water withdrawals from the Castle Hayne aquifer system at the mine averaged approximately 56.3 mgd. Of this total pumpage, the depressurizing system amounted to 56.0 mgd. The water-supply (utility) wells averaged 0.3 mgd. Prior to 1992 utility withdrawals ranged from 2 mgd to 6 mgd. The decrease since 1992 has been due to water conservation practices and increased utility use of water from depressurizing wells. The average annual Castle Hayne aquifer system withdrawal from 1965 through 1990 ranged from approximately 53 to 66 mgd, and averaged 59.7 mgd. An increase in pumping for depressurizing of the Castle Hayne aquifer system began in 2000 due to the movement of mining activity to the northeast in the new mine development block (NCPC). Four former depressurizing wells located to the west of the new area continue to be used to supply water for processing needs. As the mining activities move northeast, the ore becomes deeper, which necessitates pumping additional quantities of water from the upper Castle Hayne unit in order unit to maintain safe mining conditions. A second condition that has the potential to require additional pumpage is that the lean ore, which acts as an aquitard that covers the top of the upper Castle Hayne unit, may thin or undergo a facies change in portions of the Northeast Mine Advance. The lean ore, by nature of its low permeability, has controlled upward seepage into the pit from the upper Castle Hayne unit. If not present, increased pumpage is necessary to lower water levels below the bottom of the ore. However, it should be noted that the quantities currently permitted should be adequate for depressurizing needs if this eventuality occurs (Leggette, Brashears & Graham, Inc., 2001).

The shallow-aquifer dewatering system was described previously. The mine bench contains sump pumps for handling any runoff water. The water table well-point system was operated extensively from 1989 through 1998, but has not been required recently based on the geology encountered. The highest pumpage since operation of the system began was 2.93 mgd in March 1994. The Croatan Formation wells were only used during 1997 to 1998, with average daily withdrawals ranging up to 1.2 mgd. The Channel Sand Unit (CSU) wells have been used periodically from 1987 to 2005, with average daily withdrawals ranging from 0 to 1.2 mgd.

HYDROLOGIC MONITORING

PCS Phosphate maintains an extensive ground-water monitoring system. The purpose of monitoring is to allow PCS Phosphate to properly manage the resource in the most efficient manner possible. Monitoring wells have been constructed in the post-Croatan aquifer, the Croatan aquifer, the upper Castle Hayne unit, the lower Castle Hayne unit and the Beaufort unit.

A system of water-table monitoring wells were constructed in 1987 to monitor changes in the elevation of the water table of the post-Croatan aquifer. They are also utilized for the collection of water-quality data, primarily chloride concentrations. Typically monitoring wells that are approximately 15 feet deep with screened intervals typically extending from 5 feet bls to the bottom of the well. The Channel Sand unit monitoring wells are utilized to determine pumping effects on water levels and water quality in the Croatan aquifer. Water levels and water quality have been monitored since 1987 in this formation.

An extensive monitoring system of the upper Castle Hayne unit, both upper and lower, was established prior to 1964 for the mine vicinity and the region. Regional water levels and chloride concentrations are monitored on a quarterly or monthly basis. Several of the wells are equipped with continuous water-level recorders. The monitor wells vary in construction, but are typically 150 to 300 feet deep. The open hole interval of the well extends from the bottom of the casing (100 to 200 feet bls) to the bottom of the well. These wells are designated as County wells, Sentinel wells, Plant wells and Depressurizing wells. Several wells have been constructed that are open only to the lower Castle Hayne unit in the vicinity of the mine. They are utilized primarily to determine water-quality changes on a quarterly basis.

Additional monitoring wells have been constructed into the Beaufort unit to monitor the chloride concentrations on a quarterly basis. In years 2000 and 2001, PCS responded to a request from the NCDENR-DWR to construct additional monitoring wells in the Black Creek and Beaufort Units. These wells were constructed at 3 separate locations in the vicinity of the mine where existing Castle Hayne wells are located. All have been equipped with continuous water-level recorders by the DWR.

DEPRESSURIZING IMPACTS

Figure 2 shows the potentiometric surface of the upper Castle Hayne unit in July 2004, when depressurizing pumpage was about 61 mgd. A cone-of-depression occurs that extends approximately 10 miles to the west. Approximately 12 feet of drawdown occurs at a distance of 20 miles east of the active mine. Water levels are generally about 140 feet below msl within the immediate vicinity of the active mine block. The cone-of-depression is asymmetrical due to the wedge shape of the Castle Hayne system, the pre-existing hydraulic gradient and the thickening of the Yorktown unit to the east. This cone has maintained a similar configuration since the start of depressurizing withdrawals in the 1960's; with subtle changes due to movement of the mining center and variations in the average annual withdrawal quantities. Water-level declines due to depressurizing the Castle Hayne have periodically caused impacts to area supply wells. PCS has mitigated these impacts appropriately when necessary.

Chloride concentrations have been continuously monitored at the mine since 1965 to determine the effects of the mine operation on water quality. Chloride concentrations have been a concern to PCS due to the proximity of the mine to the Pamlico River and its tributaries which contains chloride concentrations typical of brackish water. In addition, high chloride water is known to occur in the lower Castle Hayne and Beaufort units.

Chloride concentrations in the depressurizing wells increased from 58 parts per million (ppm) at the start of mining to over 90 ppm in the early 1970’s when mining occurred near the Pamlico River (Figure 6). Chloride concentrations then decreased to less than 10 ppm by 1999 as mining moved to the south away from the river, and have now increased to about 60 ppm in 2004 as mining has moved back to the north.

Chloride concentrations in the upper and lower Castle Hayne units away from the depressurizing wells are monitored in the Plant, Sentinel, and County well networks. The average annual chloride concentration in Plant Well 30C (upper Castle Hayne unit) increased from 115 ppm in 1968 to 263 ppm in 1981. Since 1981, chloride concentrations have shown an overall decreasing trend to a current concentration of approximately 125 ppm, which is back to pre-1970 levels (see Figure 7). A similar trend is shown for Plant Well 30A, which monitors the lower Castle Hayne unit. Operating utility wells in the mine facility have varied water quality trends, with the wells operating since 1968 showing an increasing trend between 1968 and the early 1990’s, followed by a decreasing trend to the present. Of the six wells operating since the late 1980’s, four have shown a slight increasing trend.

The regional effect of depressurizing on chloride concentrations in the upper Castle Hayne unit is monitored with the Sentinel and County well networks. Of the 35 Sentinel and County wells monitored since 1968, eight showed an increasing chloride trend from 1968 to the mid-1980’s or early 1990’s, followed by a decreasing trend or a stable trend. Of the Sentinel and County wells that have been monitored since the late 1980’s, none has shown any steady increase in chloride concentration trend (Leggette, Brashears & Graham, Inc., 2004).

CONCLUSIONS

Withdrawals from the upper Castle unit for depressurizing have resulted in formation of a nearly steady-state cone of depression centered around the mine area. The amount of drawdown varies with fluctuation in withdrawal rates needed for adequate depressurization. Historical data show that short-term increases in chloride concentrations occur due to depressurizing of the Castle Hayne, especially when the withdrawals occur to the northeast. Regional water-quality monitoring wells show no long-term increases in chloride concentrations outside the mine facility. Water-level declines have periodically caused impacts to area supply wells. PCS Phosphate has mitigated these impacts appropriately, when necessary.

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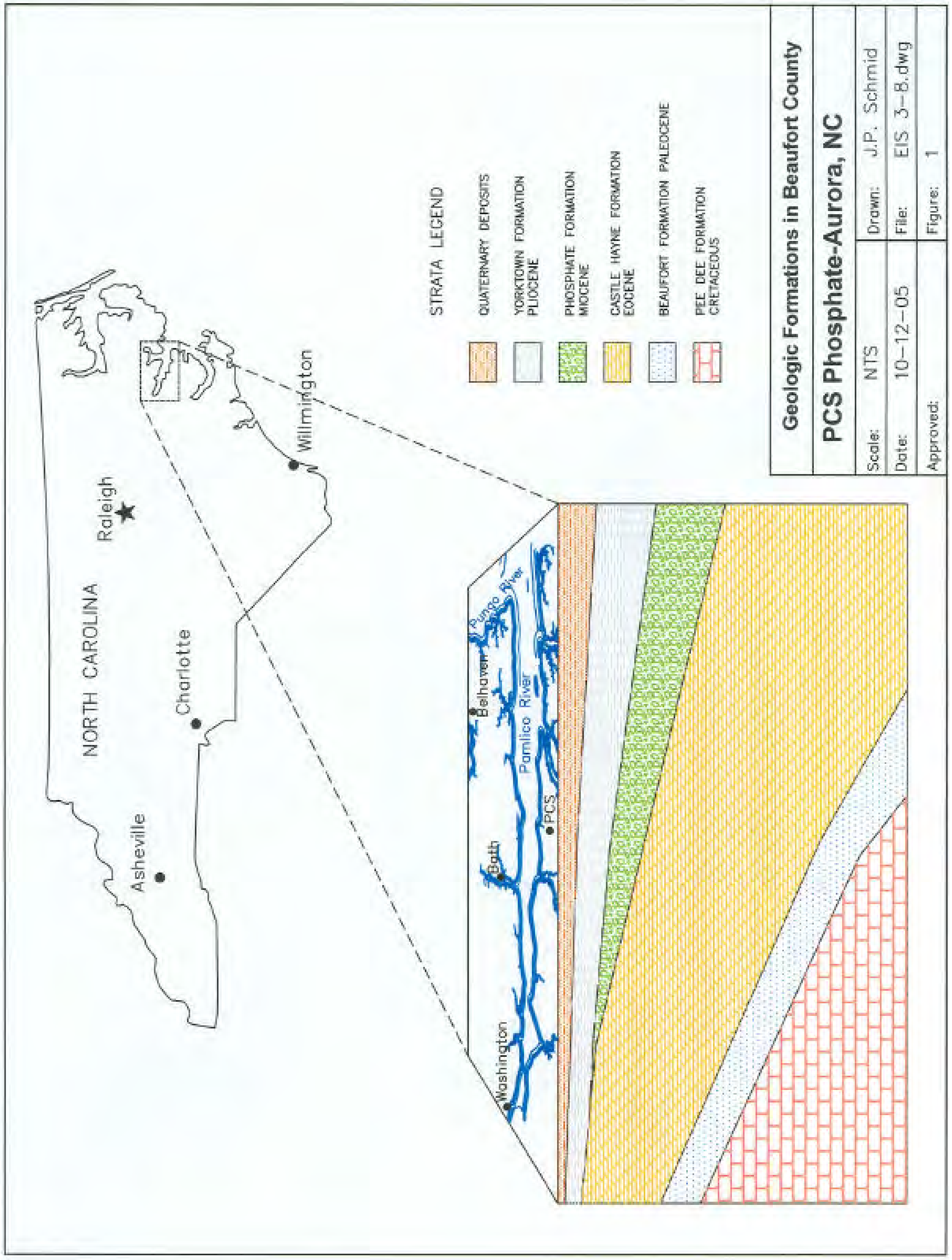


FIGURE 1 Geologic formations in Beaufort County, North Carolina.

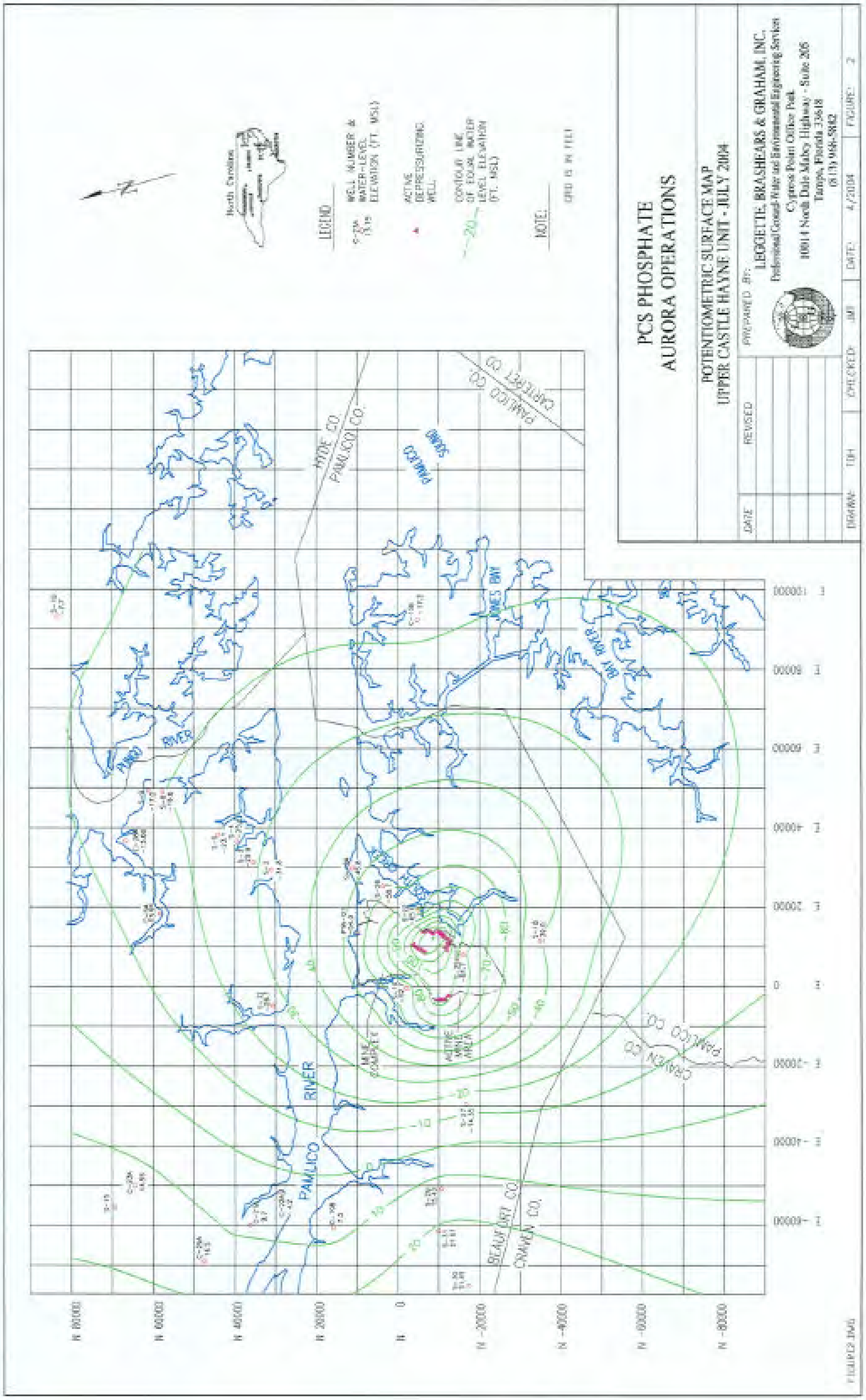
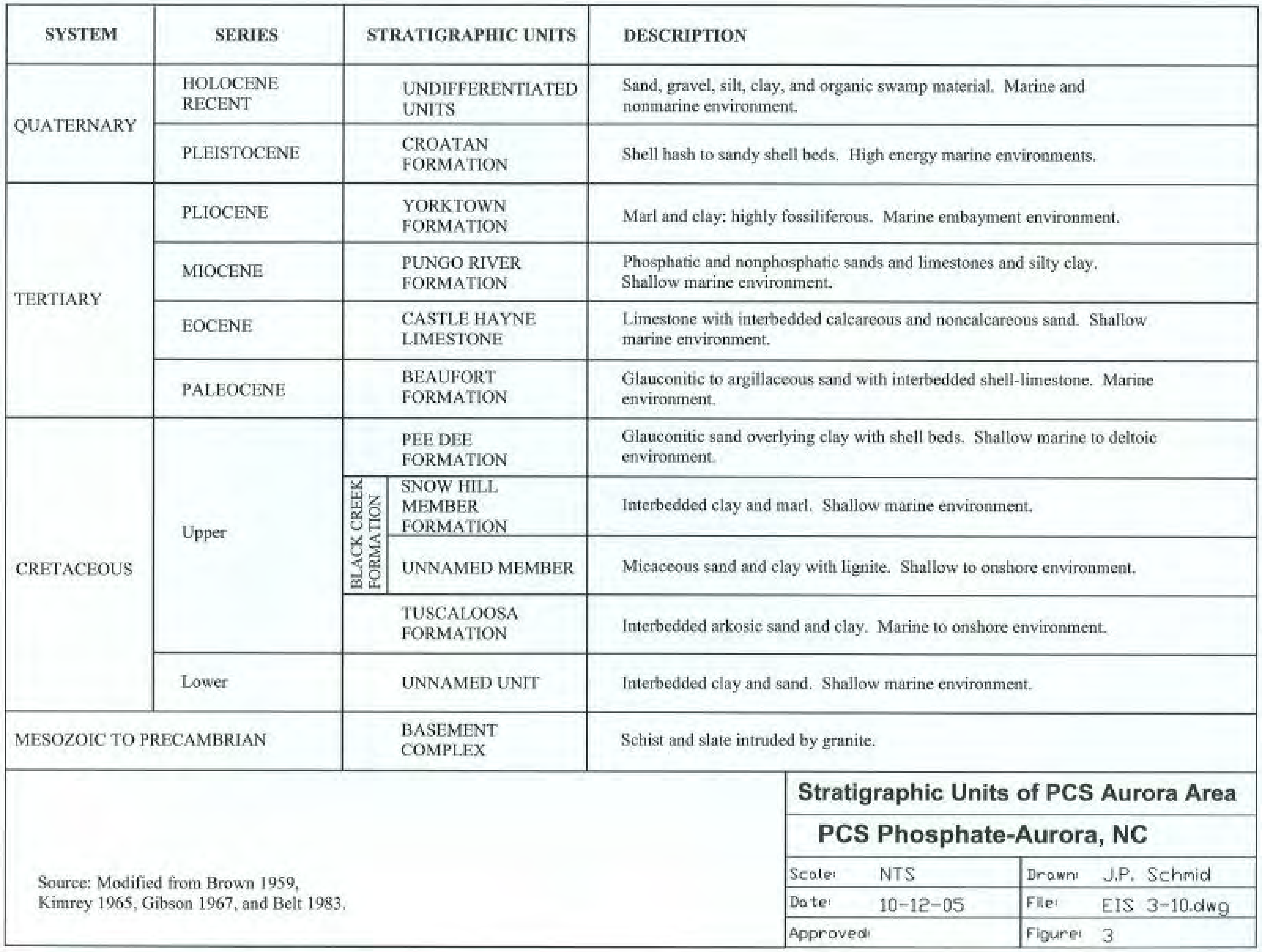


FIGURE 2 Potentiometric surface map of the Upper Castle Hayne unit.



SYSTEM	SERIES	STRATIGRAPHIC UNITS		DESCRIPTION
QUATERNARY	HOLOCENE RECENT		UNDIFFERENTIATED UNITS	Sand, gravel, silt, clay, and organic swamp material. Marine and nonmarine environment.
	PLEISTOCENE		CROATAN FORMATION	Shell hash to sandy shell beds. High energy marine environments.
TERTIARY	PLIOCENE		YORKTOWN FORMATION	Marl and clay: highly fossiliferous. Marine embayment environment.
	MIOCENE		PUNGO RIVER FORMATION	Phosphatic and nonphosphatic sands and limestones and silty clay. Shallow marine environment.
	EOCENE		CASTLE HAYNE LIMESTONE	Limestone with interbedded calcareous and noncalcareous sand. Shallow marine environment.
	PALEOCENE		BEAUFORT FORMATION	Glauconitic to argillaceous sand with interbedded shell-limestone. Marine environment.
CRETACEOUS	Upper		PEE DEE FORMATION	Glauconitic sand overlying clay with shell beds. Shallow marine to deltoic environment.
		BLACK CREEK FORMATION	SNOW HILL MEMBER FORMATION	Interbedded clay and marl. Shallow marine environment.
			UNNAMED MEMBER	Micaceous sand and clay with lignite. Shallow to onshore environment.
			TUSCALOOSA FORMATION	Interbedded arkosic sand and clay. Marine to onshore environment.
	Lower		UNNAMED UNIT	Interbedded clay and sand. Shallow marine environment.
MESOZOIC TO PRECAMBRIAN			BASEMENT COMPLEX	Schist and slate intruded by granite.

Source: Modified from Brown 1959,
Kimrey 1965, Gibson 1967, and Belt 1983.

Stratigraphic Units of PCS Aurora Area

PCS Phosphate-Aurora, NC

Scale:	NTS	Drawn:	J.P. Schmid
Date:	10-12-05	File:	EIS 3-10.dwg
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FIGURE 3 Stratigraphic units of PCS Phosphate area.

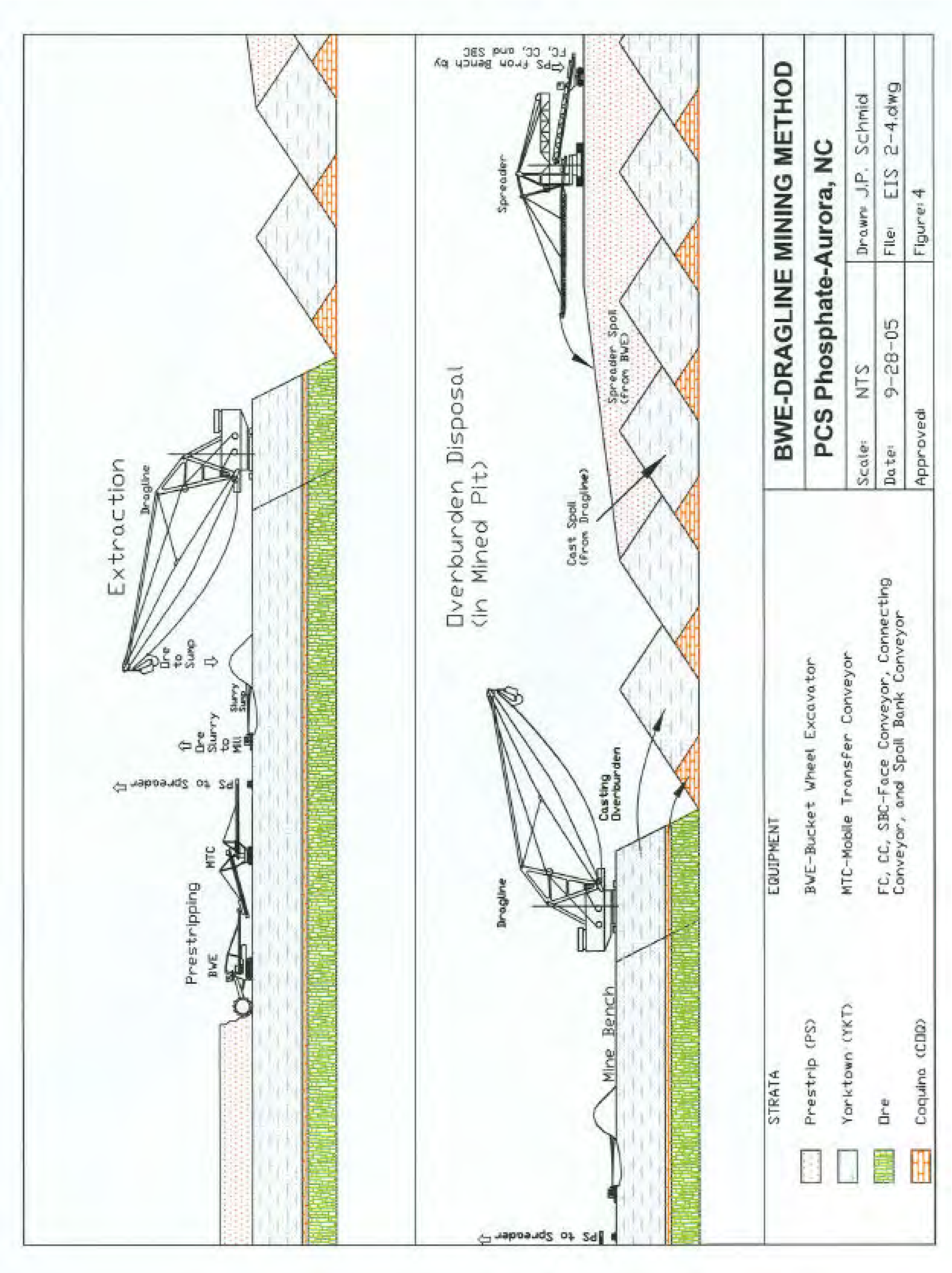

FIGURE 4 Bucket wheel – dragline mining method.

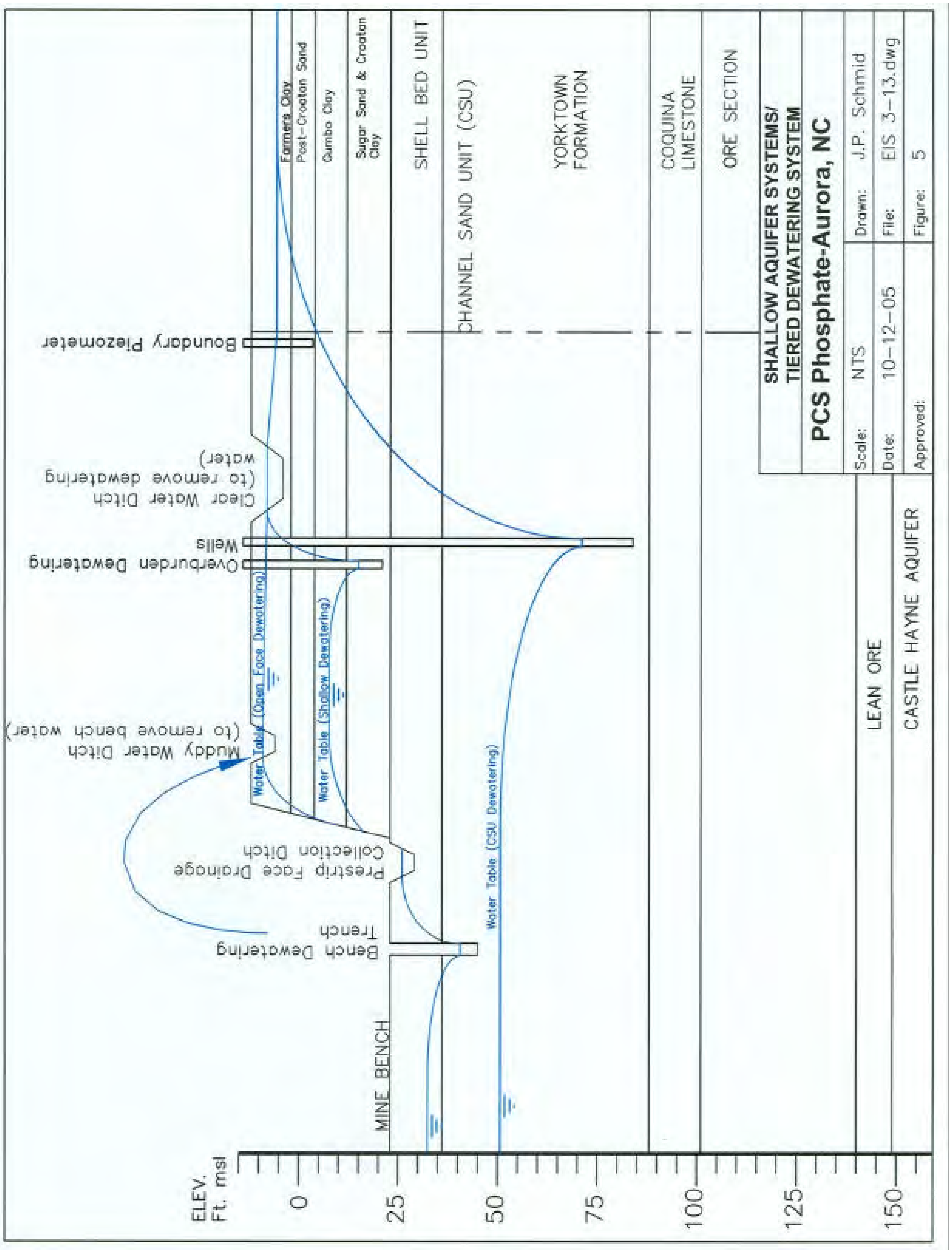

FIGURE 5 Shallow aquifer system tiered dewatering system.

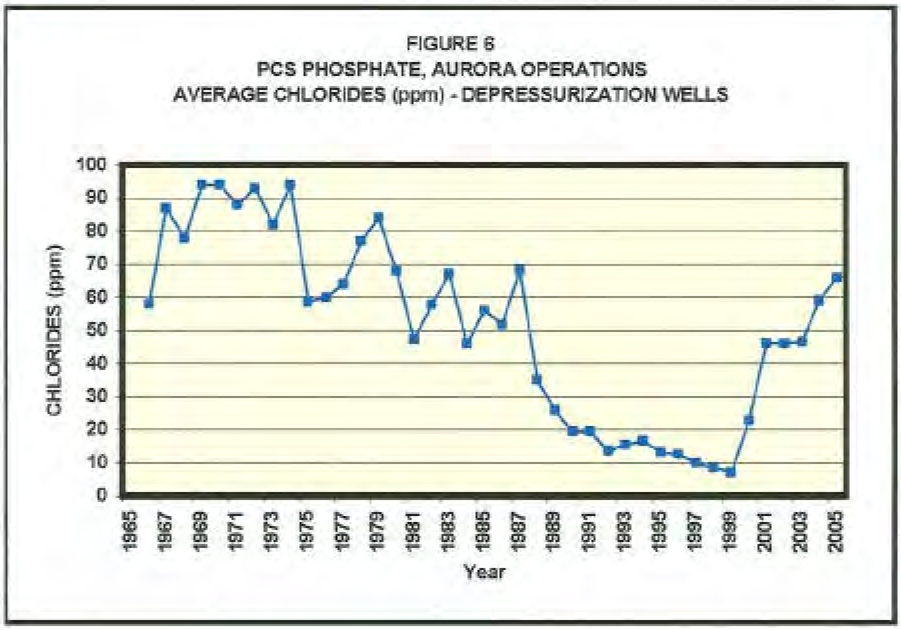

FIGURE 6 Average chloride history for depressurization wells.

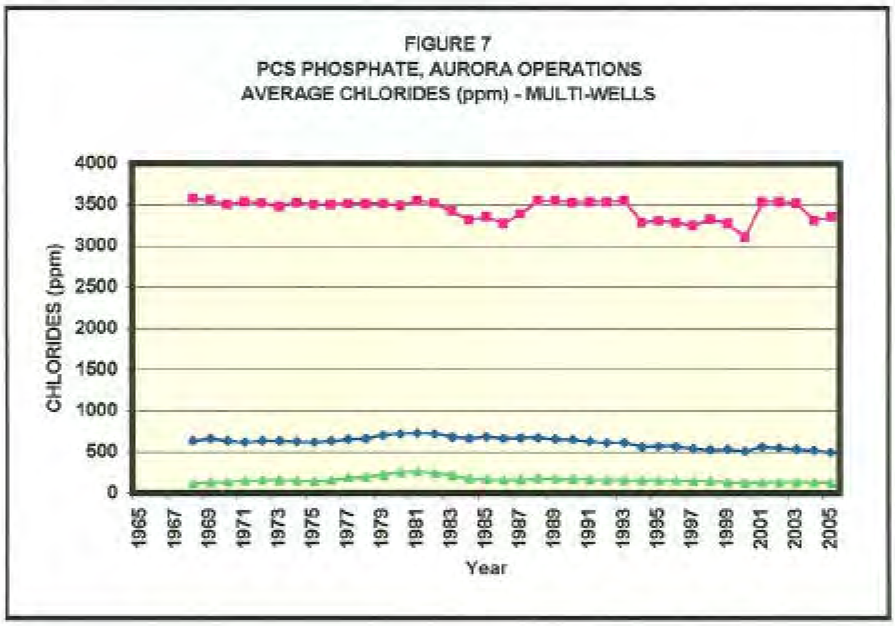

FIGURE 7 Average chloride history for multi-wells.

The phosphate resources and industries, Israel and Jordan - Developments under shadows and future forecast

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Jordanian phosphates play a significant role in the kingdom's domestic economy. However, in Israel, phosphate industry plays a lesser role these days.
Until 1948, the Jordanian phosphates were a significant contribution to the economy of Palestine. Their production (from the 1930's) enhanced the development of the fertilizer industry in the Haifa Bay area. This market and the presence of the adjacent coastal port, in return supported mining of the raw material in central Trans-Jordan. The 1948 conflict and its consequences halted activities in mining and the phosphate-related industries.

In Israel, a search for domestic resources was carried out and phosphorite ores were discovered in the Negev that enabled the recovery of the fertilizer industry by the early 1950's. New markets for relatively limited amounts of the Jordanian phosphates were found, but the beginning of production in a southern rather than central source in 1962, marked the industry's breakthrough, as demonstrated by that time record of more than 1 million tons reached by the 1960's. The Jordanian phosphate industry was hurt by a period of political and security instability in the early 1970's, the only period in which Israeli production surpassed that of Jordan (1970 to 1974). The following 14 years (1975-1989) were a real take-off for the Jordanian phosphate industry as production multiplied by a factor of five to the all time high of 6.9 million tons in 1989, the beginning of production in the huge, southern deposit of E-Shidiya, and the establishment of several active joint ventures with foreign companies.

The Israeli industry recovered from the Yom-Kippur war-related recession and the years between 1975 and 1985 mark the development of new deposits, the establishment of new facilities and technologies, reaching a 4 million tons production level which is kept up to the present.

The Jordanian industry faced another recession in 1990-1995 following the Gulf War. The late 1990's recovery was shadowed by world and domestic economic pressure that led to record losses in 1999 and 2000. Official rock production forecasts made in 1997 (8 million tons in 2002 and 10 million tons in 2010) proved to be imaginary. However, recent results clearly indicate a new upward trend, partly related to man-power reductions and to more variations in the products. In the last two decades, the Israeli phosphate industry was relatively stabile, more influenced by ownership changes rather than by world or domestic political developments. It focuses on the development of new technologies development and improved organization.

In general, the Jordanian deposits have greater reserves, preliminary higher grades, better mining conditions, lower industry salaries and fewer environmental limitations than those in Israel. Some relative Israeli advantages over those in Jordan are the well-developed infrastructures, the relative proximity of mines and facilities to residential areas, shorter transportation distances, domestic ownership of shipping, foreign-owned related industries (phosphate consuming) and a greater portion of highly educated staff. It is evident that the present policy of Jordanian phosphate industry is to continue with a gentle increase in production, to improve the efficiency of the mines and plants and to widen the list of products list for better competitiveness. The Israeli approach is to target advanced mining methods, and to develop and implement new technologies in order to produce more advanced products.

With the relative proximity of both industries, it may be plausible that in the near future there will be a further development of parallel facilities with a reduction in mining in Israel, further technological development in Jordan and later, possible supply of raw phosphates from Jordan to Israel with mutual annual production rates in the order of 10-12 million tons.

Minster, Tsevi, 2006, The phosphate resources and industries, Israel and Jordan – Developments under shadows and future forecast, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Jordanian phosphates and their generated industries play a significant role in the Kingdom's domestic economy. On the other hand, the Israeli phosphate mining industry, while being of significance in the lightly populated southern part of the country, is less important in terms of the national economy.

GEOLOGY

The Jordanian and the Israeli phosphate deposits are part of the large south- and eastern-Mediterranean phosphate belt of Upper-Cretaceous - Eocene age. Highly productive conditions combined with an upwelling regime prevailed in the southern Tethys during that time span. This, combined with a favored diagenesis and preservation promoted the generation of beds enriched in carbonate-flour apatite (francolite) (Soudry and Nathan, 2001). In places, these are of economic value.

In Israel those beds are of Campanian age and are usually well-developed within certain synclinal structures, forming fields over areas from few square kilometers to tens and even a few hundreds km^2. In Jordan, the economic phosphorite beds are considered to be somewhat younger in age and some of the fields cover wider areas (Natural Resources Authority - Jordan, personal communication).

The economic phosphorite beds in Israel and Jordan are exposed in many localities, usually at margins of the synclines, although overburden can reach tens to hundreds of meters. In some Israeli fields, the phosphorites in structural lows are bituminous and parts of the overburden (as well as some underlying beds) are composed of “oil shale” (bituminous carbonates). The phosphate beds generally exhibit significant differences in petrographic, chemical and physical properties between beds as well as between different fields, and hence diverse beneficiation techniques have been developed (Rotem Amfert Negev, Ltd., personal communications and discussions; Soudry, 2004).

PRODUCTIVE PHOSPHATE FIELDS

Mining activity in Jordan began in the 1930's, in the Ruseifa area, southeast of the capital Amman. In the 1960's work began toward the south in the El-Hasa and El-Abiad areas. Following extensive exploration, the large field of Esh-Shidiya located further to the south began operations in 1988 and is presently the major source. Prospecting activity is ongoing and a newly discovered deposit is being studied further to the southeast, near the border with Saudi Arabia. Most of the phosphate-generated industries are located at Esh-Shidiya and near Jordan's only port of Aqaba (Figure 1).

Three phosphate fields are presently being mined in Israel, all in the northeastern Negev: (1) Mishor Rotem, where most of the phosphate-based industries are located; (2) Oron and (3) Nahal Zin. A new trial mine was recently started at Hatrurim to the northeast of Mishor Rotem. Additional phosphate-based industries are located near the northern port of Haifa. Phosphoric acids, fertilizers and some raw phosphate rock are exported via Ashdod, Haifa and Eilat. Ports. The productive volume of mined phosphates in Israel is presented in Figure 2 (Rotem Amfert Negev Ltd., personal communications and discussion).

PRODUCTION HISTORY AND TRENDS

Until 1948, phosphates were an important contribution to the economy of the area, Their commercial production which began in the 1930's enhanced the development of the fertilizer industry in the Haifa Bay area. This market and the presence of the neighboring coastal port located at the terminus of the Hejaz railway (that passed within the Ruseifa mining area close to Amman) supported mining in central Trans-Jordan.

After the establishment of the State of Israel, a search for domestic resources was carried out in Israel, and phosphorite ores were discovered in the Negev that enabled a recovery of the domestic fertilizer industry by the early 1950's. To the east of the Jordan River, new markets for relatively limited amounts of the Jordanian phosphate commodities were found. However, only when the mining centers moved to a southern, rather than a central location (in 1962), was there a breakthrough in the industry, as indicated in Figure 3 (more than 1 million tons of rock production was reached by the mid-1960's) (Minerals Yearbook). The Jordanian phosphate industry was hurt during a period of political and security instability in the early 1970's, the only period in which Israeli rock phosphate production (which for the first time passed the level of 1 million tons in 1969) surpassed that of Jordan (from 1970 to 1974). The following fourteen years (1975-1989) showed a real take-off for the Jordanian phosphate industry as production multiplied by a factor of five to a record of 6.9 million tons in 1989 (Minerals Yearbook; Minster, 2002). This trend was influenced by new production in the southern of Esh-Shidiya deposit, and by the establishment of several new plants, most of them as joint ventures with foreign companies.

The Israeli industry recovered from the Yom-Kippur war-related recession and the years between 1975 and 1985 mark the development of new deposits (1985 – Nahal Zin) and the development of new facilities and technologies, and four million tons production reached (in 1999, the production figure was 4.13 million tons). In the last two decades, the Israeli phosphate rock production was relatively stable, and more influenced by ownership changes rather than world or domestic political developments. The phosphate company, Rotem Amfert Negev Ltd., within the Israel Chemicals Industries (ICL) concern, is strongly connected with sister companies in Europe and the United States which contributes to the widening the range of products based on worldwide requirements. Since 2001, the annual rock production in Israel is kept at a level of 3-3.5 million tons and efforts are being made to improve beneficiation technologies and internal organization and to promote higher environmental demands. Most of the mined phosphorite is consumed in the production of second and third generation fertilizers by the ICL and other companies, and lesser amounts are exported entirely to European sister companies (Rotem Amfert Negev Ltd., personal communications and discussions).

The Jordanian industry faced another recession between 1990 and 1995 following the Gulf War. A partial recovery in the late 1990's was overshadowed by world and domestic economic pressure that led to record losses of the Jordanian Phosphate Company (JPMC), especially in 1999 and 2000. Forecasts made in 1997 for future Jordanian rock production of 8 million tons by 2002 proved to be imaginary. The all-time record of Jordanian rock phosphate production (7.18 million tons) was reached in 2002. Recent data from Jordan indicates a new upward trend in production and efficiency which can be related to man-power reductions, better diversity in the products and improvement in relations with customers. Today, the phosphate and fertilizers industry comprises about 13% of Jordanian exports (Natural Resources Authority – Jordan, personal communications).

RESERVES

The global debate on how to obtain accurate and agreed-upon data for amounts of recoverable phosphate reserves is demonstrated in both Israel and Jordan (Notholt and others, 1989; Soudry and Shiloni, 1976). According to the Mineral Yearbook (United States Geological Survey) the reserves base for Jordanian and the Israeli phosphates is 1,700 and 800 million tons respectively for reserves of economical value. However, when actual, recoverable reserves are considered (based on the same data source), the value for Jordan becomes 900 million tons and 180 million tons for Israel! Furthermore, according to the Israeli Negev Amfert Company, reserves of economic phosphate in Israel are around 370 million tons but of these, only some 100 million tons are considered to be recoverable at present. This significant gap may be explained by a lack of official permits to begin production in new areas, and the growing impact of the domestic "green" lobby on the mining activity in existing and potential sites. A significant portion of the Israeli phosphorite sub-economical reserves have relatively high organic matter content (Shiloni and Minster, 1984). Economical-technical solution to their beneficiation would enlarge the minable reserves and could be of global significance.

SUMMARY AND FORECAST

Jordanian deposits have greater reserves, higher preliminary grades, better mining conditions, lower work force salaries and fewer environmental limitations than those in Israel. Certain advantages in the Israeli industry include a well-developed infrastructure, the relative proximity of mines and facilities to residential areas, shorter transportation distances, domestic ownership of shipping, ownership of overseas phosphate consuming industries, and a relatively large portion of highly educated staff. It is evident that the present policy of the Jordanian phosphate industry is to continue with a gentle increase in production, to improve the efficiency of the mines and plants and to widen the products list for increased competitiveness. The Israeli approach is to target advanced mining methods, and to develop and implement new technologies in order to produce more advanced products, but clearly not enlarging the mining activity.

With the relative proximity of both industries, and multi-national large projects (in particular, the ambitious Red - Dead Sea project) that may rectify the bi-national infrastructures, it is plausible that the future will see further development of complementary facilities and possibly some sort of cooperation between the phosphate producing companies and the generated industries. A combined Jordanian – Israeli annual phosphate rock production of 12-15 million tons is predicted for the next decade.

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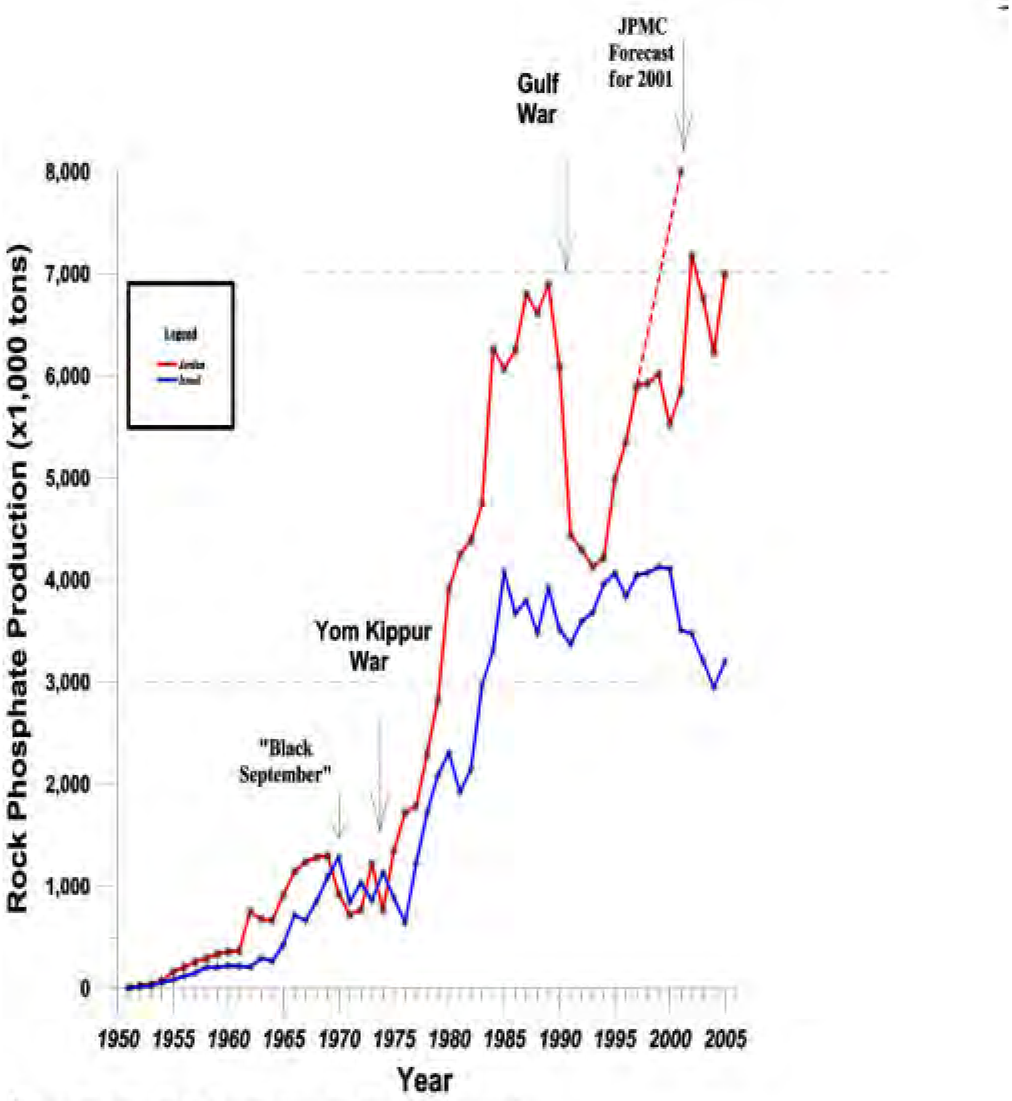
FIGURE 1 Sites of phosphate mines in Jordan and Israel.

FIGURE 2 Mining activity of phosphates in Israel, 2004, according to the mining areas (after D. Shitrit, Rotem Amfert Negev).



* - Based mainly on USGS Mineral Yearbook data on mine production

FIGURE 3 Phosphate rock production in Jordan and Israel, 1950 – 2005.

Session Two

Preparing for the future in the brick industry

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ABSTRACT

The brick industry in the United States faces many obstacles in the near future in terms of energy costs, environmental issues, and labor costs. Both raw materials and manufacturing processes will have to be studied and altered in order to meet the challenges offered by competitive building materials and governmental regulations.

The National Brick Research Center provides a well equipped lab for testing and evaluating raw materials for brick manufacturers. Both physical properties and estimated emissions are key factors in determining the usefulness of a given deposit. A low volatile content, the potential for fast firing, and a wide maturing range are necessary to meet the demands of the modern plant.

Improvements in the design of automated equipment have led to increased production rates and the necessity for high quality products. Both the cost and availability of fuels have contributed to the need for conservation and the need for innovative thinking in terms of firing brick. All of these factors have combined to force the industry to look at how things have been done in the past and how improvements can be made.

This presentation will characterize the role of the National Brick Research Center in supporting the brick industry. It will also document the many recent changes that have taken place in the industry and will look at trends and forecasts for the future.

- Click here for the presentation (~1.3 MB) – MS PowerPoint format only

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Evaluation and production of a North Carolina Piedmont clay deposit, Montgomery County, North Carolina

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ABSTRACT

The clays of North Carolina have played an important role in the history of this state and in a wider arena. North Carolina clays are found in the archeological sites of pre-Colombian peoples of this area and also in the works of folk artists throughout the state. The location and development of clay deposits for artisan and industrial applications continues to be a vital industry in North Carolina and beyond.

The objective of this project is to evaluate the quality, mineral processing characteristics, and marketability of a Piedmont clay deposit leased by Taylor Clay Products Incorporated and located near Candor, North Carolina. The buff colored, residual clay formed from felsic tuffs within the Carolina Slate Belt and is composed of kaolinite, illite, quartz, and < 5 wt.% of other minerals. After the raw material was milled and classified, the clay was found to be suitable for a variety of applications, including pottery and facing materials for bricks and ceramic glazes.

Nagle, John P., Van Jahnke, Jeff, and Miller, J. William, 2006, Evaluation and production of a North Carolina Piedmont clay deposit, Montgomery County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

The minerals of North Carolina play an important role in many aspects in our lives, from the phosphate deposits of the coastal region to the crystalline pegmatite of the western region. The clay minerals found throughout North Carolina have played an important role in the history of the state and in the current era as more deposits are used in industrial and artisan applications. Many archeological sites throughout the state that contain shards of early potters work attest to the exploitation of clay minerals by pre-Columbian peoples of this region (Trawick, 1999). Before the advent of the glass industry, potters played an extremely important role in the lives of the people that they served by creating vessels for the storage and transportation of commodities. From this predominantly utilitarian pottery industry evolved a strong folk art industry as exemplified by the contemporary works of Burlin Craig, the Ben Owen family legacy, and the potters of Seagrove and Jugtown in North Carolina (Crawford, 1964). Before modern large-scale mining operations and distribution systems for clay minerals existed, each potter may have had his or her own closely guarded deposit from which they drew their supply of raw materials. After mining operations and distribution networks for clay minerals were established, North Carolina clays found their way into much wider distribution, including incorporation into Wedgwood porcelains. One of the best-known and most widely distributed clays of North Carolina was Avery Kaolin. Clay from this deposit in Avery County, North Carolina was highly regarded for its ease of workability and for its reduction flashing characteristics in glaze applications. This deposit was exhausted by 1985, and potters who still have any of this clay jealously guard it (Presnell, 1999).

Taylor Clay Products Incorporated (TCPI) of Salisbury, North Carolina is persistently continuing the tradition of producing high quality North Carolina clays. TCPI has been primarily a brick product producer since 1949. TCPI manufactures high quality architectural face bricks that have been used throughout the Eastern United States. Their products adorn buildings such as the Central Laboratory of the Tennessee Department of Health and Environment in Nashville, Tennessee and 101 Avenue of the Americas in New York City, New York. TCPI also produces small-scale production runs of artisan clays. The focus of this research is the qualification of a clay deposit for use in artisan applications. The ultimate hope in this project is to bring to market a unique and highly desirable product such as was the case with Avery Kaolin.

The clay deposit explored in this research is from the Candor site in Montgomery County, North Carolina (Figure 1). Preliminary research by Allen and Liles (1980) classified this deposit as residual clay formed from felsic volcanic tuff in the Carolina Slate Belt. The clay is a fined grained, buff colored clay that in hand specimen appears to be devoid of impurities.

OBJECTIVES

The goal of this research is to determine the feasibility and economic viability of this clay body from Montgomery County, North Carolina as a material for the ceramic art industry in glazing applications and as a superficial colorant in the brick industry. To that end, we quantified the composition and examined potential applications through a detailed analysis of particle density, particle size distribution, clay particle recovery rates, chemical composition, and performance characteristics in ceramic applications.

METHODS

Initial Preparation

The raw clay material involved in this research project was obtained from the deposit site in Montgomery County, North Carolina. TCPI had previously exposed the clay body and had mined a representative sample of the clay, which is the raw material used in this research project. Approximately 91 kg of clay were gathered from the exposed site and transported to the North Carolina State University Minerals Research Laboratory in Asheville, North Carolina for analysis and testing.

The raw clay material was dried in an oven at 177°C for approximately four days and then milled to approximately 0.5 cm using a ten-cm by 15-cm (four-inch by six-inch) jaw crusher. (Equipment used in this project is listed in the Appendix.) The clay was then milled using an 20-cm cone mill to reduce the aggregate size of the raw clay material to less than 0.5 cm. The raw clay material was split into 9.0 kg representative samples.

The raw clay material was dispersed using three different methods to determine the desired rate of dispersion while using the least amount of time and expense. Each method varied only in the way the raw clay material was conditioned for dispersion prior to particle sizing. Subsequent processing was identical for each batch following dispersion.

Dispersion Method 1

A conditioning vessel was filled with 5 kg of water, to which 9.0 kg of raw clay material and 40 grams of 10% sodium hexametaphosphate (3.6 kg/ton of raw clay material) were added. This formed a slurry of approximately 64.4% solids. Sodium hexametaphosphate acts as a particle dispersant and is used to disaggregate any cohesive clay particles. The raw clay material was conditioned using a barber chair attrition scrubber at approximately 400 rpm for five minutes.

Dispersion Method 2

A like amount of raw clay material mixed and processed as above but was conditioned for fifteen minutes.

Dispersion Method 3

A conditioning vessel was filled with 500 ml of water, to which 500 g of raw clay material and 2.5 ml of 10% sodium hexametaphosphate were added (0.4 kg/ton of raw clay material). This formed to slurry that is approximately 50% solids. The raw clay material was conditioned using a commercial blender set on low speed at approximately 1,600 rpm for two minutes.

After initial dispersion, all of the samples were treated identically. The dispersion processes yielded a thick slurry of water and dispersed clay particles. The slurries were classified by particle size with a 91-cm (36-inch) Sweco vibratory screen sizer and a 325-mesh screen opening. The samples were divided into +325 and -325 fractions.

The undersized clay fraction was stirred and transferred to 19-liter plastic vessels to bring the height of the homogenous raw clay material slurry column to 33 cm in each vessel. Using Stokes Law and assuming an average density of clay particles of 2.7 g/cm^3, the raw clay material slurry was allowed to settle for the amount of time suitable for the desired particle size to settle out of the column. Stokes Law states that 20µ clay particles will descend to the bottom of a 33-cm water column in 13.2 minutes, and 10µ and 5µ particles will descend the same height in 52.7 minutes and 210.8 minutes, respectively. TCPI was interested in determining the best possible recovery rates for 5µ, 10µ, and 20µ clay particles from the raw clay material, so each dispersion method was used three times, one for each clay particle size of interest.

After each batch of raw clay material was dispersed, transferred to 33 cm columns, and the appropriate settling time was allowed to pass, the supernatant liquid was decanted. This decanted liquid contained the desired clay particle size. The theory behind this method of particle sizing is that after the given amount of settling time has accrued, all clay particles greater than the particle size of interest have settled out of the slurry column. That is, that in a batch that is to be clay particles of 20µ and smaller, after the allotted settling time of 13.2 minutes has passed, all particles less than 44µ but greater than 20µ? have settled out of the column. The material that had settled out of each column was collected and designated 20µ -325 tails, 10µ –325 tails, and 5µ –325 tails.

The supernatant liquid that was decanted from each settled clay slurry column contained the clay particle size range of interest and was collected in a 160-liter plastic vat. This slurry was flocked using approximately 5 ml of 95% sulfuric acid to enhance the settling of clay particles. The flocculated slurry was allowed to settle for approximately four days, at which point the clear overlaying liquid was decanted and disposed of. The resulting clay left at the bottom of the 160-liter plastic vat was the final product for each batch. This residual clay was collected and oven-dried to approximately 177°C until all residual moisture was removed from the product at approximately 4 days. Nine initial batches of clay were produced for analysis, 20µ clay, 10µ clay and 5µ clay for each of three scrubbing methods.

A mass balance of the +325 tails from each batch of clay produced was conducted to quantify the percentage of material that constituted each of six standard particle sizes. This fraction of the total mass of each batch represents particles that are sized greater than 44µ. The mass balance was conducted using standard screen meshes of 16, 40, 100, 140, 200, and 325. A nesting collection pan was used to collect residual –325 particles. The screens were shaken in a Rotap screen agitator for 15 minutes. These evaluations were completed to determine if clay particles were agglomerated in these tails, which is a sign of poor dispersion. Additionally, these tests aided in determining if an appreciable amount of –325 materials were in these tails, a sign of insufficient particle sizing subsequent to dispersion.

A sample of each clay size batch from the first scrubbing method run was evaluated for density with a gas pycnometer to insure that the settling times used were appropriate for the particle sizes in question. This pycnometer uses helium to evacuate ambient air from the sample chamber. The results from this analysis were also required for calibration of the X-ray particle size analyzer.

Samples of all sized clay batches were analyzed with an X-ray particle size analyzer (sedigraph) to determine average particle size content and mass percent cutoffs for each batch. The mass percent cutoffs are measures of the total mass of each sampler that is finer than the desired clay particle size. A 2.2-g sample of clay particles from batch was dispersed using 80 ml of 0.1% sodium hexametaphosphate. After stirring the solution for five minutes, the sample was placed in an ultrasonic bath for 15 minutes to insure an accurate sedigraph reading.

Color analysis was performed on samples of raw clay material screened through a 325-mesh screen (-325 raw clay material), 5μ clay and 20μ clay using a reflectance color analyzer. This analysis was carried out to quantify the color of the raw clay material and of two clay sizes using the Hunter *L, a, b* value index. The color analyzer measured the reflectance of the sample for three values, amber, blue and green. The raw clay material and the two sized clays were analyzed for color as well as samples of each, calcined to 1,000°C and 1,149°C.

Powder X-ray diffraction analysis was performed on samples of the raw clay material, 5μ, 10μ and 20μ clay fractions and the –325 mesh tails from the 10μ clay product. The scans were performed from 5° to 70° 2θ, at 45 kV and 40 mA and automatic divergence and receiving slits. This analysis was conducted to identify the mineral content of the various clay products.

A commercial lab performed additional X-ray diffraction analysis. This analysis was undertaken to both qualify the mineral content of the raw clay material and to quantify the weight percentages of various major elements that constitute more than approximately 5% of the total mass of the sample. This analysis was performed with a well-type X-ray diffractometer set to scan from 3° to 61° 2θ. This analysis was performed on samples of 10μ clay produced from Dispersion Method 2 and the raw clay material.

Samples of 10μ clay produced from Dispersion Method 2 and raw clay material were analyzed by X-ray fluorescence spectrometry at a commercial lab. The clay samples were milled to approximately –400 standard mesh in a tungsten carbide swing mill prior to analysis.

Sample Production

A cost-benefit analysis of the quality of the clay products derived from the three dispersion methods and their associated recovery rates were based on the purity of the clay product as compared to the rate and ease of its recovery. It was feared that the 20μ clay product from the least cost intensive method (Dispersion Method 1) would yield a product with impurity levels too high to successfully market. Additionally, the cost of producing the purest product, the 5μ clay from Dispersion Method 3, would be high due to the low recovery rates realized in initial analysis and would render this product unmarketable as well.

Guided by the target recovery rates of Taylor Clay Products Incorporated, it was decided that a 10μ clay product (Figure 2) from Dispersion Method 2 would prove to be the most economically feasible product to bring to the artisan's clay market, meeting both recovery and purity guidelines.

Approximately 6,810 g of 10μ clay was produced using Dispersion Method 2 and were given to representatives of TCPI. A portion of this material was given to Kent McLaughlin and Susie Lindsey of Fork Mountain Pottery in Bakersville, North Carolina for performance analysis as a pottery glaze in artisan applications. The potters at Fork Mountain Pottery combined 80% of 10μ clay with 20% nepheline syenite and added water to produce a slip of approximately 60% solids. This slip was applied to ceramic greenware bodies and fired to cone 10 (approximately 1,304°C).

A sample of the -325 tails from the 10µ clay sample production was given to representatives from TCPI for performance evaluation as a superficial brick glaze. A glaze was made by adding water to the 10µ +325 tails until slurry with a density of approximately 1.6 g/cm^3 was formed. This mixture was flocculated with sodium silicate. The theory behind high specific gravity glaze formulation is that in using this type of mixture, the most amount of clay tail product will be applied to clay body with the least amount of effort. This glaze was applied to the surface of green brick, allowed to dry, and then fired to approximately 1,175°C in a gas-fired kiln.

RESULTS

The calculated recovery rates for clay products tend to increase with more involved dispersion (Table 1). The recovery rates from the first two dispersion methods were analyzed, and it was decided that a longer dispersion time would positively affect the recovery rates of the clay. Thus, the time allowed for dispersion was increased in the Method 2. Additionally, upon scrutinizing the recovery results from Method 2, it was decided that a decrease in batch size and an increase in the attrition level would perhaps present an even greater influence on recovery rates. An increase in the weight percent of the –325 tails for each subsequent dispersion method was also realized. This result, too, was not unexpected. A general increase in the amount of smaller particles found from each subsequent dispersion method was predicted due to the increased time and speed of conditioning. An increase in the duration and intensity of attrition in the dispersion phase of production lead to a greater mass percent of increasingly finer particles in each batch.

TABLE 1 Recovery rates by dispersion method

		+325 Tails	-325 Tails	Clay
Dispersion Method 1				
	20µ	37.4%	25.5%	37.1%
	10µ	37.8%	38.0%	24.2%
	5µ	36.7%	50.4%	12.9%
Dispersion Method 2				
	20µ	37.7%	24.2%	38.1%
	10µ	36.3%	39.6%	24.2%
	5µ	37.0%	52.3%	10.7%
Dispersion Method 3				
	20µ	13.3%	39.0%	47.7%
	10µ	12.5%	49.6%	37.9%
	5µ	13.0%	65.1%	21.9%

A mass balance of the +325 tails from each dispersion method indicates an increase in the mass percent of smaller sized particles in Method 3 (Table 2). This was the expected result due to the vigor of the attrition in Method 3. It should be noted here that some clay particles that were greater than 16 mesh, particularly in the Method 1. The presence of these particles decreased in the longer dispersion methods. Some of these clay particles could be crushed between the fingers. The increase in recovery rates with subsequent dispersion techniques is probably at least partly due to the dispersion of these types of agglomerated particles insubsequent batches. No significant amount of –325 particles were found in any of the +325 tails from any of the batches, though the -325 mesh fraction positively correlated with increased agitation. These tails represent an average of about 1.5% of the total mass of each batch.

The average density as determined by the gas pycnometer for the clay of interest was 2.729 g/cm^3. Settling times were deemed adequate because the assumed density was close the determined density from the pycnometer. The x-ray sedigraph results show a decrease in the average particle size for Method 3 (Table 3). This is explained by the greater attrition intensity in Dispersion Method 3. Ideally, the mass percent finer than the target particle size for each batch of clay produced should be 100%, but this is not the case. Although these results show a high purity level, all of the batches appear to contain some particles that are greater than the target particle size. The small percentage of particles greater than the target particle size for each batch is not expected to adversely affect the performance characteristics of the clay products.

TABLE 2 Mass balance by dispersion method

Mesh Size		16	40	100	140	200	325	-325
Dispersion Method 1								
	20μ	9.0%	29.7%	26.3%	6.9%	9.1%	14.6%	4.0%
	10μ	9.9%	27.8%	25.1%	8.9%	6.0%	17.9%	4.2%
	5μ	8.9%	27.1%	27.4%	6.6%	8.9%	14.1%	6.8%
Dispersion Method 2								
	20μ	12.2%	30.7%	23.5%	7.4%	2.8%	16.4%	6.5%
	10μ	11.7%	32.9%	24.6%	5.7%	7.6%	12.5%	4.8%
	5μ	11.7%	29.4%	23.8%	6.2%	7.6%	12.7%	8.3%
Dispersion Method 3								
	20μ	0.3%	8.2%	32.1%	10.0%	15.0%	31.8%	3.1%
	10μ	0.2%	6.5%	30.3%	12.8%	11.6%	36.5%	3.1%
	5μ	0.3%	6.8%	31.6%	10.1%	13.7%	28.7%	9.4%

(continued)

TABLE 3 Particle size by dispersion method

Sample Name		Average Particle Size in Microns	Mass Percent Finer Than Target Particle Size
Dispersion Method 1			
	20µ Clay	4.915	96%
	10µ Clay	3.886	96%
	5µ Clay	2.479	91%
Dispersion Method 2			
	20µ Clay	4.194	97%
	10µ Clay	3.144	98%
	5µ Clay	2.284	96%
Dispersion Method 3			
	20µ Clay	3.861	98%
	10µ Clay	3.021	98%
	5µ Clay	2.103	94%

The color analysis that was performed used Hunter *L, a, b* values to quantify the color of the clay samples. The *L* axis of the Hunter scale refers to the tint of the sample, 0 equals black and 100 equals white. The *a* and *b* axis of the Hunter scale have no definite numerical limits, where a positive *a* is red while a negative *a* is green. Positive *b* values indicate yellow while negative *b* values indicate blue. This analysis also yielded a whiteness index using the ASTM E-313 method for –325 raw clay material, 5µ clay, 20µ clay and samples of each calcined to 1,000°C and 1,149°C. All of the samples demonstrated high Hunter *L* values and high whiteness indices. All of the samples were a white to buff color, so high values for this axis was not expected but trend towards the positive *a* axis, red, in the finer samples and in the higher oven temperature samples.

The initial powder X-ray diffraction analysis performed at University of North Carolina Asheville on samples of the raw clay material, 5µ, 10µ and 20µ clay and the –325 mesh tails from the 10µ clay production indicated the presence of quartz, illite, and kaolinite. This is not an unexpected outcome because all of these minerals are found in many types of clay and typically are found as secondary minerals from felsic volcanic tuff, the origin of this clay deposit.

The X-ray diffraction analysis performed by a commercial lab confirmed the initial identification with quantitative analysis of samples of 10µ clay from Method 2 and the raw clay material. This analysis provides the weight percentages of various major elements that constitute more than approximately 5% of the total mass of the sample. The raw clay material sample contained 39% illite, 48% kaolinite and 13% quartz while the 10µ clay sample produced 17% illite, 21% kaolinite, and 60% quartz. Both of these samples include less than 5% of unidentified minerals.

The X-ray fluorescence analysis performed by a commercial lab on samples of 10µ clay produced from Method 2 and the raw clay material yielded a broader representation of the constituent minerals in the samples. Results included 13 common minerals although only three minerals were present in amounts greater than approximately two weight percent. The results showed 54.7% SiO_2, 31.7% Al_2O_3, and 3.92% K_2O in the raw clay material and 79.0% SiO_2, 14.0% Al_2O_3, and 1.67% K_2O in the 10µ sample.

DISCUSSION

As with any pilot scale production plant, a full-scale plant presumably could produce higher recovery rates more efficiently. Although the recovery rates from these tests were acceptable by TCPI, some equipment limitations may have detracted from the final yield. Certainly, the time required to make the final product could be lessened through the use of automated conveyance systems instead of the manual means used. Using a production system of a greater volume could also decrease the time required to make the final product. Both of these issues deal only with the time required to produce the final clay product but not with the quality of the product. Any improvements made in the quality of the final product in large-scale production likely would be incremental and not ultimately cost effective.

The settling method used to size the clay in this production was effective and is used widely in the industry. As with other aspects of this research, more expensive and time consuming methods could be used to gain a finer cut in clay particle sizes but would not be economically justified in large scale production. The clay size particle cuts produced here were acceptable to TCPI, but a small amount of finer clay always will be involved in the coarser clay sizes due to the position of finer clay particles in the settling column. Some fine particles will settle with the coarser particles simply because they are at the bottom of the column to begin with.

The amount of sodium hexametaphosphate used in all methods of clay production was excessive. This should not pose any problems to end-users unless their application is sensitive to high residual sodium levels. The only problem that this overuse incurs is simply an issue of higher cost. The amount of sodium hexametaphosphate used to effectively disperse the clay particles is approximately half of that used here, approximately 1.8 kg/ton.

The expense involved in drying the clay product is high and should be considered before large-scale production of this clay. All clay used in suitability tests was wet (about 80% solids) when delivered. For this project, the time and expense involved in drying the clay produced here was not cost effective, so dewatering was accomplished by decanting after a week of settling by gravity.

The artists at Fork Mountain Pottery found this clay to be a good addition in glaze applications. The glaze produced a beautiful brown-red finish when fired in a reducing environment.

In the brick industry, overrun of bricks are commonplace. TCPI wanted to determine whether the tails from this clay could be applied to overrun bricks to change the appearance of the brick and perhaps find another venue for excess bricks that otherwise become waste. TCPI found that this clay makes an excellent face coating for bricks and is utilizing this clay for this purpose with good results.

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APPENDIX

Equipment Used

Milling

Denver 10-cm by 15-cm (4-inch by 6-inch) jaw crusher set to an outlet tolerance of approximately 5 cm.

Denver No. 2 Coffee Mill set to an outlet tolerance of approximately 0.5 cm.

Particle Dispersion and Conditioning

Dispersion Methods 1 and 2 were accomplished using a barber chair attrition scrubber. The blender used in Dispersion Method 3 was a K-TEC Blendtech model ABC set at its highest speed, approximately 1,600 rpm.

Particle Sizing

Sweco brand 112-cm (44-inch) vibrating screen sizer with a 325-mesh screen installed. The edge of the screen was sealed with silicone rubber sealant to prevent oversized particles from passing into the –325 particle collection vessel.

Material Drying

All of the samples produced were dried using gas fired pizza style ovens set at approximately 177°C in stainless steel pans until the products were dry to the touch.

Mass Balance

The mass balance determinations were made using Fisher Scientific Test Sieves designated ASTM E-11 specification. Test sieve numbers 16, 40, 100, 140, 200 and 325 were used.

Pycnometer

Micromeritics Multi-Volume Pycnometer model 1305.

Sedigraph

Micromeritics X-Ray Sedigraph model 5100.

Color Analysis

PhotoVolt Light Reflectance Meter model 577.

Calcining Oven

Thermolyne Type 46200 High-Temperature Muffle Furnace

X-Ray Diffraction

Philips powder X-Ray diffractometer PW-3050, X'pert operating system;

The Mineral Lab Company, Lakewood, CO, performed additional powder X-ray diffraction analyses.

Scanning Electron Microscopy

FEI Quanta 400 environmental scanning electron microscope. Uncoated, unpolished specimen.

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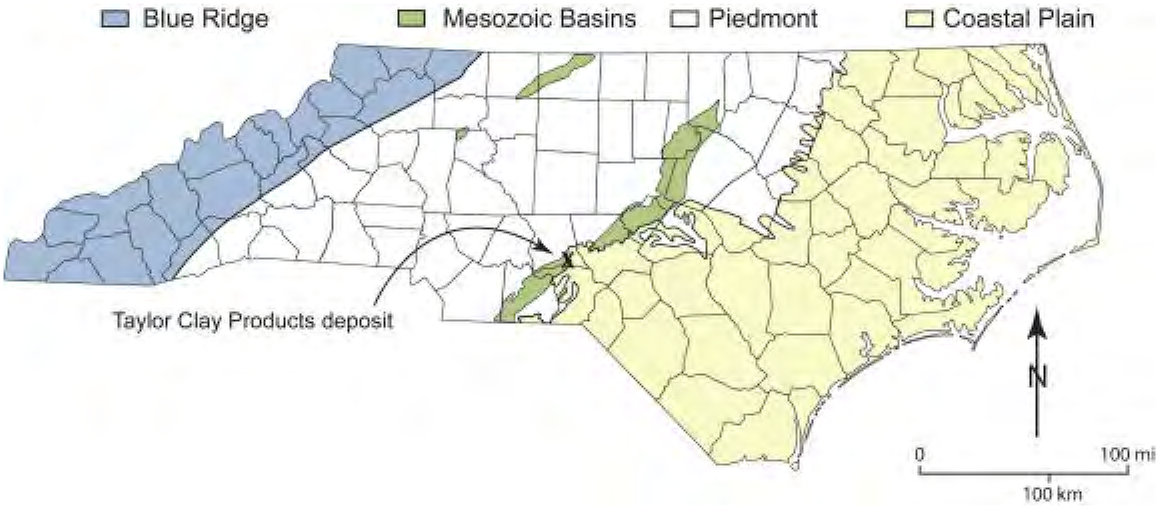

FIGURE 1 Location of Taylor Clay deposit, Montgomery, County, North Carolina.

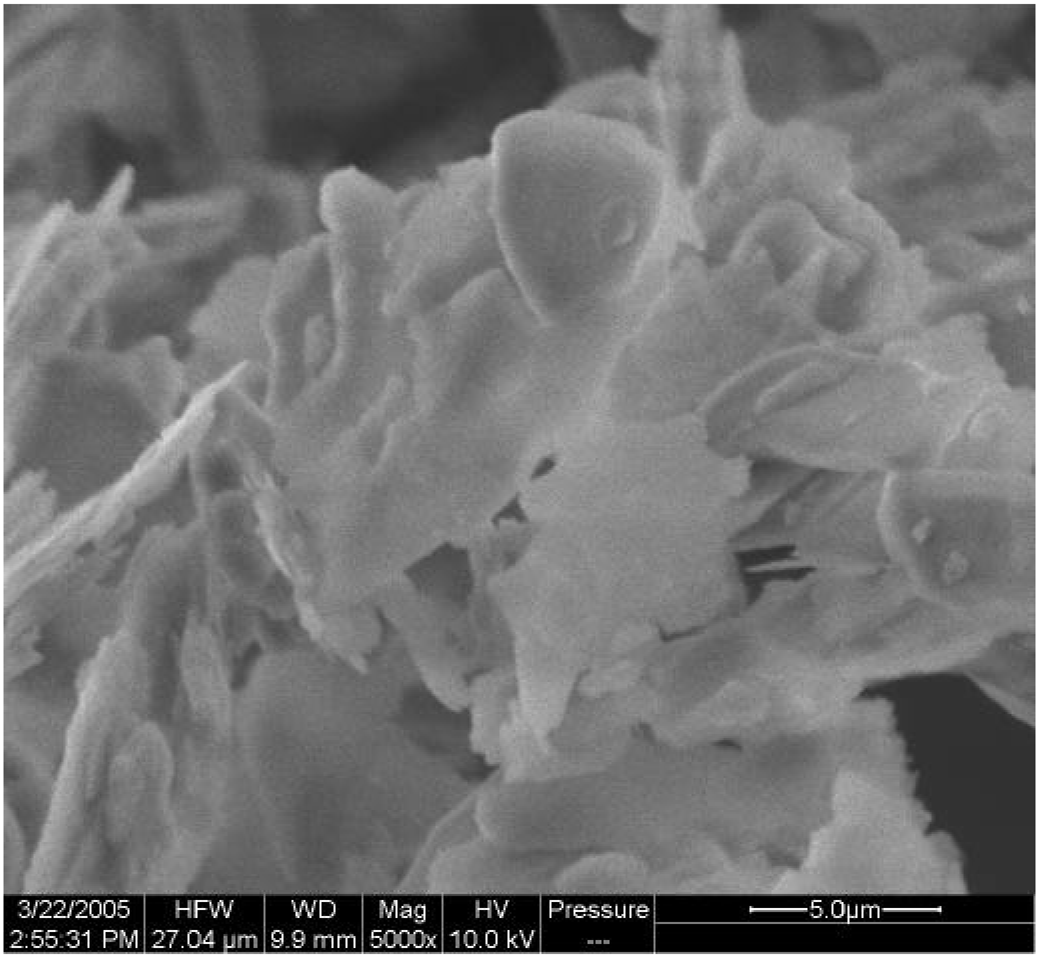

FIGURE 2 Scanning electron microscope image of 10m clay product.

Important industrial clay deposits of the world

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ABSTRACT

Important kaolin, bentonite, and palygorskite-sepiolite deposits that are processed for international and regional applications are described. The location, geology, physical and chemical properties and primary applications of the above mentioned clay deposits are discussed. Ball clays are kaolinitic clays and are included with the kaolins. The bentonite deposits include those that are comprised mainly of sodium montmorillonite, calcium montmorillonite, magnesium montmorillonite (Saponite) and lithium montmorillonite (hectorite). Palygorskite and sepiolite deposits are relatively rare in contrast to kaolin and bentonite deposits but are important industrial clays. The term attapulgite is used interchangeably with palygorskite, but the International Nomenclature Committee favors palygorskite. The term Fuller's earth is so used in England for the absorbent calcium bentonite and sometimes in the United States for both calcium bentonite and palygorskite when they are used as absorbents and bleaching earths.

Wordwide, approximately 40,000,000 tons of kaolin are mined and processed annually, 11,000,000 tons of bentonite, and 2,700,000 tons of palygorskite and sepiolite. Thus, it can be seen that the clays are important industrial minerals.

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INTRODUCTION

The most important clay deposits discussed in this paper are kaolins, bentonites and palygorskite and sepiolite. Ball clays, which are kaolinitic clays, are included as part of the kaolin section. Sodium and calcium bentonite deposits are described and also included is hectorite, which is lithium montmorillonite. Palygorskite and sepiolite deposits are important clays used for many industrial applications. There are a multitude of clay deposits in the world, but only the major world class deposits that are marketed worldwide and/or regionally are described.

Kaolins and Ball Clays

Over 500,000,000 tons of the sedimentary kaolins located in Georgia and South Carolina have been mined since the middle 1700's. In the late 1700's, kaolin was shipped from Savannah, Georgia to England where it was used by Wedgewood to make fine china. These shipments continued until about 1800 when the primary kaolins in the Cornwall area of Southwestern England became available. In the 1800's, the major use of these kaolins from Georgia and South Carolina were for ceramics and in the late 1800's, were also used as filler in paper. With the invention of on-machine coaters in the early 1930's, the use of kaolin as a major paper coating pigment grew dramatically. In the 1950's through 2000, over 4 million tons of coating grade kaolins were used annually by the paper coating industry around the world. Through the 1980's, kaolins were the primary paper filler, but with the advent of alkaline pulping calcium carbonate became the major filler for paper because of its high brightness.

The kaolins in Georgia and South Carolina are sedimentary or secondary deposits which occur as lenses and beds of late Cretaceous and early Tertiary age. The kaolins were derived from weathered granites and gneisses and phyllites on the Piedmont Plateau (Figure 1). In late Cretaceous times, the residual weathering products of granites and gneisses were eroded and transported to the coastline which at that time, was what is now known as the fall line (Figure 1). The fall line is the boundary between the crystalline rocks of the Piedmont and the Coastal Plain sediments. These detrital weathering products were deposited in lagoons, estuaries, oxbows, lakes, and ponds on the broad deltaic platform which was 30 to 50 km wide and about 150 km long extending from Macon, Georgia to Aiken, South Carolina (Kogel, et.al. 2002). The Cretaceous kaolin beds range from 2 to 12 meters thick. The Tertiary kaolin deposits are generally larger in areal extent and thicker than the Cretaceous kaolins (Murray and Keller, 1993).

The Cretaceous kaolins are relatively coarse with a particle size ranging from 55 to 75% less than 2 microns. These coarse kaolins are often referred to as soft kaolins. The Tertiary kaolins are much finer with a particle size of about 85% less than 2 microns or finer and are often called hard kaolins. The typical properties of the soft and hard kaolins are summarized by Kogel, et.al. (2002). Dombrowski (1993) reviewed the theories for the origin of the Cretaceous soft kaolins and the Tertiary hard kaolins. His research showed that the Cretaceous soft kaolins were derived from granites and gneisses and the Tertiary hard kaolins were derived from phyllite and metavolcanic source material. The mineral kaolinite is the dominant mineral present in the kaolins from Georgia and South Carolina. Other accessory minerals commonly present include quartz, muscovite, biotite, partially altered feldspar along with minor amounts of halloysite, smectite, magnetite, ilmenite, rutile, anatese, zircon, tourmaline, kyanite and iron minerals including hematite and goethite (Murray, 1976).

ENGLAND - The largest and highest quality primary kaolin deposits in the world are located in the Cornwall and Devon areas in Southwestern England (Figure 2). These kaolins were first discovered in 1746 (Wilson, 2002). Wilson estimated that the total production since their discovery has been about 170,000,000 tons. The kaolinite was derived from late stage magmatic and hydrothermal decomposition of feldspar in granites (Bristow, 1993). The kaolinite content in the altered granites ranges between 10 and 20%. Extensive drilling has shown that the typical kaolin deposit is funnel or trough like in shape (Figure 3). Dewu and Dorrance (1993) have shown that uranium is the main source of radiogenic heat that has resulted in a hydrothermal circulation system. Additional minerals present are quartz, feldspar, muscovite, tourmaline, and other heavy minerals.

BRAZIL - the lower Amazon region in Northern Brazil has two areas where sedimentary kaolins are mined and processed primarily for use by the paper industry (Figure 4). The first deposit is on the Jari River which was discovered in 1970. The kaolin is Pliocene in age and is called the Belterra clay (Murray, 1981). The deposit is large and thick and is approximately 12 km in length, 5 km wide and up to 40 meters thick. The kaolin is very fine in particle size and is classed as a hard kaolin. The source of the Belterra kaolin is the crystalline rocks on the Guyana Shield about 15 km to the north (Murray and Partridge, 1982).

The second area where sedimentary kaolins are being mined and processed is along the Capim River south of Belem in the State of Para. The kaolin layers occur in the Ixipuna Formation of Tertiary Age. The kaolin deposits underlie low lying plateaus which range from 2 to 3 km in length and width and have elevations of 30 to 60 meters above sea level. In the Capim Basin are two layers of kaolin, a lower layer of relatively coarse kaolin which is a soft kaolin, and an upper layer of fine kaolin, which is a hard kaolin. Currently, there are two operating mines as shown on Figure 4. The kaolin is partially processed at the mine sites and is then transported by pipeline to Barcarena, a port on the Guama River, a large tributary of the Amazon (Figure 4). The kaolin is then further processed and dried or prepared for slurry shipments at Barcarena.

CZECH REPUBLIC - The kaolin deposits in the Czech Republic are residual deposits which were formed by weathering of granites in the Karlovy-Vary region in Western Czech Republic. Also an arkose of carboniferous age has been kaolinized by residual weathering (Kuzvart, 1984). The kaolinization of the lithium micaceous granites took place in Cretaceous and Paleocene time (Neuzil and Konta, 1965). The kaolin from the Czech Republic is used as a filler and as a ceramic clay and is shipped to other European countries.

NEW ZEALAND HALLOYSITE - A high quality halloysite deposit is located on the North Island of New Zealand about 240 km north of Auckland. The halloysite was formed by hydrothermal alteration of rhyolite flow rocks on which residual weathering has been superimposed (Harvey and Murray, 1993). The halloysite is wet processed to produce a very fine product which is about 90% less than 2 microns or finer and is comprised of a very high halloysite content. The major impurity in the halloysite clay is Opal C-T. The processed halloysite is exported worldwide because of the whiteness, strength, and translucency it provides in fine china ceramic products.

Ball Clays

The term ball clay is used to describe fine grained, highly plastic sedimentary kaolinitic clay with minor quantities of organic matter. Ball clays have high green and fired strength and fire white or off white in color (Burst and Hughes, 1994). The term ball clay originated in England when the clay miners would cut squares of the plastic clay that weighed from 30 to 50 lbs. They would then roll the highly plastic squares, which would become rounded into balls hence the term ball clay. These balls of clay would then be loaded in wagons and transported to the processing plant (Hosterman, 1984). The color of ball clays range from light gray to nearly black depending on the amount of lignitic material present. The principal mineral present is kaolinite along with minor quantities of quartz, illite, smectite and feldspar. The most important ball clay deposits are located in the United States, England, Germany, and Ukraine. The ball clay deposits are lenticular in shape and were deposited in swamps, lakes and oxbows on upper deltaic plains and on river flood plains.

UNITED STATES - the largest ball clay producing area is located in Western Kentucky near Murray and Tennessee near Paris. The age of most of these ball clay deposits is Middle Eocene with a few of Lower Eocene age (Olive and Finch, 1969). The ball clay deposits are lenticular and vary considerably in size and shape. The thickness of the deposits range from 2 to 10 meters.

ENGLAND - The principal ball clay deposits in England occur in the Bovey Basin southeast of Dartmoor in Devonshire; in the vicinity of Petrockstow in North Devonshire; and in the Wareham and Poole regions of Dorsetshire. These English ball clay deposits occur in sedimentary rocks of Tertiary age and are of probable lacustrine origin (Scott, 1929). The ball clay is very fine grained and plastic and ranges in color from cream to dark gray or brown. The ball clay deposits in England and in the Kentucky-Tennessee area are similar in mineralogy and physical properties.

GERMANY - The ball clay deposits occur in the Westerwald area north and east of Koblenz on the Rhine River. These fine-grained plastic clays are tertiary in age and were deposited in subsidence depressions in Devonian age rocks. Most of the ball clay mined is supplied to the ceramic industry in Italy for ceramic tile (Willis, 2002). Also, these Westerwald ball clays are used in the manufacture of heavy clay products including brick and conduit tile.

UKRAINE - A relatively new source of ball clays is located in Ukraine about 70 km north of Donetsk. The age of the ball clay is Tertiary with a thickness up to 4 meters (O'Driscoll, 1998). The mineral content ranges from 55 to 70% kaolinite, 25 to 30% illite, and 5 to 10% quartz. These Ukrainian ball clays burn white or near white because the content of iron is low ranging from 0.6 to 0.8 percent. They are very plastic and have a high modulus of rupture. Most of the production is shipped to Turkey, Italy and other East European countries.

Bentonites

Smectite minerals are the dominant component in bentonite, which is a rock term. Ross and Shannon (1926) defined bentonite as follows: "Bentonite is a rock composed essentially of a crystalline clay-like mineral formed by devitrification and the accompanying chemical alteration of a glassy igneous material, usually a tuff or volcanic ash; and it often contains variable proportions of accessory crystal grains that were originally phenocrysts in the volcanic glass. These are feldspar (commonly orthoclase and oligoclase), biotite, quartz, pyroxenes, zircon and various other minerals typical of volcanic rocks. The characteristic clay-like mineral has a micaceous habit and facile cleavage, high birefringence and a texture inherited from volcanic tuff or ash, and is usually the mineral montmorillonite, but less often, beidellite." The difficulty in using the above definition for bentonite as an industrial mineral commodity is that it is based on origin and is restricted to volcanic ash, tuff or glass parent material. Deposits consisting of smectite having other origins or parent materials cannot properly be called bentonite. Therefore Grim and Guven (1978) defined bentonite as any smectite clay so is independent of the mode of origin.

Sodium Bentonite

The largest and principal producing area of sodium bentonite in the world is in the Western United States in Wyoming, Montana and South Dakota (Figure 5). The bentonite beds occur in the New Castle, Mowry and Bell Fourche Formations of Upper Cretaceous age (Knechtel and Patterson, 1962). The most important bed is the Clay Spur Member which ranges in thickness from about 50 cm to 2 m (Grim and Guven, 1978). The Clay Spur bentonite was altered from rhyolitic ash from volcanoes located west of the Mowry Seaway into which the ash fell (Slaughter and Early, 1965). The trace element chemistry of the clay Spur bed provides strong evidence that the ash altered while in contact with Mowry seawater (Elzea and Murray, 1990). This Western sodium bentonite is a high swelling, viscous and thixotropic clay which is utilized around the world in drilling fluids and foundry mixes.

Southern United States Calcium Bentonites

The bentonites which occur along the Gulf Coast are generally referred to as Southern or non-swelling bentonites. The major deposits are located in Texas, Mississippi and Alabama in formations ranging in age from Upper Cretaceous to Middle Tertiary (Grim and Guven, 1978). Another important calcium bentonite deposit is located in Arizona.

The calcium bentonites in Texas are best developed in the Tertiary Jackson and Gueydan Formations in Gonzales and Lafayette counties. One particular deposit in Gonzales County is white and is used in ceramics, organoclays, cosmetics, and other value added applications. In Mississippi and Alabama, the calcium bentonites are used primarily as bonding clays for foundry sands. In Arizona, a calcium-magnesium bentonite off-white in color occurs near Cheto, Arizona. Kiersch and Keller (1955) described the origin of the Cheto deposits which are Pliocene in age. This bentonite is used as a source to make special catalysts and bleaching earth.

ENGLAND - The most important calcium bentonite in England is located in Redhill in Surrey near London. This bentonite is Cretaceous in age and is called "Fullers Earth" in England (Robertson, 1986). Fullers Earth is defined as any clay which has a high absorbent capacity and/or is a natural bleaching earth. The major uses of the bentonite are a foundry sand bonds and in some drilling muds. A large use is to make granular cat litter.

GERMANY - Calcium bentonite deposits are located near Moosberg and Lanshut in Bavaria about 40 km north of Munich. The bentonites are Upper Miocene in age which were altered from acid vitreous tuffs (Grim and Guven, 1978). Primary uses include bleaching earths for clarifying edible oils and to bind foundry sands. The bleaching earth is shipped throughout Europe and into the United States.

GREECE - The best known and most widely used bentonites in Greece are located on the Island of Milos. These bentonites are Pleistocene age and were derived from pyroclastic flows (Christidis, 2001). The Milos bentonite is exported for use in iron ore pelletizing, cat litter and foundry bonding clays.

ITALY - Important calcium bentonite deposits are located on the Island of Sardinia (Carta, et.al., 1977). These bentonites are used to make acid activated bleaching earths and foundry bonding clays. The bentonites are shipped and used in North Africa and the Middle East.

Hectorite

A rare lithium bentonite called hectorite is mined near Hector, California and north of Winnemucca in Nevada. These lithium clays are very viscous and have a high swelling capacity. The major use is to make high quality organoclays.

Palygorskite and Sepiolite

Palygorskite and attapulgite are synonymous terms for the same mineral. Palygorskite is the name the international nomenclature committee recommends because it predates the name attapulgite. However, many producers and users use the name attapulgite because it has been and is still used in their literature. Palygorskite and sepiolite are magnesium aluminum silicates and their most unique property is their elongate shape. This elongate shape gives these minerals the property of not settling or flocculating in the presence of soluble salts and complex organic systems including paint. For this reason, these minerals have many special applications in drilling muds, pharmaceuticals and cosmetics.

UNITED STATES - Palygorskite sedimentary deposits are located in North Florida near Quincy and in South Georgia near Attapulgus (Figure 6) and are Middle Miocene in age (Merkl, 1989; Krekeler, 2004). The palygorskite was deposited in estuaries and marine lagoons of high salinity. The thickness of these clays is about 2 to 3 meters. The major impurity minerals are quartz and dolomite.

CHINA - Palygorskite is mined near the provincial boundary of Anhui and Jiangsu Provinces. The processing plants are located at Mingguang in Anhui Province and at Xuyi in Jiangsu Province. The deposits are Middle Miocene in age. The deposits are the alteration product of a basaltic ash (Zhou and Murray, 2003). The Geological Survey of China estimated that there are over 200 million tons of reserves. The deposits are relatively thick ranging between 3 and 6 meters. Minor amounts of smectite, quartz and dolomite are the main contaminants. These clays are exported to many Pacific Rim countries including Australia, Malaysia, Japan, Taiwan, Korea and the United States. They are used in drilling fluids, paints, tape joint compounds and as suspending agents in many pharmaceutical formulations.

SENEGAL - Palygorskite is mined near the town of Theis which is about 100 km east of Dakar. The palygorskite overlies an aluminum phosphate deposit which is also mined. The palygorskite is early Eocene in age and ranges from 2 to 6 meters in thickness (Wirth, 1968). The palygorskite beds extend south-southwest from Theis to the southern border of Senegal, a distance of about 100 km. The processed palygorskite is shipped mainly to Europe from Dakar, where it is used in drilling fluids and as a carrier for agricultural chemicals.

SPAIN - The largest commercial sepiolite deposit in the world is located at Vicalvaro just south of Madrid. The sepiolite was precipitated in an evaporite sequence in Tertiary lakes (Huertas, et.al., 1971). The thickness ranges from 1 to 5 meters. Palygorskite is produced at Terrejon el Ruhe, Almeria, and Caceres. Spain is the largest producer of palygorskite-sepiolite clays in the world. Galan (1996) described the many uses of these clays. The primary uses include drilling fluids, pet litter, agricultural carrier, paint, floor absorbents and animal feed binders.

SUMMARY

Important kaolin deposits located in Georgia and South Carolina in the US, the Cornwall District in Southwestern England, the lower Amazon region in Brazil and in the Czech Republic are described. Halloysite from the North Island of New Zealand is also described. Ball clay deposits located in Western Kentucky and Tennessee in the US, in Devonshire and Dorsetshire in England, the Westerwald area in Germany and in Ukraine are discussed. Bentonite deposits which include sodium, calcium and lithium types are described. The largest and highest quality sodium bentonites are located in the Western US in Wyoming, Montana and Western South Dakota. Calcium bentonites located in Arizona and the Gulf Coast region of the United States are described along with deposits in England, Germany, Italy and Greece. Hectorite is located and mined in California and Nevada and these deposits are the only significant lithium deposits operating presently. Palygorskite and sepiolite deposits from the South Georgia-North Florida area in the United States, from Central China, Senegal in West Africa and Spain are discussed.

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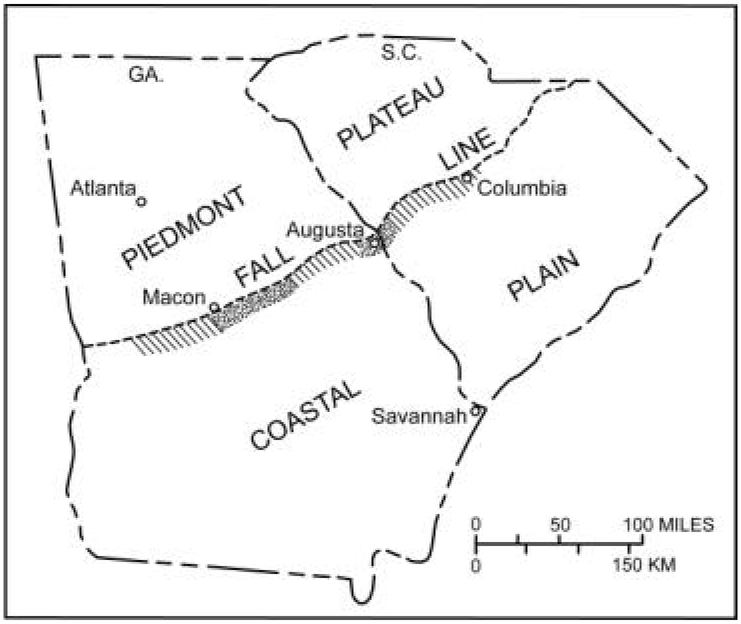

FIGURE 1 Map showing location of kaolins in Georgia and South Carolina.

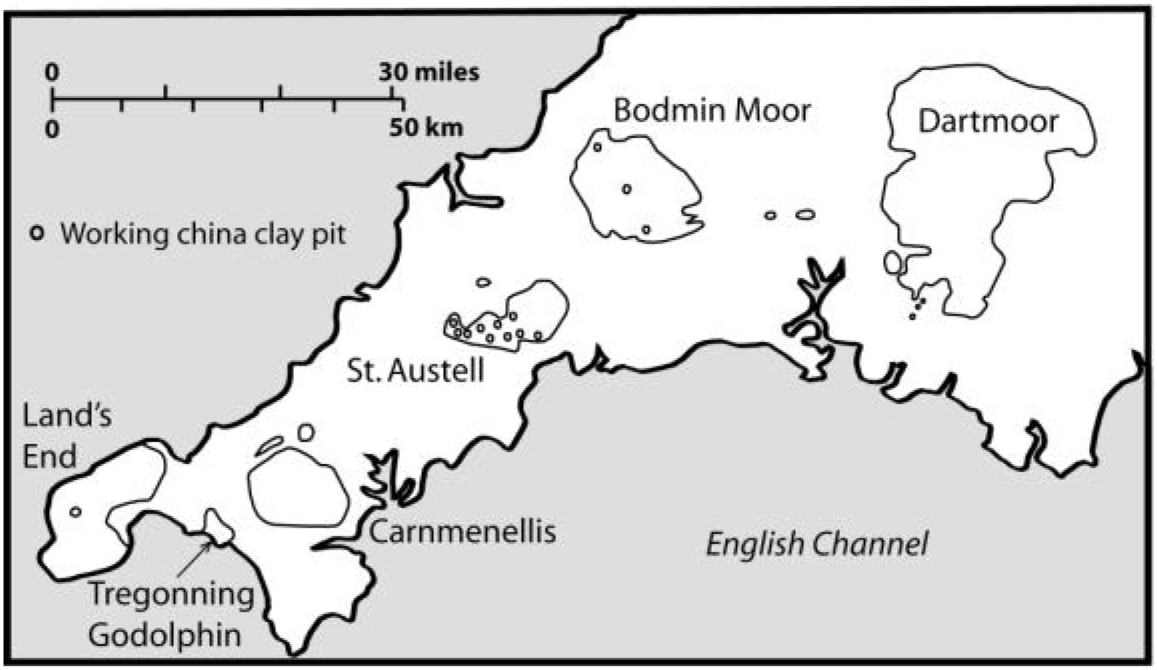

FIGURE 2 Location of kaolin mines in SE England Cornwall District.

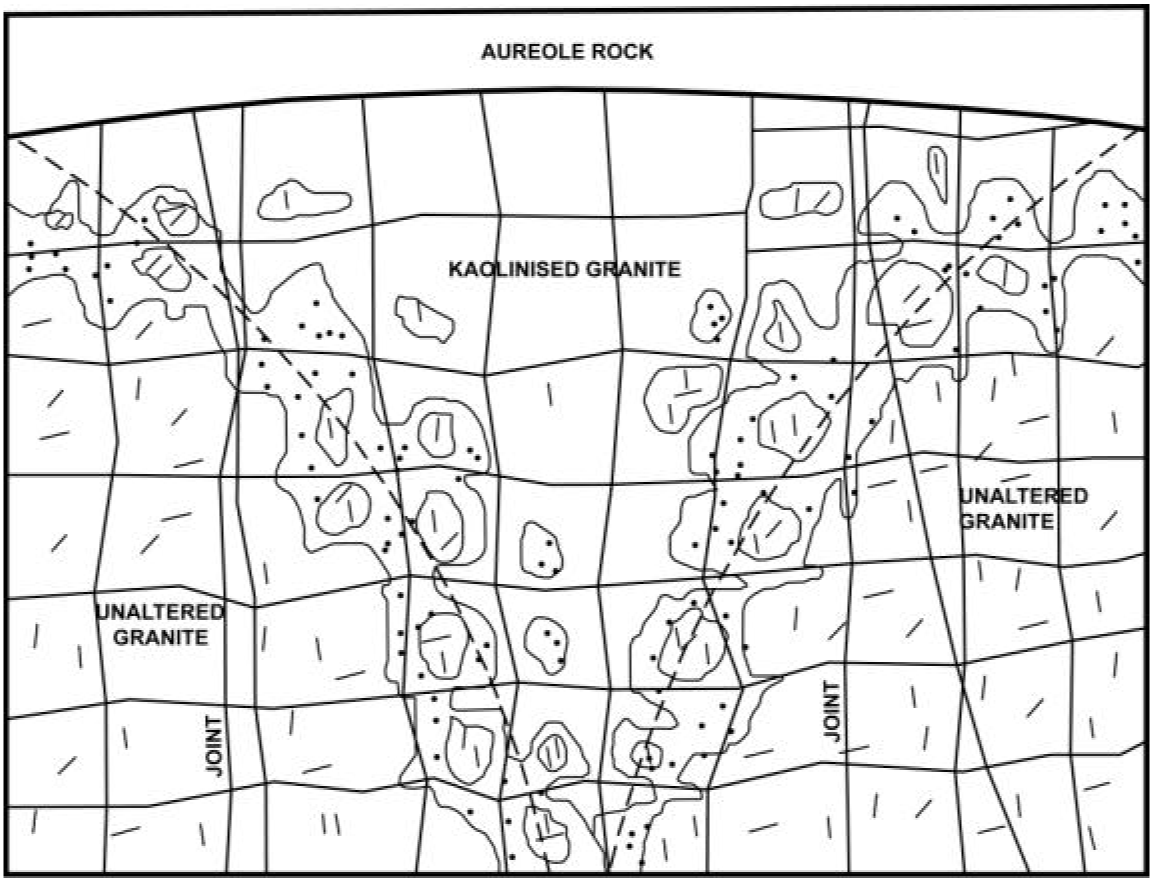

FIGURE 3 Funnel-shaped English kaolin deposit.

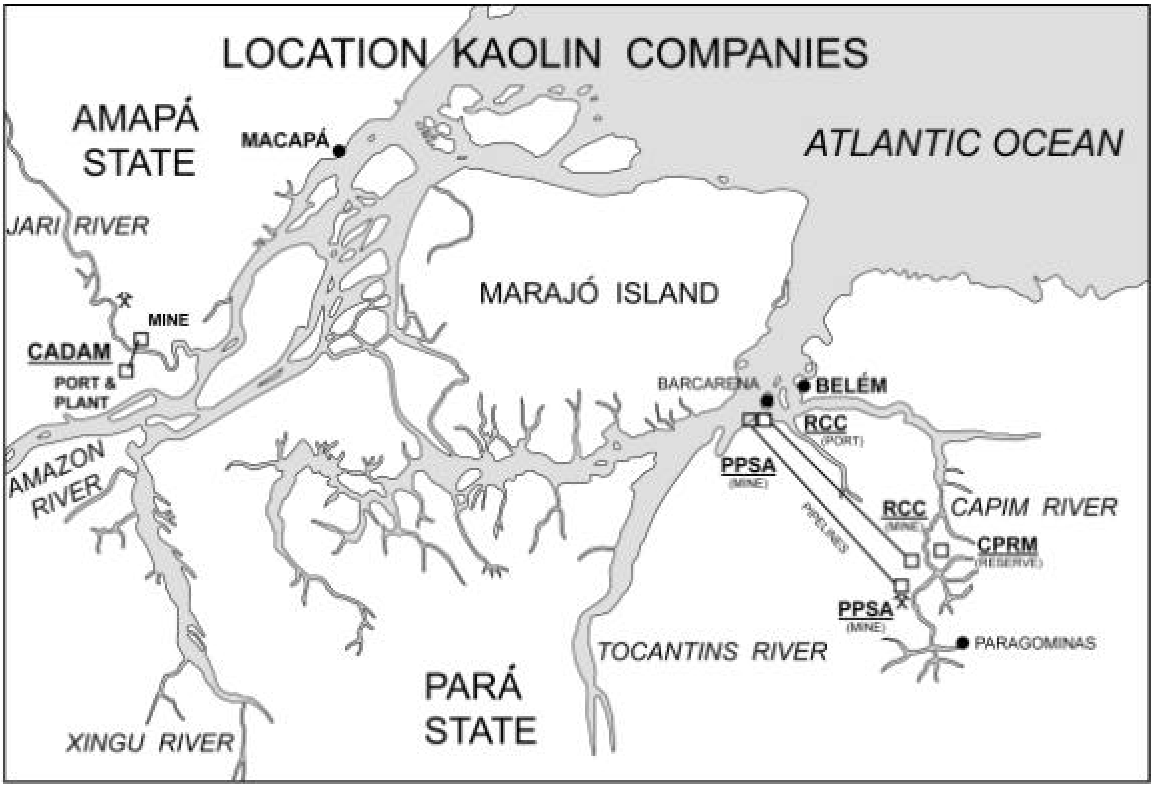

FIGURE 4 Location of Brazil kaolins.

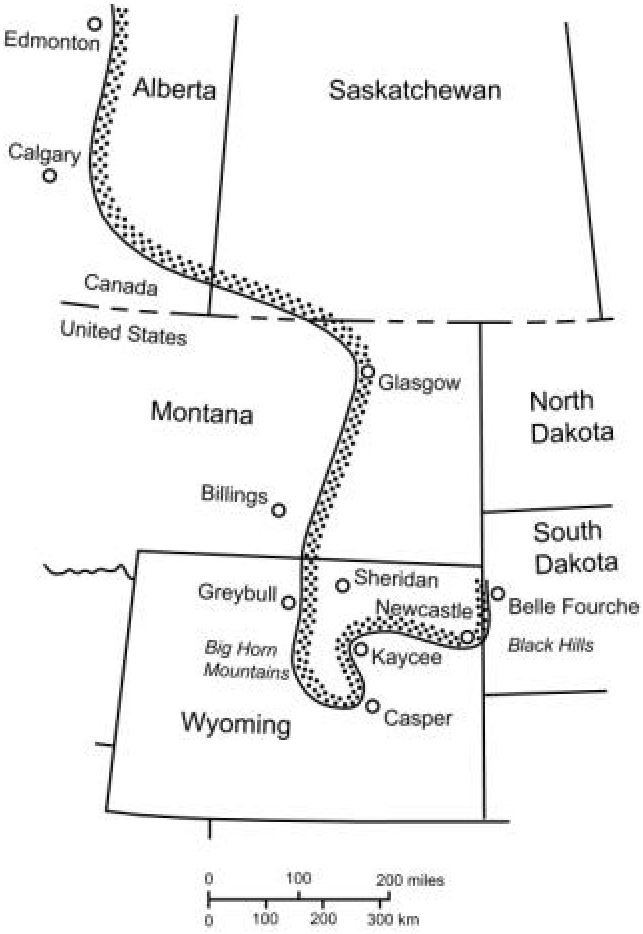

FIGURE 5 Location of western sodium bentonite.

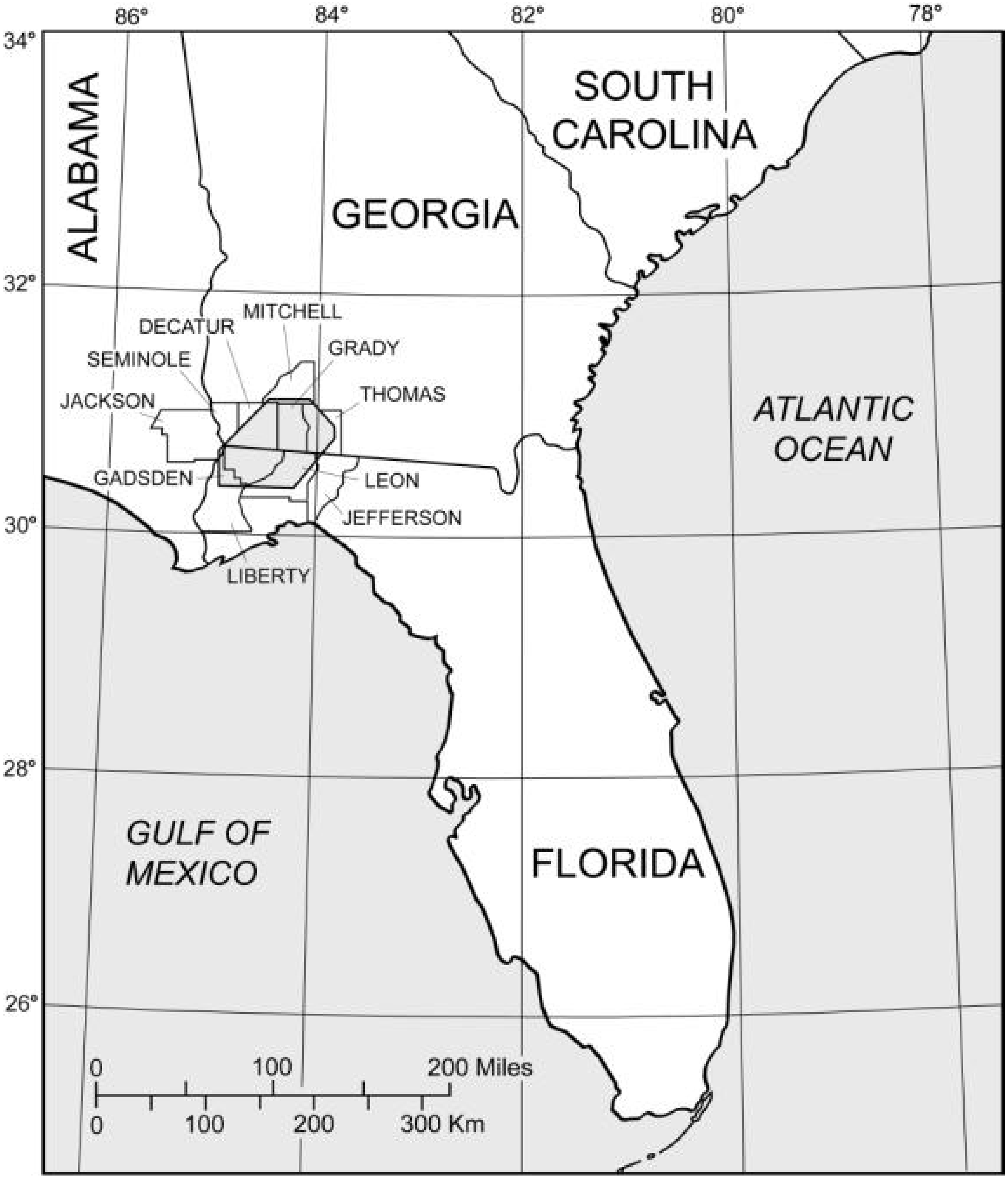

FIGURE 6 Location of palygorskite in S. Georgia and N. Florida.

Keynote speaker

Industrial minerals – Buy them here or offshore?

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ABSTRACT

In just the last few years many commodities formerly viewed as in excess supply have suddenly become supply limited. Historically low commodity prices have responded by suddenly increasing to record levels or at least to levels not seen in many years. Of all the Industrial Minerals, construction aggregates represent the largest volume and, in some areas, the strongest growth. The problems being experienced by aggregates producers mirror or amplify the problems being experienced by all industrial minerals producers. Reserves of many industrial minerals, once thought to be inexhaustible are rapidly being depleted by growing demand or being "sterilized" by development, exclusionary zoning, regulation, and public opposition driven by environmental or community concerns. How are construction aggregate and other industrial minerals producers responding to these trends? What changes will we see (or need to initiate) in the future to help assure an adequate supply of mined products? Is underground mining becoming more common in the aggregates industry? Will there be enough mining engineers and other minerals professionals to provide the skilled personnel necessary to supply the increased demand?

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Session Three

Policy issues for aggregates in the UK

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ABSTRACT

The extraction and use of aggregates is the largest sector of the non-energy mineral business in the UK with consumption running at around 250 million tonnes per annum. Of this some 70% is from onshore primary aggregate deposits (sand and gravel or crushed rock), 5% from dredging gravels or sands from offshore deposits and the remaining 25% from recycling of demolition wastes, waste from other mineral operations (such as waste from the extraction of China clay) or waste from other industrial activities (steel slag, coal combustion ash, etc). The UK exports about 12 million tonnes of aggregate, mostly marine dredged sand and gravel and imports about 3 million tones most of which is probably armour stone for coast protection.

Resources and reserves are substantial. However a range of issues have developed or are developing that will have a significant impact on the supply of aggregate in the future. These include 'Balkanisation' of supply following devolution within the UK, decisions hindering both the development of 'super-quarries' and local supplies, a shrinking supply from some recycled sources, failure to understand that some recycled aggregates are stock not flow resources, resource depletion in parts of the country, sterilisation by design or default, transportation complexities, etc. These physical issues and the resulting outcomes are made more complex and uncertain by a lack of clear and realistic policies for aggregates coupled with policy decisions in relation to non-mineral issues that purposely or incidentally limit options for supply. Overall, despite the imposition of supposed strategic planning, the position has become more uncertain. The background and the implication of these issues will be described.

Cowley, John, 2006, Policy issues for aggregates in the UK, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Aggregate Consumption in the UK

The extraction and use of aggregates in the UK is, as in many developed economies, the largest sector of the non-energy mineral business with consumption running at around 280 million tonnes per annum. In the UK aggregate consumption overtook coal in the late 1960's. Iron ore extraction dramatically fell in the 1960's and virtually ceased by 1980. Base metal production has been small since the 1950's to virtually non-existent since 1990. Extraction of a number of industrial minerals such as China Clay, gypsum, ball clay, silica sand and limestone for cement continues and although some are constrained due to resource access, the supply policy issues for such minerals tend to be very local. It is the supply of aggregates that has produced and continues to produce a range of policy difficulties across the country. The main issue is ensuring future supply and the solution to this requires a countrywide approach if it is to be resolved satisfactorily.

Of the current consumption of aggregate some 70% is produced from onshore primary aggregate deposits (sand and gravel or crushed rock), 5% from dredging gravels or sands from offshore deposits and about 25% from 'waste' such as recycling of demolition wastes, waste from other mineral operations (colliery spoil, slate waste, sand from the extraction of China Clay) or waste from other industrial activities (slag, coal combustion ash, etc). This is apparently the highest level in percentage terms of the contribution of 'wastes' to meet overall aggregate demand in any European nation, although the accuracy and transferability of data on this is uncertain, which is somewhat surprising given the common objective in Europe to maximise aggregate supply from wastes.

Current aggregate consumption reflects an economy that is at a steady state with the proviso that major infrastructure works are needed, manufacturing and heavy industry are in a reducing cycle and the housing market is lagging behind demand. The future level of aggregate consumption will probably need to address the shortfall in housing and infrastructure and, in particular, substantial investment that cannot be postponed in coast protection, flood alleviation and water supply. The policy of concentrating development on 'brownfield' sites, which sites may be difficult in engineering terms, creates a heightened demand for aggregate compared to developing 'greenfield' sites. This is offset to a degree by the reduction in intensity of use of aggregates in some sectors of construction flowing from the use of steel or timber frame and cladding and the increased use of plasterboard for internal walling.

As Table 1 shows, there has been a shift in the proportion of crushed rock to sand and gravel used as aggregate since 1955 reflecting both the greater quantity of construction primarily demanding rock (principally highway and other infrastructure works) and the substitution by crushed rock for gravel in concrete in areas where gravel resources were and are declining.

(Continued)

Table 1

Material	1955	1975	1995	2004
Crushed Rock %	31	48	63	61
Sand & Gravel %	69	52	37	39
Production in Million Tonnes	88	227	240	203

Source: UK Mineral Statistics, UK Minerals Yearbook, Aggregates Factsheet

Aggregates are normally defined as being hard granular materials suitable for use either on their own or with the addition of cement, lime or a bituminous binder in construction uses such as concrete, mortar, roadstone, asphalt, railway ballast, drainage courses, etc. Aggregate is also used as bulk fill, such as free draining rock fill, but fill operations can also require dense impervious material such as clay which lies outside the terms hard and granular and is not normally considered an aggregate mineral.

The Main Aggregate Resources

The main aggregate resources in the UK are various gravel and sand deposits and rock suitable for crushing.

The major sand and gravels are normally found as superficial deposits of Pleistocene and Holocene age. River Terrace gravels associated with fluctuations in sea levels tend to produce the cleanest gravels with, in many cases, almost an ideal mix of coarse to fine aggregate for use in concrete. The coarse aggregate is mainly flint derived from the chalk or other strong siliceous rock (quartzite, sandstone), although limestone gravels are also found. These deposits tend to be no more than 10 metres thick and typically range between 2 metres to 6 metres. They are found either as broad terraces in lowland areas or narrow strips alongside steeper valley sides.

Glacial gravels are found as isolated deposits in till. They are less consistent than terrace gravels and can contain a higher proportion of soft rock. They can be up to 30 metres thick, but can rapidly vary in thickness. Fluvio-glacial deposits representing outwash and associated reworked materials tend to be consistent locally but variable across the country. They can be in excess of 10 metres thick but most are thinner. These deposits include coarse and fine aggregate although sheet like deposits of fine to very fine material are prominent.

Alluvial fan deposits and beach or dune deposits of fine or coarse aggregate are minor sources. Some of the fine aggregate is of marginal commercial value. Production from beach deposits is shrinking due to concerns about coast erosion.

Sand and gravel can be produced from a range of unconsolidated bedrock of Carboniferous or younger age. These may have originated as desert, river or marine deposits and typically are mainly composed of quartz fine aggregate and quartzite or flint coarse aggregate. Deposits range from clast supported conglomerates through to fine sands. The sand deposits may be either of mixed sizes or nearly single sized. The bedrock deposits can exceed 350 metres or may be no more than 5 metres thick.

The most important sources of crushed rock today are the various outcrops of Carboniferous Limestone scattered across the UK. The outcrop of this rock is significantly smaller than that of sandstone or igneous rock but the rock has excellent physical characteristics for meeting a range of aggregate uses, notably in concrete.

Limestone and dolomite are produced. The Carboniferous Limestone is in excess of 1000 metres thick in the south of the country, where it is steeply folded, but thinner and more variable although less folded elsewhere. Other limestones ranging from Precambrian to Cretaceous age are found scattered locally across the UK. These tend to be variable in outcrop and may not have such consistent aggregate properties.

Igneous rock is the second most important aggregate source due primarily to production for roadstone end uses from intrusions in central England and for general aggregate use in Scotland, northern England, west Wales and south west England where there is a deficit of limestone. A variety of intrusive and extrusive rocks are crushed including 'granites', gabbros and lavas. There has been a slow shift away from less consistent local outcrops of basic intrusions into 'granites'.

Sandstone outcrops extensively in the UK but the resources of value for aggregate are more limited, although still substantial. Most sandstone is too weak to make good aggregate and is used for less rigorous end uses. However, some small outcrops of Palaeozoic sandstone in northern England have properties, particularly resistance to skidding, that make them suitable for road surfacing. In south Wales and south west England, extensive areas of Devonian and Carboniferous sandstones have been indurated to the extent that they form substantial resources of roadstone, although in some areas extraction is complicated by the presence of inter-bedded shale and clay.

Marine dredged gravel and sand is extracted from the continental shelf and landed at locations along the east and south coast of the UK, the Bristol Channel and Liverpool Bay. This material is similar to the onshore superficial sand and gravel deposits.

Aggregate derived from wastes meets a significant proportion of demand. These are derived from three main sources. The biggest potential source today is waste from slate and China Clay extraction. These materials are found in highly rural areas in the west and north of the UK distant from the main markets and with poor transport facilities. Various coal combustion wastes, colliery spoil from mines and slags from the metallurgical industries arise, concentrated mainly in the old industrial areas of south Wales, northern England and the middle Scotland. Finally aggregate is derived from construction and demolition works, road planings, foundry sand, glass, etc. This is currently the largest source of waste derived recycled aggregate with arisings mainly either from the main urban areas throughout the UK and therefore well placed to meet demand or from more dispersed sources including old military bases, disused runways and worn out infrastructure.

Location of Aggregate Resources

Ideally aggregate quarries should be located near to centres of demand. This makes good economic sense and typically meets the demands of sustainability for a host of sustainability considerations (fuel use, material use, pollution reduction, risk reduction, less pressure on environmental thresholds, employment and social benefit, conflict reduction, greater trade-off potential, etc).

However, the geology of the UK and the geography of demand do not meet this ideal. In simple terms a line between the Exeter and Hull separates relatively soft Mesozoic and younger rocks to the east (mainly soft limestone, sandstone and clay) overlain in parts by thin superficial sand and gravel, from harder limestone, sandstone and igneous rocks to the west. This line basically separates 'lowland' UK from 'upland' UK. East of the line high quality sand and gravel deposits are found but only limited quantities of rock of highly variable character some of which is weak. To the west substantial outcrops of high quality rock occur but limited, poor and variable sand and gravel is found.

This is a simplistic model because small inliers of Carboniferous Limestone and even smaller inliers of igneous intrusions are found in the Bristol - Mendip Hills area and the Leicester - Charnwood Forest area just east of the Exeter – Hull line. This has telling consequences on the perceived value, use and pressure on the resources and quarry units in these relatively small areas, which currently produce around 40 million tonnes of crushed rock or about 20% of the total production of primary aggregate in the UK. A number of these units depend on core extraction permissions granted almost 60 years ago but now have reserves for less than 20 years. Some cannot be expanded laterally and the implications on supply from these areas could be profound.

Similarly, deposits of gravel and sand are located within land to the west, although these tend to be more variable in petrology and quality and may be marginal in relation to specification. While important as sources of fine aggregate, these deposits are not of such strategic importance as the crushed rock resources of the Mendips etc.

A further complication to this simple framework is that much of the rock west of the Exeter – Hull line, such as in Mid-Wales, Southern Scotland, The Pennines and South West England consists of mudstone, shale and thin or weakly cemented sandstone and limestone with normally limited aggregate potential, and further complicated in Northern Scotland by the dominance of schists and gneiss which are difficult aggregate materials. Nevertheless, substantial outcrops of aggregate quality limestone, sandstone and igneous rock are located here.

Both areas contain either superficial or bedrock deposits that are very localised and effectively unique in characteristics. Such deposits require specific approaches to their use in say concrete mixes and this may limit their use outside a traditional area. Some of these materials may not meet ideal specification but perform well in certain uses provided tried and tested methods are used. They may not perform well in other circumstances.

An extreme example of a very local sand aggregate in ‘upland’ UK is the dune sand worked at one site near Lands End which is unique in its characteristics in that it can be purchased either ‘pink’ or ‘white’, depending on whether the old dune being worked was contaminated with historical iron pollution from base metal mining, transported by the appropriately named Red River, or not. The ‘pink sand’ in this context does not quite convey the same elegance as the term ‘pink sand’ does in relation to The Bahamas but while not an ideal sand it does provide an acceptable and locally available aggregate.

Similarly some of the limestones in ‘lowland’ UK are quite acceptable, provided they are handled properly, for end uses that might on paper be reserved for other aggregate such as Carboniferous Limestone. Crushed Portland Limestone from the island of Portland that is unsuitable for dimension stone is ‘softer’ than Carboniferous Limestone and has a relatively high porosity. These factors might restrict its use in concrete and roadstone. However, if these characteristics are taken account of in mix design and placement it can produce a high strength concrete, preferred by users to mixes using either Carboniferous Limestone of flint gravels, and a satisfactory roadstone.

There is a danger in discounting these local resources that can expand the nations available aggregate resource base if properly handled. The added advantage is that this reduces the focus on the consistent and more versatile qualities of the major aggregate resources and avoids the tendency to waste the potential value of some of that resource in end uses where other less consistent resources could be used. However, there is also a danger in relying too heavily on such local resources because of the inherent limitation of the resource and the technical issues in their use as aggregate.

Resources and reserves are therefore heavily skewed in relation to population, and hence demand, such that the extreme south east of the country with 35 % of the population has only 5% of the aggregate reserves and an estimated 0.5% of the resources. In comparison highland Scotland has around 0.5% of the population of the UK but around 50% of the estimated resources.

However, the UK aggregates market is also supplied from sand and gravel deposits lying on the extensive continental shelf around the UK. Fortuitously coarse gravels and sands are found around the east and south coasts and can supplement supply to the adjacent landward areas. Also fortuitously sands are dominant in the west coast deposits and can make up for a lack of sand in the adjacent landward areas there. Unfortunately, there is no such thing as a free lunch in relation to the environment and concerns about fisheries and coastal erosion, made more prominent by a perception of possible rising sea levels due to global warming, has created a desire in some areas to restrict extraction by marine dredging.

Location and supply issues have therefore increased alongside the growth in demand generally, and with specific concerns about growth in demand in the London and south east England area which continues to be the centre of economic activity in the Country, and continues to draw in aggregate. The pressure on aggregate resources is substantial in many parts of the country as existing reserves are utilised and as it becomes more difficult to replace those reserves. This is a particular problem in relation to gravel deposits in the south east of England. Reserves can be maintained by upgrading otherwise poor or marginal deposits but this process also has limits.

Part of the problem is the growing level of constraint to extraction caused by environmental designations and sterilisation of deposits by development. Action is being taken to declare two new National Parks in the already severely overcrowded south east of England, which will have a negative impact on future extraction of aggregate from regionally important deposits of sand and gravel. At the same time housing, there is a housing requirement of some 1.7 million units for the south east of England over the next 10 years, continues to be built over valuable aggregate resources because procedures to protect resources from sterilisation are mainly ineffective.

Intensity of Use

Table 2, shows there is a relatively low intensity of use of aggregates in the UK compared to similar states in Europe where about 50% more aggregate is produced per head of population than in the UK. The reasons for this have not been satisfactorily explained. If, as is probable, utilisation of waste in other European states is higher than shown in the table, the difference between the levels of consumption of aggregate in the UK and other states would be even larger.

It is claimed that this low intensity of use might reflect the success of actions and policies (the Aggregates Levy for example) to minimise the use of primary aggregate materials in accordance with sustainability objectives. However, the UK has only rarely reached rates similar to that common in France or Germany and the current low intensity of use was apparent well before sustainability became a policy objective.

Table 2

2003 AGGREGATE PRODUCTION & INTENSITY OF USE						
Country	**Pop**	**Primary**	**Waste Derived**	**Total**	**% Waste**	**Intensity of Use**
Austria	8.2	92	3	95	3	11.58
Belgium	10.3	57	7	64	11	6.20
Czech Republic	10.3	50	3	53	5	5.05
Denmark	5.4	38	Nil	38	0	7.09
Finland	5.2	98	Nil	98	0	18.55
France	59.8	393	9	402	2	6.72
Germany	83.3	476	50	526	10	6.31
Ireland	3.9	100	1	101	1	25.90
Italy	57.7	355	3	358	1	6.20
Netherlands	16.3	16	1	17	6	1.04
Norway	4.5	50	1	51	2	11.40
Poland	38.6	145	3	148	2	3.82
Portugal	10.1	88	Nil	88	0	8.74
Slovakia	5.4	20	Nil	20	0	3.70
Spain	40.1	437	1	438	1	10.92
Sweden	8.9	67	8	75	11	8.45
Switzerland	7.3	29	3	32	9	4.38
UK	59.8	203	74	277	27	4.63

Source: European Aggregates Association & European statistics
Population in millions, Aggregate in million tonnes

It could be argued that this low intensity of use may also reflect inadequate attention to infrastructure improvement in the UK over decades, given the acknowledged long back log of works required in water supply, flood prevention, highways, drainage schemes and similar works. Water supply problems in the south east of England have been a problem for at least the last forty years but could have been substantially resolved by improvements in local infrastructure to reduce leaks and major works to bring surplus unused water from northern England. None of these actions, which would be aggregate hungry, have been undertaken.

A further consideration is that the UK uses brick and building stone to a greater degree than many European states throughout construction and particularly in housing. That will have an impact on aggregate use. Concrete blocks and concrete units were used more widely in the 1950's in an attempt to both to speed up and industrialise construction but problems with the damp UK climate, compounded by heating systems in high-rise blocks, have not favoured that method of construction. Bricks remain the favoured external walling material for housing, followed by dimension stone. However, concrete block virtually eliminated the use of bricks in internal walls from the 1960's onwards.

Construction materials and methods in the UK have become more diverse over the last fifty years and this will have affected the intensity of use of aggregate, but the changes in materials used (steel and glass instead of concrete or brick) seem to primarily reflect fashion and architectural/engineering design considerations (low-rise rather than high-rise) rather than sustainable development considerations related to resource use. Similarly the use of plasterboard instead of concrete block for internal walling is driven by cost, speed of construction and cleaner working conditions and not by a desire to reduce consumption of aggregate. Some recent government funded research suggested that these 'new' materials are more sustainable in terms of embodied energy and environmental impact compared with brick and block. However, that only considered a short time period compared with the typical 100-year plus life of brick and block and ignored the exported environmental impacts.

Further substitution of aggregates, either natural or waste derived, in construction would lead to a reduction in the intensity of use of aggregate and in relation to the use of natural aggregates could be presumed to be a process assisting sustainable development objectives. For example, *in-situ* soil stabilisation techniques using cement/lime hydraulic binders may replace capping layers in road construction. However, this process is cement hungry. That is also a consideration in the use of China Clay sand and slate waste in concrete where higher levels of cement are needed compared to using natural sand. Substitution may therefore produce a range of negative sustainability impacts.

The issues of materials substitution are complex and alternative construction materials, such as cement, lime, steel and glass are all energy intensive to produce and transport and may give rise to other undesirable impacts, perhaps in more sensitive locations with less rigorous regulation than pertains in the UK.

Given the back log of construction and the type of works involved it is more probable that heavy construction materials, primarily based on natural primary aggregate, rather than the lightweight materials of steel, glass and plastic, will dominate construction. That would lead to an increase in intensity of use of aggregate in the UK towards that of similar European nations.

Current Policy and Issues

All mineral extraction operations in the UK require a valid planning permission issued normally by a Mineral Planning Authority (MPA), typically a 'shire' county, to undertake extraction. Reserves of aggregate (reserves in this context being that volume with a valid planning permission for extraction) vary from location to location. It is a requirement of individual national policies that reserves in each MPA area should be maintained. That does not mean that every existing site should have such reserves, as some quarries might be so poorly located that extensions could not be justified in environmental terms, but it does require that reserves overall are maintained for a sufficient period of time to enable production to be assured. However, despite that requirement reserve shortfalls, particularly in relation to sand and gravel but also for rock, occur in a number of MPA areas.

It is certain that if the economy stays as it is then consumption is unlikely to fall in the future and more probably it will rise, but at what rate is unclear. Aggregate extraction is not normally considered to be a desirable neighbour and therefore any prospect of extensions to existing quarries or the development of new quarries typically initiates objections from local residents. With other resource conflicts, such as the impact on protected landscape areas, habitats or water resources, gaining a planning permission is both a long drawn out process and not necessarily a successful process. Maintaining supply is therefore a necessary but increasingly contentious and difficult issue. The supply options for the future are more complex for a range of reasons reflecting on the one hand a resource scarcity issue and on the other increasing constraints on the resources that are left. The resource scarcity issues include physical depletion of resources in certain locations as well as factors such as adequacy of transport links. The constraints on resources include both environmental and economic considerations.

Meeting demand has therefore been one of the main responsibilities of policy for aggregate supply nationally and locally. The first steps in that process is to assess future demand and relate that to available and unconstrained resources. For, while resources are large, considerations such as protection of high quality agricultural land than often overlies river terrace gravels, groundwater in limestone, or areas protected for landscape and habitat, substantial reduced the available resource.

Unfortunately demand forecasts produced in the UK tended to become very misleading, sometimes grossly underestimating demand and sometimes grossly overestimating demand. They, or rather the perceived impact of overestimates on the scale of future quarrying, became a valuable weapon in the hands of organisations committed to limiting individual or total aggregate supply as they could be used to produce distorted conclusions about the impact of aggregate production.

Part of the problem here has been the sporadic and ineffective approach of central government to the collection of statistics on sales and the production and interpretation of the forecasts. If forecasts were reviewed on a regular basis then the impact of changes in the economy and on demand estimates would not be so dramatic and more easily assimilated within society.

The collection and publication of sales statistics have tended to lag well behind the relevant year. Currently the last comprehensive data for most of the UK relates to 2001. A survey of 2005 sales and reserves has been proposed, although at this time it is possible that it may be cancelled, postponed or slimmed down to meet financial cutbacks. This might mean that demand estimates and provisions are based on increasingly dated information at a time when, with rapidly depleting reserves and uncertainty about future supply sources, any errors might have significant consequences on supply. Given the lag in translating surveys into forecasts and then into policy, both nationally and locally, and the implications on the grant or refusal of applications for planning permission for extraction, this can hardly be described as planning the supply of aggregate.

Forecasts of aggregate demand, and the resulting amendments in policy to meet changed conditions, have tended to be reviewed not on a regular basis but only when things were perceived as so bad for economic or political reasons (either because there were severe supply difficulties or an apparent excess of new permissions in sensitive areas) that government had to act. Unfortunately the UK government then acted quickly to change a situation, but typically just when conditions were moving in a counter direction. The resulting changes in policy then become doubly harmful, because of that lag in response time and its dislocation with events on the ground.

Policy therefore started to chase events (it became reactive, instead of proactive) and continues to do so. And, because there has always been vagueness at national level about the mechanisms to manage and ensure supply, how supply will be assured in the future is uncertain. This is complicated by resource scarcity issues and an inherent attitude of decision and policy makers at all levels to avoid the politically sensitive arena of promoting shifts in supply to meet future demand.

Strategic resource planning is supposed to be about offering indicative guidance for the future, within which detailed local decisions can be taken. If we are not careful we are entering a period where weak strategic planning will provide some resources, but not a certainty of supply, and where in default ad-hoc decisions will make up for the shortfall.

So where do we go from here and what factors impinge on future options for aggregate supply in the UK. A number of relevant considerations and solutions need to be considered and some particular UK focused matters are described below.

DEVOLUTION

The UK is formed by the union of four nations or provinces, plus some off-shore states and throughout history there has been a degree of antagonism or cultural elitism between them. Each nation also has some pronounced internal regional differences.

Due to the geographical dislocation between the location of aggregate resources and demand the supply of aggregate has traditionally involved movements from one nation/region to another. Aggregate from Wales has for example traditionally supplied the demand in adjacent areas of England, such as Liverpool and Birmingham. However, until recently there was little movement of aggregate between Scotland and other parts of the UK. As resources become more limited in some locations such cross-border flows might become more desirable and more prevalent, as long as planning, or other policy does not inhibit them.

There has always been a level of devolution of some powers of government to the nations and regions of the UK, but with some oversight by the UK government. This was seen by some as a level of tokenism and following major economic and political issues during the 1970's and 1980's ("It's Scotland's Oil" for example) it created a growth in nationalist political parties and the call for self-government. The response of the incoming Labour government of 1997 to the growth in interest in nationalist parties, and the supposed dissatisfaction of English regions with the centralised control from London, was to provide some devolution of powers both to the countries of Scotland and Wales and to regions in England.

The concept of devolution had an underlying theme that the new bodies would be able to adjust policy in those areas for which they had powers in a direction that expressed the different characteristics of the country or region.

The range of powers subsequently devolved varies. Scotland and Wales became devolved nations in July 1999 following the enactment of the Scotland Act 1998 and the Government of Wales Act 1998, and took over all planning functions, including mineral planning policy and control from that date. The Regional Development Agencies Act 1998 provided for a measure of strategic control by Regional Assemblies of matters relevant to the economy and the environment within the region. Although effectively this was only an involvement in strategic planning policy, it provides for a regional assembly to influence mineral planning policy and thereby decisions.

However, there is no over-arching policy framework at the UK level to identify how the policies of the individual nations for aggregate supply match to that required by the country as a whole and even within England policy on supply between regions is becoming tenuous.

Not surprisingly therefore, an issue such as the supply of aggregates, which raises concepts of resource exploitation, off-loading environmental costs or the bearing of an apparent excessive level of environmental costs, and the particularly sensitive political issue of central government, or other areas, effectively dictating what should be provided from say Wales into England, etc, has become an interesting area for seeing devolution at work. This has already started to have some impact on strategic and local planning for aggregates as nations or regions act to protect their unique character. We have therefore a developing 'Balkanisation' of aggregate supply policy and decisions.

Some developing aggregate supply policy objectives seek direct impacts by proposing a reduction in supply within a region, because of the apparent resource shortfall or sensitivity of the environment and thereby seeking additional supply from elsewhere. However, that approach, while effective in the short-term, has the potential to be eventually overturned by reasoned argument.

An alternative, more subtle, insidious but apparently pragmatic approach being adopted in some areas is not to directly challenge the amount of the call on resources, but to stress that while policy will allow say export from one area to another, that will be subject to the detailed environmental assessment of the proposal. On the face of it that is an eminently practical and environmentally responsible approach. However, certain essential activities of society are neither desirable neighbours nor can they be undertaken without some harm to the immediate locality. That policy approach therefore effectively precludes unattractive but necessary development, such as the extraction of aggregate, which cannot but cause some degree of harm.

The decision on the Rodel super quarry at Lingerbay on the island of Harris and policy in Scotland to provision of aggregate from Scotland to shortage areas in England, or indeed elsewhere in Europe, is an example of the above problem. Rodel followed on from Glensanda and was brought forward in one of the areas identified in various studies and policies as a potential location for a super quarry to provide aggregate to areas in England. The policy background prior to devolution was not that different from policy after devolution, but the potential overview from the UK was replaced by a determination of the development application solely by Scotland.

The application to extract about 550 million tonnes of rock was submitted in 1991 and was subject to a public inquiry. This was a long process with the report of the inquiry being issued in 1999 recommending approval partly on need to supply aggregate to other parts of the UK. On 1st July 1999 the Scottish Executive (the Scottish parliament) became responsible for final determination which it issued in November 2000. The Executive decided to refuse the application noting that while the development would provide some local jobs the impact on the landscape was unacceptable. Such impact could have been put aside if need for the aggregate was justified. However, the killer point made by the Executive in the decision letter was that need relates to a demand in England set out in policies that apply only to England which have no legality in Scotland and which were therefore irrelevant to the decision.

On the face of it policies produced by the Highland Council, which contains the main potential super quarry sites, would still support the development of a super quarry, but it is made clear in policy guidance that the decision on any application will take account of the reasons for refusal at Rodel. Given the conclusion of the Scottish Executive and the local policy background it is unlikely that any super quarry will be developed in Scotland to supply England, until some fundamental policy change occurs across the UK.

Devolution might lead to protectionist policies towards aggregate supply, but it can also lead to harmful policies because an introverted approach fails to identify better, in economic and environmental terms, opportunities for supply. South Wales has a substantial resource base of crushed rock but has minimal resources of sand. Currently sand for concreting and mortar, amounting to about 1.0 million tonnes per annum, is sourced mainly from marine deposits in the Bristol Channel. Due to concerns about coastal erosion the Welsh Assembly wishes to reduce dredging for sand and replace it by another source within Wales. It has investigated up grading of crushed rock fines, crushing weakly cemented sandstones to liberate sand size grains, recovery from wastes and supply from the limited onshore sand and gravel resources. These approaches have failed, and will fail, to produce satisfactory solutions because of performance considerations or, in the case of the onshore sand and gravel, because the deposits are essentially sand poor with gravel in a silt matrix and therefore any sand produced will rapidly run out. So far the alternative of using abundant sand resources from England has not been considered.

IMPORTS AND EXPORTS

Imports of aggregate are seen as a potential solution to the supply problem in the south east of England, although currently it appears that the UK exports more crushed rock to Europe than it imports. Statistics on imports and exports into the UK are somewhat conflicting and unfortunately mix aggregate and non-aggregate end uses together. Information on exports and imports from/into other European countries are also imprecise.

It is reported that UK exports about 12.0 million tonnes of aggregate, of which up to 8.0 million tonnes is marine dredged sand and gravel taken directly from the UK Continental Shelf to ports in Europe. Exports of rock, principally from Glensanda in Scotland are about 4.0 million tonnes. Exports are primarily to the adjacent European coastline from Spain around to Poland. Rock was sent to the east coast of the USA in the late 1980's until cheaper imports from Mexico undermined that market.

Statistics indicate that the UK imports by sea about 3 million tonnes of rock. Imports are currently mainly from coastal or near coastal quarries in Norway with smaller volumes from France, Ireland and Italy. Research indicates that only a minority of this is aggregate and probably most of the aggregate imported is primarily to meet specialist aggregate uses for surface dressing. The majority of imports are considered to probably be armour stone for coast protection.

Imports therefore only make up less than 1% of the supply of aggregate to the UK. Additional sources of imports to increase this proportion have been postulated including Spain, Africa and the maritime states of Canada. One scheme proposed in the late 1980's was based on a quarry in Newfoundland. If that had come forward it would have produced the strange prospect of ships carrying aggregate crossing each other in mid-Atlantic and wondering what hell was going on.

Some Irish data indicates that exports to the UK exceed 1 million tonnes per annum from one quarry that would exceed the total reported elsewhere. However, data on Irish production of aggregate is not collected systematically (aggregate production for 2003 for Ireland was estimated at being anywhere between 50 to 100 million tonnes) and it is impossible to confirm total Irish production let alone the detail of exports or imports.

Small amounts of crushed rock are imported from Italy of which the majority may be marble chippings for decorative uses but this may also include pumice and volcanic scoria for use in lightweight concrete blocks. Imports of aggregate have also been reported from Spain, Greece and Turkey but this is probably inaccurately recorded in statistics and is more likely to be dimension stone or decorative chippings.

Countries, such as Ireland and Norway that export to the UK also export to countries other than the UK, notably Belgium, The Netherlands, Germany and Poland. The beauty of sea transport is its flexibility to move aggregate to the market that offers the best margins, subject to any long-term tied contracts, and imports to the UK could disappear overnight. Current suppliers into the UK may therefore neither maintain the existing rather limited imports nor increase imports.

It is sometimes assumed by certain interest groups in the UK that exports to the UK are acceptable to the exporting countries. That is not always true regardless of the apparent abundance of resources and lack of political or environmental constraints. There is some increasing resistance to exports in principle, although there is little opportunity to put that resistance into practice given the extent of some permitted quarries and, in some countries the more relaxed approach, compared to the position that prevails in the UK, to granting quarrying operations new extraction permits. This resistance is more likely to increase than decrease. Indeed that is the situation that has developed internally between the countries of the UK as explained earlier in this paper.

There are logistical and resource concerns in relation to any increase in supply from France, Spain and Ireland. Norway has substantial resources of rock and of its annual production of around 37 million tonnes in 2004 about 8 million tonnes was exported to other countries.

Nevertheless, despite the abundance of resources in Norway supplying 10% of the demand of the UK would require total Norwegian production to rise by about 20 million tonnes, an increase of over 50%. But the potential demand on Norwegian resources would probably also include increased demand from Germany, etc. Supplying 10% of the demand for aggregate arising from the states around the North Sea would require an annual export from Norway of about 100 million tonnes per annum. Such an increase in exports may not be acceptable.

AGGREGATE FROM WASTES

For economic reasons recovery of aggregate from various other mineral, industrial or construction activity has always been a significant element of supply in the UK. This could be seen in the common crushing of reject dimension stone, the use of base metal mine waste in metal mining areas, the use of furnace bottom ash in concrete blocks (‘breeze blocks’), concrete blocks and houses made with China Clay sand, the crushing of WW II runway concrete and the use of other materials. Substantial volumes were also used as fill and hardcore on development sites.

Some of these sources tended to fluctuate in quality and quantity and until recently there was no attempt to systematically assess the volumes or use of the arisings, but the amount of old runway concrete, colliery spoil and coal combustion products utilised indicates that this was substantial. Some of these wastes needed careful processing and placement and as some materials were not sourced properly that occasionally caused failure in construction notably sulphate problems with colliery spoil and ‘mundic’ problems with concrete made from metal mining waste.

Even so large arisings of consistent product from a single source could produce acceptable aggregate to replace virgin stone and a significant proportion of waste was used in aggregate. However, a substantial amount of construction and demolition waste was landfilled. The landfilled element typically consisted of various hard materials such as, brick, block, tile, stone, concrete mixed with soft materials such as metal, timber, clay, paper, etc, where recycling costs did not justify screening out the potentially usable elements.

The introduction of sustainable development concepts in the 1990s created a policy environment that sought to maximize supply of aggregate from alternative materials of all sorts. Encouraging the efficient use of materials through construction practices and methods that consume less material and from recovery of wastes has become an important element of this strategy, enforced or assisted by financial and legislative mechanisms, such as the Landfill Tax or the Aggregates Levy and the European Landfill Directive, to divert suitable waste away from landfill and into replacing, in part, the call on primary aggregates.

Table 3

WASTE USED AS AGGREGATE(million tones)	1970	1990	2003
Colliery Spoil	7.0	2.8	0.8
China Clay Waste	1.0	1.5	2.3
Slate Waste	0.1	0.5	0.7
Coal Combustion Waste (FBA & PFA)	8.7	5.7	3.8
Ferrous Slags	9.0	4.4	2.3
Road Planings	?	6.0	7.5
Rail Ballast	?	?	1.2
Non-Ferrous Mining Waste	?	?	Nil
Others	?	0.1	?
Construction and Demolition Waste (C&DW)	?	11.0	45.8
Total (excluding C&DW)	25.8	21.0	18.6

Source:
1970, Aggregates The Way Ahead, Report of the Verney Committee, DoE, 1975
1990, Occurrence and Utilisation of Mineral and Construction Wastes, DoE, 1991
2003, Mineral Planning Factsheet: Aggregates, ODPM, 2005
'nil' means no arisings
'?' means arisings but no statistics collected
Note: Landfill Tax and Aggregate Levy introduced between 1990 and 2003
Others includes: Incinerator ash, glass, non-ferrous slags, foundry sand,etc.

In the past details of concrete, brick etc recycled for aggregate use was not collected. If we exclude such recycled construction and demolition waste, actual gross aggregate supply from recycling has fallen from around 25.8 mtpa in 1970 to about 18.6 mtpa now. Recycled construction and demolition waste used as aggregate is currently about 46 million tonnes per annum as shown in Table 3 above.

While waste is clearly is being recovered there is a level of creative accounting or uncertainty in the statistics of use. For example, the use of alternative aggregates (particularly that arising from construction and demolition waste) in some fill end uses is not a substitute of a primary aggregate by a waste derived aggregate but the replacement of other material (clay, shale, chalk), that would normally be considered as a non-aggregate, by a waste derived aggregate. Similarly, overburden from ball clay extraction, which overburden can contain substantial volumes of gravel and sand suitable for aggregate use, is now defined as waste to avoid the Aggregate Levy whereas previously it was treated as an adventitious arising of aggregate and included in aggregate statistics. Further, published data, research and good practice notes indicate that most of the waste derived aggregate reported in statistics as being recovered, is being used for uses such as fill, capping, hardcore, etc where such material has always been used or where weak rocks such as chalk or clay were previously used. Significantly, the utilisation of slate and China Clay waste, which represent some of the largest volumes of stockpiled and annual arisings, still remains low.

Prospects for the continuation of supply of waste derived aggregate vary considerably. Wastes are often perceived as being a continuous stream and in the context of an urbanised society the generally perception is that volumes of waste are increasing. Indeed current aggregate supply policy in each of the nations is based on a continuous and apparently unconstrained and growing potential. That may be true of biodegradable waste but the picture in relation to wastes that might be utilized as aggregate is different and more complex. In that context, suitable waste for use as aggregate might derive from 'stock' resources, such as stockpiles of material left behind by previous mineral operations or 'flow' resources of demolition waste. Waste may also arise as a 'flow' resource from industrial processes or recovery of material such as slag from the metallurgical industry or glass from general household waste.

The position on future arisings is therefore related to the size of the 'stock' resource and the annual arisings of 'flow' resources. This is also complicated by the perception of the desirability or not of working stockpiles of old waste. This is a major consideration in the UK because much of the tabled data on availability of wastes for use as aggregate is dominated by stockpiles of colliery spoil, China Clay waste etc, which have now become part of the landscape through restoration works. Such resources are not available in the normal sense and the commencement of working of these areas as alternative sources of aggregate raises issues that are no different than a new primary aggregate quarrying operation. Indeed, some of these restored stockpiles are located in areas where visual impact of workings would be severe and where there are significant local access problems. To that extent such resources are not truly available and their recovery may cause more extensive amenity impacts compared with working primary aggregate. It is unlikely that recovery from such stockpiles accords with sustainability.

A particular problem with China Clay and slate waste is that these materials arise in locations distant from the main sources of demand for aggregate and where there is poor access to transport links that could move any significant quantities to areas of demand. This has been a problem that has bedeviled any major increase in utilization of these materials over the last forty years. This problem has been reviewed a number of times but in each assessment the conclusion is that major investment in rail and/or port facilities is needed to enable any enhanced recovery but that such investment is difficult to justify or fund.

Some wastes, such as slag and coal combustion products, are utilised to a much greater extent than slate or China Clay primarily because they arise near major urban areas and can be utilised locally. There are, however, limited stocks of this material and with the decrease in the scale of the metals industry in the country such arisings are also likely to decrease in relation to meeting an alternative source of aggregate.

According to statistics, the production of aggregate from construction and demolition waste has increased dramatically over the last twenty years. As previously noted there is some concern that this increase partly relates to the enhanced collection of data about this activity, whereas previously such information was only collected sporadically. However, it is clear that such wastes have recently provided a substantial contribution towards the total demand for aggregate. The continuation of this substantial contribution into the future is however a debatable point. Much of the recent arisings of material relate to the demolition of old industrial and commercial activities related to heavy industry, transport and storage operations. These are not flow resources but stock resources and each demolition and recovery activity reduces that stock. Therefore, future supply from demolition must drastically decrease as the stock of suitable structures is utilised.

An example of this position is Greenham Common Airbase, a former RAF/USAF base located near Newbury in southeast England. This was constructed during 1941/42 and remained in operation until the late 1980's, when it was last used as a cruise missile base. Following closure, the concrete runways were broken up and about 1.0 million tonnes of crushed concrete was used to assist the construction of the Newbury By-Pass. Once that crushed concrete aggregate had been recovered the stock of suitable waste derived aggregate was reduced and there is no such substantial replacement source in the area to maintain that level of contribution.

COASTAL QUARRIES AND SUPER QUARRIES

Supply by ship from quarries around the coast, including coastal super quarries within the UK or elsewhere, became a substantial part of the potential supply solution from the early 1970's. So far supply is considerably less than was postulated then or in recent assessments. The prospect for significant development of such sources of supply now looks rather bleak.

For many decades coastal quarries have supplemented aggregate supply to those areas of the UK where indigenous aggregate resources, particularly roadstone, were inadequate. Traditionally small coasters engaged in general cargo would carry aggregate or rock as back haul. A typical example would be a ship taking coal from Sunderland on the northeast coast to Falmouth in Cornwall returning to London with aggregate from coastal quarries and then picking up fertilizer or animal feed for the next leg back to Sunderland before leaving with another load of coal to another port. This pattern was repeated around the country but the essential point is that the transport of aggregate was effectively a fill-in job 'in ballast' (although ballast earning an income), between appreciable more valuable cargoes.

Volumes involved were not large but the throughput could therefore be handled with unsophisticated equipment in small ports. Investment cost in plant at the loading wharf was therefore not onerous and overall transhipment costs were relatively minor. Rail and certainly road transport was not an alternative due to distance and commonly an inadequate or no infrastructure. The development of such markets also made profitable quarry units that were typically located distant from any major markets and provided jobs and income in sometimes isolated and economically deprived areas such as west Cornwall and northwest Wales. Nevertheless the volumes of aggregate shipped were small in relation to overall consumption.

Various factors from the 1960's onwards changed much of the economic advantage of this operation. Reduction in the use of coal for heating, partly due to air pollution control legislation, but also the replacement of 'town gas' generated locally from coal by ‘natural’ gas from the North Sea, significantly reduced the movement of coal by coastal ships around the country.

Legislative changes and grants for rail freight handling terminals, to remove freight from roads, unintentionally made it economically attractive to transfer bulk transport of goods such as fertilizer from coastal shipping to rail and in addition improved the potential for inland quarries to serve areas with inadequate resources. The substantial improvement of the road network also made viable long distance hauls both of goods such as coal but also of aggregates such that commonly understood market areas of no more than 20-30 miles rapidly expanded to well in excess of that figure.

That long distance movement of aggregate, particularly crushed rock, by road was, as in the case of coastal shipping, often subsidised by return loads of grain, apples, animal feed, etc and also by sand back into areas with little natural sand. Together, these and other factors significantly reduced the traditional prospects for shipping of aggregate from isolated coastal or near coastal quarries and a number of units stopped such operations. By 1973 coastal shipping was transporting only about 1.5 million tonnes out of a total production of around 256 million tonnes of natural aggregate.

Perversely the late 1960’s and early 1970’s were a time when major shortfalls in aggregate supply were apparent or predicted for ‘lowland’ UK and major studies undertaken across the country identified the need for methods to transport aggregate from the major resource areas in ‘upland’ UK to meet this shortfall. This was partly resolved by substantial investment in railheads at quarries and in the demand areas. However, the potential attractions of coastal transport to move large quantities in an ordered manner as opposed to the previous somewhat disordered pattern of supply, encouraged both regulators and industry to revisit the potential of coastal quarries and shipping.

This was expressed in two concepts that were developed at the same time. One concept was to utilise existing permitted coastal or near coastal quarries with substantial reserves (circa 50 million tonnes plus) working limestone or igneous rock on the southwest and west coasts of the country and to invest in efficient transport and loading facilities to enable the shipping of around 1.0 million tonnes per annum from such units.

The second concept was to identify potentially very large resources (circa 500 million tonnes), mostly in ‘greenfield’ locations, to develop what became known as coastal super quarries, to enable the shipping of around 10.0 million tonnes per annum. Such potential resource areas were principally restricted to a few large coastal igneous outcrops in Cornwall and Wales but with a significantly larger potential in the Highlands and Islands of Scotland with, in addition, the prospect of similar quarries being developed outside the UK (Norway, Spain, etc) but serving the UK.

Policy for aggregate supply initially identified the broad advantages of such supply options, with specific levels of supply being identified from the early 1980’s. By 1989 guidance for aggregate supply to the south east of England indicated an increasing supply by sea from coastal quarries reaching circa 7.0 million tonnes by 2006. There has been fluctuations in guidance of the indicated supply from coastal quarries but current guidance still seeks an average of circa 7.0 million tonnes to the south east of England over the period to 2016. However, it is notably that the postulated level of supply from coastal quarries, notably from Glensanda, has never been achieved regardless of the potential in place.

Schemes for smaller coastal quarries were developed during the 1970’s, but these all failed to get off the ground. The reasons for this failure were varied and included a combination of environmental constraints, problems with shipping charters, investment returns on improved handling facilities and uncertainty of market penetration. The potential still exists for small (circa 1.0 million tonne per annum) coastal quarries around the coastline of England, Wales, Northern Ireland or Scotland. However, local policy against such development has hardened and it seems unlikely that proposals for such sites will come forward in the short-term.

A number of sites for super quarries have been identified but other than Glensanda and Rodel, no sites have come forward. Glensanda represents the only super quarry to have been developed in the UK over the last thirty years. Probably, as noted above, in relation to the Rodel proposal, Glensanda came forward at a time when the concept of super quarries was first discussed, but got approved before policy started to interfere with the development of such sites. Nevertheless, and despite the demand for aggregate and the extent of the market served, it has yet to achieve the approved production rate of 12.0 million tonnes per annum and is currently producing up to 6.0 million tonnes. The original permission for extraction runs to 2014 and an extension application is now waiting determination.

It is not clear why production at Glensanda has not reached the 12.0 million tonne target. It should be noted that the ships used to take aggregate from Glensanda are also involved in the trade of other bulk minerals such as gypsum and coal picked up at ports outside the UK. That might suggest, given the difference in value of cargoes, that aggregate sales do not drive shipping, that aggregate is taken to destinations where high value return load cargoes are available and that total aggregate sales are therefore influenced by the availability of such cargoes.

Taken together it seems unlikely that any further super quarries or coastal quarries will be progressed in the short to medium term.

IMPLICATIONS

Reserves and Resources

Shortfalls in supply from some traditional resource areas will start to be felt within the next 20 or so years. Existing major production areas may not be able to maintain local supplies or supplies to more distant markets at current levels. Resource depletion is a real possibility in certain locations.

The Impacts of Devolution

Devolution has provided an apparently justified approach of limiting aggregate resource development in one area without properly considering the impacts across the whole country. This is a natural and expected outcome, which will be a self-perpetuating and enforcing process unless an over-arching policy approach is provided.

Supply from Imports

It cannot be assumed that the existing laissez-faire approach to aggregate resource exports into the UK will continue into the future. More probably the relatively low level of exports to the UK, and in total, does not give rise to major concerns in exporting countries. If demand were to increase, perhaps associated with a permit application for a major new operation, then that position could change. It is therefore unlikely that exports to the UK will grow to such a level that they could supplant a substantial amount, say 10% or more, of indigenous UK primary aggregate supply.

Supply from Wastes

The supply of waste derived aggregate has probably reached a ceiling or will reach that ceiling soon. The resource base of waste derived aggregate is smaller and shrinking at a faster rate compared to natural aggregate. While waste will continue to contribute towards aggregate supply it will fall in proportion requiring primary natural to replace it.

Supply from Coastal Quarries and Super Quarries

This issue is wrapped together with the impact of devolution and supply solutions via coastal quarries will depend on a clear statement set out in an over-arching policy. Concentration on Super Quarries may have distorted the picture. They have a part to play but smaller coastal or near coastal quarries may also have an importance. However, the viability of coastal quarries is uncertain.

CONCLUSIONS

It is likely that total UK aggregate demand will not fall below the present level of 280 million tonnes per annum in the future. A falling off in supply from wastes will put additional pressure on primary natural aggregate sources. Resource scarcity issues in some parts of the UK are becoming severe although extensive resources exist elsewhere which could supply those areas. These resources are not always ideally located in relation to demand and additional transport facilities will be needed to bring aggregate from more distant locations. This may require new coastal quarries, including super quarries, and new inland quarries. This paper has not dealt with other relevant considerations such as the potential supply from marine aggregate, the concerns about availability of quay space to unload sea borne aggregate in the future, conflicts relating to line capacity on the rail network or the potential of inland waterways. All these factors need to be considered in a strategic manner across the whole of the UK for a period of say the next 25 to 35 years. That strategic approach is currently missing.

Sand and gravel deposit evaluation - variogram analysis and its implication for reserve definition

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ABSTRACT

Geostatistical analysis of sand and gravel grading data has only rarely been used as part of the deposit evaluation process. These attempts have generally indicated that while kriging provides some additional information in reserve assessments the quality of the drilling data is insufficient to justify such treatment and that the time and the cost of such analysis is not justified.

Simple and rapid variogram analysis however provides critical information on the variability of the deposits and, in particular, whether the deposit has been sufficiently drilled to define the changes in deposit geometry and quality. This is central to the requirements of reserve definition under international reporting codes.

Variogram analysis has been undertaken on exploration drilling data gained from sites in a range of geological settings. These include fluvial, fluvio-glacial, glacial, Sherwood sandstone and Greensand deposits. In the UK fluvial deposits have been the preferred source of sand and gravel due to their cleanliness, consistency and proximity to urban centres. Depletion of easily worked fluvial deposits and regional variation in availability has led to increasing exploitation of the more complex fluvio-glacial and glacial sources.

The standard practice of exploration involves drilling by flight auger, shell and auger and, more rarely, reverse circulation techniques supplemented by trial pitting. Typical borehole spacings are around 100m, but this ranges from 250m to approximately 75m depending on company practice and deposit characteristics. The variogram analysis reveals important insights into the sufficiency of this approach.

In the traditional fluvial deposits studied the ‘ranges’ defined by the variogram are between 200 and 400m. Drill spacng should ideally be between 50 and 75% of this range for adequate definition of quality variation, suggesting that drilling is adequate in these deposits. In the more complex glacial deposits however these ranges are as low as 10m, and in almost all cases are less than 100m. The dimensional parameters of the deposits, e.g thickness, have significantly longer ranges than the quality i.e. grading parameters, supporting anecdotal evidence from industrial experience that estimation of quantity (volume and tonnage) is generally more successful than the estimation of deposit quality.

These results suggest that in many cases, particularly for more complex deposits, the density of drilling used is insufficient to define continuity of the deposit quality. This raise an important question of corporate governance and whether these deposits can accurate be defined as proven reserves under international reporting codes.

Jeffrey, Kip, 2006, Sand and gravel deposit evaluation – variogram analysis and its implication for reserve definition, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Traditional sand and gravel deposit assessment has involved the use of trial pitting and drilling to define the vertical and lateral extent of the deposit, and recover samples from which the quality of the deposit can be estimated. In the UK the deposits are generally drilled by flight auger due to the speed and cheapness of the technique. This allows more holes to be drilled but concerns over the representativeness of the samples particularly near and below water-table mean that the sample grading results must be considered with care. Shell and Auger drilling is also used and experience suggest it is able to recover better quality samples in some geological environments. Fines loss below water table or when water is added during the drilling process is however again seen as problematic. Trial pitting is frequently used to supplement drilling in order to recover bulk samples for processing trials and particularly to assess the coarse gravel to boulder (‘oversize’) fraction in some deposits that are not recovered or are comminuted during the drilling process. More rarely geophysics is deployed to solve local interpretation problems particularly where deposit depth or overburden thickness changes rapidly, in channel deposits for example.

Boreholes are typically drilled on an approximate grid or offset grid pattern with spacings of around 100m. In obviously complex deposits some infill drilling at 75m or even 50m may be undertaken but equally some of the country’s largest deposits are drilled out at spacings of around 200m.

Estimation of the overall deposit size from these investigative techniques has involved various geometric techniques involving contouring or sections and increasing using computerized volume calculation. The quality of material has typically been estimated by using averages of the grading analysis weighted for intersection thickness in each borehole or pit. Overall deposit estimates may be supplemented by assessment of separate horizons or zones where the deposit changes significantly in character.

Despite the generation of a significant borehole dataset during these evaluations geostatistical analysis has rarely been used in such deposits and received wisdom is that it is seen as a ‘hammer to crack a nut’. Attempts include those reported by de Fleuy and Newton (1974), Royle and Hosgit (1974) and Arthur (1994). This latter account represents the most comprehensive examination of the subject and the issues relating to using data of this sort are reviewed in detail by Hack (2002 and 2005).

These studies focused mainly on the potential improvements in estimation of deposit thickness and tonnages. Most involved the use of kriging to evaluate the geometric parameters such as deposit and overburden thickness rather than quality parameters such as silt content or individual particle sizes abundances.

Arthur (1994) concluded that when undertaking reserve estimates based on kriging the small differences seen between the traditional and geostatistical approaches cannot be sensibly considered without first addressing the inaccuracy of the drilling process.

While full scale block kriging represents a significant investment in time and technical expertise that may not be warranted in such deposits, simple variogram analysis is both rapid and relatively straightforward to use with the existing drilling data. The analysis indicates the variance or semi-variance between samples at incremental distances (the lag) apart in the deposit. The results are presented as a graph of variance against distance and generally show that the holes closest to a chosen borehole are generally better at estimating its value than those further away (Figure 1). Beyond a critical distance however (the Range) boreholes are equally as bad at estimating the value however far away they are located.

The technique has the potential to address two major problems faced by industrial geologists. Firstly how to estimate the number of holes, and hence what budget is needed, to drill a site; and secondly how to demonstrate that the deposit has been drilled sufficiently to call it a reserve as opposed to resource under both company and international reporting codes.

SCOPE AND EXPERIMENTAL PROGRAMME

In order to assess the validity of the variogram approach three separate but linked projects have been undertaken in the UK between some of the major aggregate producers and the University of Leicester, funded by the Aggregate Levy. A series of sites were assessed to see if geostatistical and other techniques offer useful additional information during the evaluation process, particularly with a view to promoting maximum resource utilization. As part of the overall study comparative performance of several geophysical methods and different drilling techniques were also assessed.

The studies were undertaken on multiple sites containing deposits that represent the main sand and gravel sources in the UK. The deposits were of different ages, formed by a variety of geological processes, and were the source of a variety of different aggregate products.

They included fluvial, fluvio-glacial, glacial, Sherwood Sandstone and Greensand deposits. In the UK fluvial deposits have been the preferred source of sand and gravel due to their cleanliness, consistency and proximity to many urban centres. Depletion of easily worked fluvial deposits and regional variation in availability has led to increasing exploitation of the more complex fluvio-glacial and glacial sources. Sites were selected that were considered as typical by the producing companies and for which sufficient data was available or could be acquired.

Data was compiled from existing borehole surveys and new detailed drilling programmes were also undertaken allowing various spacings and drill patterns to be compared. For this part of the study flight auger drilling was the main technique used. The samples were collected and tested using the usual industry practice and the resultant gradings were used in the variogram analysis.

Variogram analysis was undertaken for ‘deposit geometry factors’ such as depth, thickness and overburden thickness as well as the ‘deposit quality factors’ from the grading analyses.

Quality parameters are a difficult subject on which parallel studies are being completed but since the aggregates acceptance is dependant on its % passing value from a sieve analysis falling within a specification envelope, the individual grading size ranges are the most important primary data.

VARIOGRAM ANALYSIS

The drilling and grading data were initially analysed with traditional statistics and their distributions examined. Because of the intrinsic properties of the % passing data the values always fall with sieve size, and the actual % passing value for a particular sieve is constrained by the amount of material on the coarser sieve sizes. To produce a more robust analysis the % retained data is used. The distributions of % retained values in the main sand sizes are generally reasonably normal while the distribution of the coarse and fine ends of the grading distribution are skewed due to the number of zero and near zero % passing values respectively. As a result ‘outliers’ were generally not extracted unless clearly anomalous and creating difficulty in variogram modeling. Log transformation of the data was also only required in a few cases.

The data for deposit geometry was modeled and produced reasonably good variograms that approximated to a spherical model. The ranges, nugget factor and sill values (Figure 1) were extracted from the model in each case. The results for three of the deposits types studied are reported here and given in Table 1.

The data for each of the grading sieve sizes was also analysed. Most also approximated to spherical model although exponential and linear models were also used. The results of the most significant size fraction are also given in Table 1.

TABLE 1 Range, Sill and Nugget factor derived from modeled variograms of grading and drilling data for three sand and gravel deposits of different geological setting

SITE 1 - FLUVIO-GLACIAL DEPOSIT

Variogram	Nugget Factor (Co)	Sill (Co+C)	Range (Ao)
% Gravel	10.50	41.08	700.00
% Sand	21.23	58.90	906.15
% Silt	5.17	12.76	892.00
Overburden thickness	0.05	0.16	253.21
Deposit thickness	Hole Effect		
20mm %R	1.36	2.56	1214.34
14mm %R	0.85	2.56	679.84
10mm %R	0.94	2.54	367.69
3.35mm %R	Not determined		
2.8mm %R	0.74	1.43	131.44
2.36mm %R	Not determined		
2mm %R	0.67	0.97	777.47
1.18mm %R	Not determined		
1mm %R	1.11	1.98	573.52
600um %R	Not determined		
500um %R	2.05	4.22	910.54
150um %R	Not determined		
125um %R	5.04	14.81	723.98
75um %R	Not determined		

SITE 2 - GLACIAL DEPOSIT

Variogram	Nugget Factor (Co)	Sill (Co+C)	Range (Ao)
%Gravel	61.04	61.04	PNE
%Sand	4.20	44.57	148.10
%Silt	37.29	37.29	PNE
Overburden thickness	0.01	8.53	531.47
Deposit thickness	0.01	8.72	295.16
20mm %R	1.28	1.28	PNE
14mm %R	0.67	8.47	46.00
10mm %R	0.49	6.81	60.00
3.35mm %R	Not determined		
2.8mm %R	0.65	0.65	PNE
2.36mm %R	Not determined		
2mm %R	0.44	0.44	PNE
1.18mm %R	Not determined		
1mm %R	0.62	4.14	228.94
600um %R	Not determined		
500um %R	1.95	1.95	PNE
150um %R	Not determined		
125um %R	10.54	41.88	240.51
75um %R	Not determined		

SITE 3 - RIVER TERRACE DEPOSIT

Variogram	Nugget Factor (Co)	Sill (Co+C)	Range (Ao)
%Gravel	110.00	241.20	1262.00
%Sand	101.20	246.60	1853.00
%Silt	2.16	4.32	523.00
Overburden thickness	0.15	0.49	290.00
Deposit thickness	0.13	0.99	415.00
20mm %R	25.22	25.22	PNE
14mm %R	5.00	13.04	153.92
10mm %R	12.29	12.29	PNE
3.35mm %R	0.01	17.37	168.00
2.8mm %R	Not determined		
2.36mm %R	2.94	8.89	1201.00
2mm %R	Not determined		
1.18mm %R	2.67	8.27	501.00
1mm %R	Not determined		
600um %R	4.45	10.48	1322.00
500um %R	Not determined		
150um %R	3.32	8.50	418.87
125um %R	Not determined		
75um %R	2.40	3.46	190.72

DISCUSSION OF VARIOGRAM RESULTS

The range value is particularly important as it indicates the distance away at which a borehole becomes so poor at predicting the value at the original location that they are essentially independent. Holes at any further distance away in the deposit are no worse at the prediction. In evaluation practice borehole spacing should be no more than 50% to 75% of this distance so that continuity of the quality and quality can be assured and demonstrated.

The data for the terrace deposits show that these generally more consistent deposits have ranges between 280m to over 1800m for the geometric parameters and main silt:sand:gravel fractions. The individual sand size fractions also have similar ranges but curiously the coarser gravel components display a 'pure nugget effect' (PNG). This is where, at the drilling spacing used, the nearest holes are still no better at prediction than those further away. This implies high variability for that size range in the deposit or drilling that is insufficiently close to define the range. Despite this anomaly the typical 100m borehole spacing is more than adequate for most aspects of estimation in these deposits and in many cases drilling costs could be reduced by drilling fewer wider spaced holes.

The fluvio-glacial site is a channelised but extensively reworked sand and gravel deposit. Compared to the fluvial deposit it demonstrates slightly lower ranges for the sand and gravel components but longer values for the silt and fine sand size fractions. Most significantly the deposit thickness variogram demonstrates a 'hole effect' indicative of 'structure' within the deposit, caused in this case by shallow channels cutting the deposit. The normal borehole spacing will again be adequate within deposits demonstrating this type of spatial variability.

The glacial deposit by contrast shows a pure nugget effect for gravel and silt contents and a number of coarse sand and gravel size fractions. The remaining gravel sizes have short ranges of 45-60m. Sand fractions did show longer ranges of between 100 and 200m. The longest ranges were for deposit geometry factors. The typical drilling spacing of 100-200m at this site is clearly insufficient to define the ranges for most of the important deposit quality parameters. The deposit geometry and some finer sand sizes are however sufficiently addressed. It is interesting to note that the main quality control issue at the site is predicting the proportion and grading of the gravel component.

These data suggest that the ability of the industry's typical drilling spacing, at around 100m, is sufficient to predict deposit geometry in most simple deposits but that in the more complex glacial deposits, is unable to accurately define deposit quality. Although not reported in detail here other deposit types, most notably Greensand deposits also demonstrate very short ranges or PNG effects indicating insufficient drilling. This concurs with anecdotal evidence in the industry that suggests reserve estimation practice is reasonable at predicting deposit tonnages but less successful in predicting deposit quality and the distribution of quality variations.

EVALUATION IMPLICATIONS

The use of simple variogram analysis can be used to indicate the likely drill spacing required in different types of deposit and so allow better budget planning. It can also be used on an individual site basis to indicate if sufficient drilling has been undertaken to address the variability of that deposit.

Reserve definition under international reporting codes requires that the drilling or sampling programme has demonstrated continuity of the deposit and its grade distribution. In the metal mining industry the main evidence used to demonstrate this is the variogram. A well formed variogram with sufficient data to yield a clearly defined range, and drill spacings between 50 and 75% of that range would be such evidence. Only in cases of extreme 'nugget effect' are alternative approaches widely utilised.

If the same approach is used in sand and gravel deposits there is a strong indication that insufficient drilling is being undertaken for such a reserve classification. This is potentially a sensitive issue of corporate governance but since almost all companies in the sector use similar evaluation criteria it is more a case of promoting improved industry best practice.

As the 'competent person' signing off reserves how can the geologist demonstrate continuity of grade and dimension? Variograms have the potential to do this. It places power back in the hands of the geologist to indicate that without sufficient investigation a deposit should not be immediately be assumed to be classified as a reserve. More importantly it also will lead to fewer problems in prediction of deposit size, and more specifically quality

CONCLUSION

It is recommended that sand and gravel drilling data is more widely subjected to variogram analysis to assess deposit variability. This can be used to define appropriate borehole spacings for different deposit types and justify the required drilling budget or need for follow-up drilling. It can also be fundamental in the justification of reserves. Further work is nearing completion on assessing a wider range of deposit types, novel quality definition methodologies and the role of drilling method on reserve estimation.

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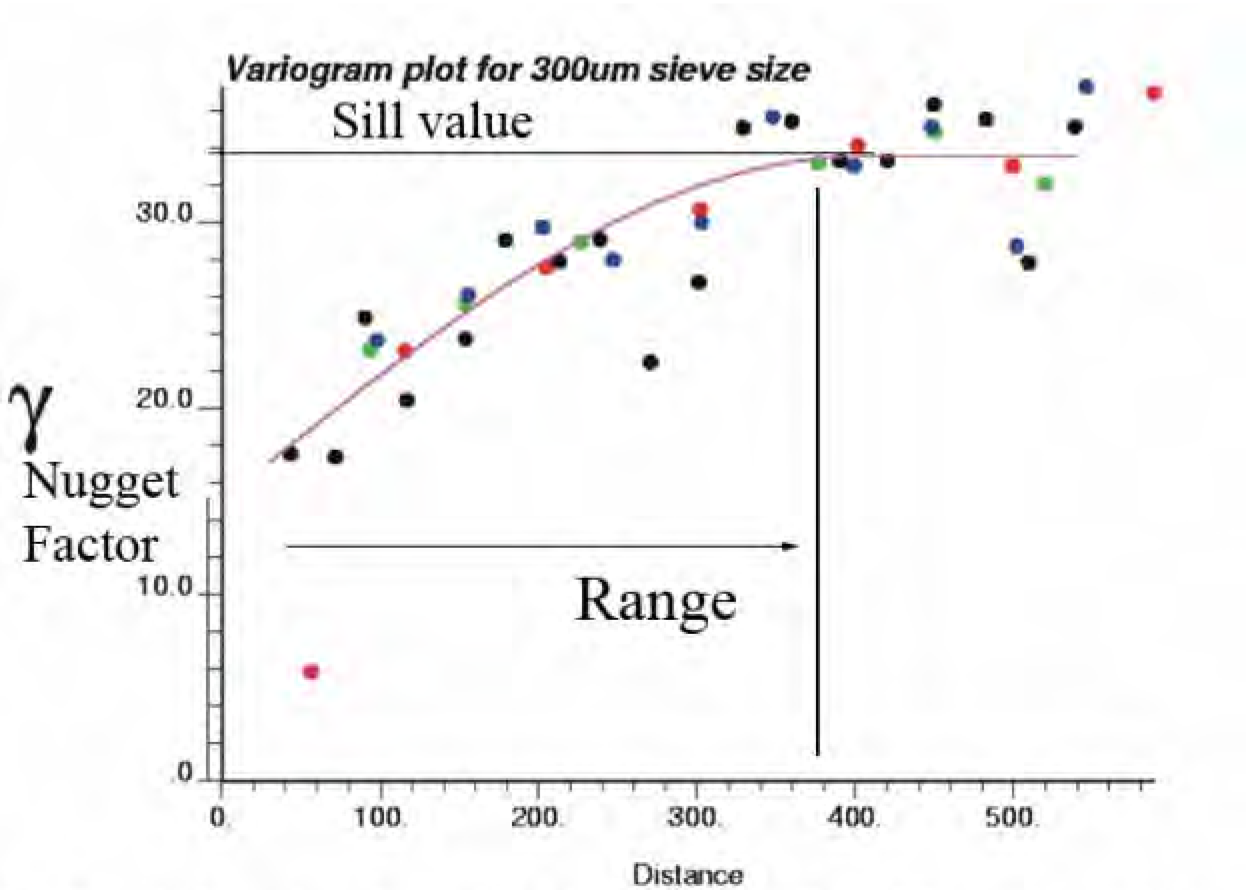

I. Omni-directional semi-variogram plot for 300um sieve size.

FIGURE 1 Example of semi-variogram for a sand sample with superimposed spherical model and indicated position of range.

New strategies for permitting aggregates mining operations

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ABSTRACT

With an annual output of about 2.7 billion metric tons produced from more than 9,000 crushed stone and sand and gravel operations, the aggregates industry is, by tonnage, the largest mining industry in the United States. Despite the relatively low unit value of its basic products, the aggregates industry is a major contributor to and an indicator of the economic well-being of the Nation.

As urban areas continue to grow and the need for aggregates increases, expanding current operations or permitting new ones becomes an increasingly difficult task. Therefore new strategies for permitting aggregates operations need to be considered. One such strategy is long-term multi-purpose land-use development projects in which mining is just one early phase of the project. These kind of long-range planning and development projects are good examples of long-term land use, proper resource management, and planned development, which would benefit many interested parties.

Another strategy is illustrated by the new Mid-Atlantic Green Highway Initiative, designed to foster partnership between the public and the private sectors. This initiative creates a voluntary, collaborative effort for improving upon natural, built, and social-environmental conditions while sustaining life-cycle functional requirements of the transportation infrastructure.

These strategies of multi-purpose development planning and public-industry partnership activities are important for the future growth of the aggregates industry.

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INTRODUCTION

Crushed stone and construction sand and gravel, the two major types of natural aggregates, are among the most abundant and accessible natural resources. Natural aggregates have been used from the earliest times of civilization for a variety of purposes, construction being one of the major uses. Crushed stone and construction sand and gravel are major basic raw materials and a fundamental building block of modern society. The widespread use of natural aggregates is due to their general availability throughout the country, suitability for many applications, and relatively low cost.

On a tonnage sold or used basis, the aggregates industry produced more than 85 percent of the approximately 3.3 billion metric tons of nonfuel minerals mined in the United States in 2005. By volume, the three largest segments of mining in the United States are aggregates, coal, and industrial minerals. The tonnage of crushed stone and construction sand and gravel produced accounts for more than two-thirds of the total of these three segments and is nearly three times the tonnage of U.S. coal produced (Figure 1). The value of total mined aggregates in 2005 was one-third of the total value of nonfuel mineral materials mined in the United States.

Notwithstanding the low unit value of the basic products, crushed stone and construction sand and gravel are major contributors to the well-being of the United States. Since 1997, the Federal Reserve Board has used quarterly aggregates production data reported by the U.S. Geological Survey (USGS) in its calculation of Industrial Production Indexes for the United States.

HISTORY OF U.S. AGGREGATES PRODUCTION

Growth in Aggregates Production

Over the past century, the production of aggregates increased from about 58 million metric tons in 1900, when the collection of production statistics for crushed stone and sand and gravel began at the USGS, to 2.9 billion metric tons in 2005. Consumption went from a modest three-quarters of a ton per person in 1900 to a staggering 9.8 tons per person in 2005.

In 1945, at the end of the World War II, the total U.S. production of aggregates was 328 million tons. In the 1950s, as construction activity increased and the Interstate Highway System was begun, the production of aggregates “took off.” By 1958, the total U. S. production of aggregates reached 1 billion tons, and in 2005 the total was 2.9 billion tons (Figure 2). Cumulatively, in the first 50 years of the 20th century, a total of 12 billion tons of aggregates were produced in the United States while in the last 50 years that total reached 78 billion tons, a more than 6-fold increase.

Until the 1970s, especially during the construction of new roads and highways, more construction sand and gravel was produced in the United States than crushed stone. In 1972, the annual production of crushed stone was more than that of construction sand and gravel for the first time. The dominance of crushed stone has continued since that time and will probably continue into the future. One major reason for this trend is the fact that a stone quarry produces much more aggregates from a significantly smaller footprint, or area of land, than a construction sand and gravel operation. Rock formations are normally hundreds of feet thick while mined sand and gravel deposits are usually surficial alluvial deposits less than 50 feet thick. To produce the same amount of aggregates, a construction sand and gravel operation would affect a much larger land area than a crushed stone quarry. In addition, the flat alluvial terraces that are the main source of sand and gravel deposits are also preferred farm land and construction sites for new residential or commercial developments. This competition for land use is a major impediment in obtaining mining access to those areas. Despite increasing environmental and land use concerns, production continues in remaining quarries and sand pits around heavily populated areas because of high demand (Figure 3).

Prices Over Time

In recent years, the average unit price (price of a metric ton of material f.o.b. plant) of aggregates has increased almost every year, even if by a relatively small percentage (Figure 4). For example, in the last 35 years the unit price of crushed stone increased from $1.74 in 1970 to $6.01 in 2004, while the unit price of construction sand and gravel increased from $1.22 to $5.33 for the same interval. But if these prices are converted to 1970 constant dollars by removing the effect of inflation (using the consumer price index), the unit price of crushed stone shows a decrease from $1.74 in 1970 to $1.23 in 2004, while the unit price of construction sand and gravel decreased from $1.22 in 1970 to $1.09 in 2004 (Figure 4). This trend was partly achieved by the aggregates industry through significant increases in productivity resulting from more efficient equipment and increased levels of automation.

The above mentioned prices are average unit prices for total U.S. production of crushed stone and construction sand and gravel. These average unit prices vary by ***kind of stone*** (such as, granite or limestone) for crushed stone, and by ***use*** (such as, aggregate for concrete or finely ground limestone for reacting with gases in smokestacks) for both crushed stone and construction sand and gravel. For example, the 2004 average unit prices for crushed stone by kind of stone ranged from a low of $4.30 for calcareous marl to a high of $7.58 for slate. By use, the average unit price of crushed stone ranged from a low $2.38 for refractory stone to a high of $50.71 for slate flour.

Uses of Aggregates

Natural aggregates have a wide variety of uses. Imagine our lives without roads, bridges, streets, bricks, concrete, wallboard, and roofing tiles or without paint, glass, plastics, and medicine. Every small town or big city and every road connecting them were built and are maintained with aggregates. Crushed stone and sand and gravel used for construction purposes are defined as construction aggregates. More than 90 percent of asphalt pavements and over 80 percent of concrete consists of aggregates. Even the binder in concrete, the cement, is made from stone (limestone).

In addition, paint, paper, plastics, and glass normally require sand, gravel, or crushed stone as a constituent. When ground into powder, limestone is used as an important mineral supplement in agriculture, medicine, and household products. Natural aggregates are also being used more and more to protect our environment. Soil erosion-control programs, water purification, and the reduction of sulfur dioxide emissions generated by coal burning electric power plants are just a few examples of what are defined as industrial uses of natural aggregates.

Major Producing States

The major crushed stone and construction sand and gravel producing States for the last 30 years and their rankings are shown in tables 1 and 2, respectively.

The production of natural aggregates is closely related to a State's population and the level of industrial development of a specific area, as well as to the distribution of natural resources. Major public works projects and commercial and private developments have a significant impact on the demand for and therefore production of aggregates. The information collected by the USGS represents production for consumption as reported by the aggregates producers. No information is collected from the producing companies regarding the areas where the produced aggregates are used, because of the complexity of such an undertaking.

TABLE 1 Leading States in the Production of Crushed Stone, 1975-2005 (million metric tons)

1975		1980		1985		1990	
State / Production		State / Production		State / Production		State / Production	
Illinois	55.0	Texas	69.4	Texas	77.8	Pennsylvania	86.9
Pennsylvania	54.5	Florida	60.1	Florida	62.9	Texas	74.2
Texas	42.7	Pennsylvania	55.4	Pennsylvania	58.8	Florida	67.5
Missouri	35.4	Illinois	48.4	Georgia	47.3	Illinois	56.9
Ohio	35.1	Missouri	43.8	Virginia	46.9	Virginia	53.9

1995		2000		2004		2005p	
State / Production		State / Production		State / Production		State / Production	
Texas	81.1	Texas	121.0	Texas	122.0	Texas	135.0
Pennsylvania	80.9	Pennsylvania	97.9	Pennsylvania	112.0	Florida	112.0
Florida	68.0	Florida	93.0	Florida	105.0	Pennsylvania	109.0
Missouri	66.7	Georgia	76.5	Georgia	79.5	Illinois	83.3
Illinois	61.4	Illinois	76.0	Illinois	76.5	Georgia	80.5

p Preliminary

TABLE 2 Leading States in the Production of Construction Sand and Gravel, 1975-2005 (million metric tons)

1975		1980		1985		1990	
State / Production		State / Production		State / Production		State / Production	
California	80.2	California	102.1	California	102.3	California	120.0
Alaska	43.7	Alaska	40.7	Texas	52.4	Michigan	48.7
Michigan	42.7	Texas	40.5	Michigan	34.5	Texas	41.8
Illinois	35.4	Ohio	32.2	Arizona	33.6	Ohio	40.4
Texas	35.1	Michigan	29.5	Ohio	29.9	Washington	36.5

1995		2000		2004		2005p	
State / Production		State / Production		State / Production		State / Production	
California	98.4	California	148.0	California	166.0	California	160.0
Texas	61.1	Texas	80.8	Texas	81.7	Texas	86.6
Michigan	53.5	Michigan	75.6	Arizona	79.6	Arizona	84.8
Ohio	45.3	Arizona	59.4	Michigan	69.5	Michigan	67.8
Arizona	40.1	Ohio	51.2	Minnesota	54.9	Minnesota	59.5

p Preliminary

In the past, almost all aggregates were used in close proximity to the production sites. As the demand for aggregates increased, especially in urban areas, significant amounts of aggregates have been shipped farther to satisfy local demand. In many areas, aggregates are being distributed more and more through sales or distribution yards. These sites, usually within urban areas, are located at significant distances from the quarry or the pit and have a railroad or a waterway connection with the production site.

Where the pit or quarry is in one state and the market is in an adjacent state, significant amounts of aggregates are shipped across the state line. The increasing volume of such shipments makes it difficult to determine the origin and final destination of aggregates products in many cases.

Past Growth of the Industry

As the production of crushed stone and construction sand and gravel increased over the years, so did the number of active operations and the average output per operation. In 1945, there were 1,470 active quarries producing an average of 89,800 tons of crushed stone, and 2,103 pits producing an average of 61,300 tons of construction sand and gravel. The number of operations increased each year until 1975 when the total peaked at 5,425 crushed stone quarries, and 6,799 construction sand and gravel pits. Average production per operation in 1975 was 151,000 tons for crushed stone (table 3), and 94,000 tons for construction sand and gravel (table 4).

TABLE 3 Crushed Stone, 1945-2005[1]

Year	Number of Companies	Number of Plants	Total Production (metric tons)	Average Production/Plant (metric tons)
1945	NA	1,470	132,000,000	89,800
1950	NA	1,622	208,000,000	128,000
1955	NA	2,175	390,000,000	179,000
1960	NA	2,888	494,000,000	171,000
1965	NA	3,236	641,000,000	198,000
1970	NA	4,550	792,000,000	174,000
1975	NA	5,425	818,000,000	151,000
1980	1,865	4,395	892,000,000	203,000
1985	1,790	3,557	908,000,000	255,000
1989	1,716	3,416	1,100,000,000	322,000
1995	1,503	3,110	1,260,000,000	405,000
1999	1,475	3,467	1,540,000,000	444,000
2000	1,367	3,453	1,550,000,000	449,000
2004	1,329	3,128	1,590,000,000	508,000
2005p	NA	NA	1,650,000,000	NA

p Preliminary   NA Not Available

[1] Data are rounded to no more than three significant digits

TABLE 4 Construction Sand and Gravel, 1945-2005[1]

Year	Number of Companies	Number of Plants	Total Production (metric tons)	Average Production/Plant (metric tons)
1945	NA	2,103	129,000,000	61,300
1950	NA	2,500	229,000,000	91,600
1955	NA	4,206	376,000,000	89,400
1960	NA	4,699	474,000,000	101,000
1965	NA	5,560	595,000,000	107,000
1970	NA	5,918	665,000,000	112,000
1975	NA	6,799	639,000,000	94,000
1980	NA	6,057	693,000,000	114,000
1986	4,323	5,797	801,000,000	138,000
1990	4,094	5,665	826,000,000	146,000
1995	4,010	5,742	910,000,000	158,000
2000	3,901	6,204	1,120,000,000	181,000
2004	3,892	6,270	1,240,000,000	198,000
2005p	NA	NA	1,260,000,000	NA

p Preliminary NA Not Available

[1] Data are rounded to no more than three significant digits

As the aggregates industries matured, the major companies started to grow faster, either by building larger operations or through acquisitions. Stricter environmental and permitting regulations made it more difficult to start a new operation than to acquire an existing one with significant reserves. In the 1980s, some Australian, British, and French companies began buying existing operations and companies in the United States and became major players in this market.

Some of the acquired companies continued to operate as semi-independent organizations, but with the benefit of financial and management support provided by the new parent company. As a result of these acquisitions, the number of operations and companies in the U.S. decreased, especially in the crushed stone industry, while the average production per operation continued to increase.

From the peak of 5,425 reached in 1975, the number of crushed stone operations decreased to 3,557 in 1985, and has stabilized over the last decade at around 3,250. At the same time, the average production per operation increased steadily over the years from 151,000 tons in 1975 to 508,000 tons in 2004. The number of companies producing crushed stone decreased over the years from 1,865 in 1980 to 1,329 in 2004 (table 3).

The number of construction sand and gravel operations decreased from 6,799 in 1975 to 5,665 in 1990, but increased again over the following 14 years to 6,270 in 2004. The average production per sand and gravel operation increased steadily over the years and reached 198,000 tons in 2004. The number of companies producing construction sand and gravel decreased from 4,323 in 1986 to 3,892 in 2004 (table 4).

Another effect of the consolidation in both industries can be seen by reviewing the production and the number of operations owned by large companies. In 1985, the top 10 crushed stone companies operated 344 quarries and produced 25 percent of the U.S.

total of crushed stone. In 2004, the top 10 companies operated 927 quarries and produced 45 percent of the U.S. total (tables 5 and 6).

TABLE 5 U.S. Market Share for the 10 Leading Companies in Annual Production

Crushed Stone			Construction Sand and Gravel		
Year	Number of Operations	U.S. Market Share	Year	Number of Operations	U.S. Market Share
1985	344	25%	1984	158	13%
1989	491	29%	1990	177	15%
1995	518	31%	1995	265	14%
1999	649	35%	2000	520	18%
2004	927	45%	2004	575	24%

TABLE 6 U.S. Production of Aggregates in 2004 by Size of Company's Production Tonnage

Rank	Number of Companies	Percent of All Companies	Production/Company (thousand metric tons)	Total Production (thousand metric tons)	Percent of U.S. Production
1-13	13	0.3	> 25,000	1,070,000	37.9
14 - 30	17	0.4	10,000 - 25,000	273,000	9.6
31 - 58	28	0.6	5,000 - 10,000	204,000	7.2
59 - 356	298	6.2	1,000- 5,000	581,000	20.5
357 - 1282	926	19.4	250 - 1,000	455,000	16.1
1283 - 2235	953	20.0	100 - 250	151,000	5.3
2236 - 4777	2,542	53.1	< 100	96,300	3.4
Total	4,777	100.0	NA	2,830,000	100.0

NA Not applicable

A similar situation existed with the sand and gravel companies. In 1984, the top 10 construction sand and gravel companies operated 158 pits and produced 13 percent of the U.S. total, while in 2004 the top 10 companies operated 575 pits and produced 24 percent of the U.S. total. The 10 leading U.S. aggregates-producing companies listed in descending order of their total production are shown in table 7.

TABLE 7 The Top 10 Aggregates Companies in 2004, by Production Tonnage

Rank	Company Name
1	VULCAN MATERIALS CO.
2	MARTIN MARIETTA AGGREGATES
3	HANSON BUILDING MATERIALS AMERICA
4	OLDCASTLE, INC./MATERIALS GROUP
5	RINKER MATERIALS CORPORATION
6	LAFARGE NORTH AMERICA, INC.
7	CEMEX, INC.
8	AGGREGATE INDUSTRIES, INC.
9	MDU RESOURCES, INC./KNIFE RIVER CORP.
10	FLORIDA ROCK INDUSTRIES, INC.

Additional information regarding aggregates producers, such as their ranking in terms of total output, number of operations, and States where those operations are located, can be found in the USGS Directory of Principal Aggregates Producers, Directory of Principal Crushed Stone Producers, and Directory of Principal Construction Sand and Gravel Producers, which are published annually and are available on the USGS Minerals Information Web site at http://minerals.usgs.gov/minerals.

THE FUTURE OF THE AGGREGATES INDUSTRY

Growth of the Aggregates Industry in the Next Decades

The rapid growth in the production of aggregates during the second half of the 20th century was in large part due to the construction of roads and highways in the United States. According to the U.S. Department of Transportation's Federal Highway Administration, planning of the superhighway system in the United States began in the late 1930s, and the current interstate highway system was created by the Federal-Aid Highway Act of 1956, popularly known as the National Interstate and Defense Highway Act of 1956. This year is the celebration the 50th anniversary of the passage of the Act and 50 years of improvements in the Nation's road system. The Interstate Highway System contains over 42,700 miles (68,500 km) of roads, all at least four lanes wide, and was officially regarded as completed in 1991, although some construction work continues. Despite the fact that about 80 percent of the cost of building this road system was funded by the Federal Government, the highways are owned, designed, built, and maintained by the States in which they are located; the only exception is the Federally-owned Woodrow Wilson Memorial Bridge on the Capital Beltway near Washington, DC (I-95/I-495). This bridge is currently being replaced, and ownership of the new Woodrow Wilson spans will be conveyed jointly to Maryland and Virginia upon completion.

Recognizing that the United States needs a transportation system that will sustain the Nation's economic strength and enhance its competitiveness in the global market place, the U.S. Congress approved the National Highway System (NHS) in 1996. This newly defined road system of 160,000 miles (256,000 km) includes the Interstate Highway System, the Strategic Highway Network (STRAHNET), the Major Strategic Highway Network Connectors, and the Intermodal Connectors. About 98 percent of all roads included in NHS are complete. While the NHS roads represent only 4 percent of the Nation's roads, they carry more than 40 percent of all highway traffic, 75 percent of heavy truck traffic, and 90 percent of tourist traffic. These major roads as well as the significantly larger number of smaller roads serving communities all over the Nation constitute one of the major sources of demand for aggregates. The other major drivers of the U.S. economy that influence the demand for aggregates are population growth and economic development.

Over the past 25 years, U.S. crushed stone production has increased at an average annual rate of about 2.3 percent. During the same time period, construction sand and gravel production experienced a smaller annual growth rate of about 1.6 percent. Over this period, much of the growth in production was in response to the need for aggregates for the construction, modernization, and maintenance of the National Highway System. In the future, aggregates will continue to be needed for the modernization and maintenance of the existing U.S. road system as well as for additional construction related to increased security on our roads and in our urban and industrial areas. In addition, it is also expected that the modernization of U.S. airports will consume significant amounts of aggregates. Finally, increased production will be needed for a growing population that will be dependent on continually increasing commercial, governmental, and residential building construction.

Using conservative assumptions and using the year 2004 as a base, annual growth rates for aggregates production in the 1-3 percent range over the next 25 years seem likely (Figure 2). Based on projections of 2.1 percent for the production of crushed stone, and 1.3 percent for the production of construction sand and gravel, by 2030, annual U.S. production of crushed stone may be on the order of 2.8 billion tons, an increase of more than 69 percent compared with that of 2005. The annual production of construction sand and gravel would be 1.8 billion tons, or an increase of about 43 percent. At these levels of production, the amount of crushed stone to be produced during the next 25 years will be about 55 billion tons, substantially more than the total quantity of crushed stone produced in the twentieth century. The total projected cumulative production of aggregates—crushed stone and construction sand and gravel—for the next 25 years is estimated to be 92 billion tons, slightly more than the total amount of aggregates mined between 1900 and 1999. These projections suggest that very large quantities of crushed stone and construction sand and gravel will be needed in the future and will have to come, at least in part, from resources yet to be delineated.

Land Development

Permitting new or existing operations will continue to be a major and increasingly difficult task of the aggregates mining process in the future. One solution to this problem is to submit land development plans for a specific area in which mining is just one phase of the development process. The final objective of any successful land development project is to produce buildable land for facilities like housing developments, schools, industrial parks, water reservoirs, or recreational areas.

The first phase of such a project would be a geologic investigation of the potential mining area that will define the outline of the deposit, the thickness and quality of the overburden, the depth to the ground water table, the quality of the aggregates and the thickness/volume of the deposit.

The second phase of any land development plans should start with a site analysis of the area to be developed, analysis that would collect information about the current and future land use plans and policies, transportation system, and site access. A detailed survey of the existing terrain, vegetation and surface drainage also has to be conducted. Information about the population projections for the county and State as well as information about local, State, and Federal regulations that may have an impact on the proposed area for development would also have to be collected.

The final stage would be the determination of the long range mining/building schedule of the proposed development project. This would include such aspects as determining which areas would be mined, the sequence of the stages of construction, and the alignment of temporary as well as permanent road systems. The final reclamation of the mined areas would be an essential part of the total development project.

Development Projects

(i) Proposed Butts Co., GA mine site, Vulcan Materials Co.
(ii) Hunt Midwest SubTropolis Underground Industrial Park, Kansas City, MO.
(iii) Lafarge's Specification Aggregate crushed stone quarry in Jefferson Co., CO – an example of sustainable management of natural resources.
(iv) Bay Harbor Resort in Petoskey, MI, on the shore of Lake Michigan – a multi-use mine reclamation project around an active limestone quarry.
(v) Lafarge's Howe Pit in Jefferson Co., CO, is a reservoir that supplies water to the Denver metropolitan area while at the same time the mining continues.

Mid-Atlantic Green Highways Initiative

Another strategy is illustrated by the new Mid-Atlantic Green Highway Initiative, designed to envision the future of transportation and environmental protection by fostering partnership between the public and the private sectors. This initiative creates a voluntary, collaborative effort for improving upon natural, built, and social-environmental conditions while sustaining life-cycle functional requirements of the transportation infrastructure. Some of the guiding principals of the Green Highways Initiative are:

(i) Achieve goals through voluntary participation and public/private partnerships;
(ii) Use market-based approaches and economic incentives;
(iii) Provide communication and support networks to avoid duplication and help streamline business practices;
(iv) Recognize and encourage existing environmental stewardship practices among transportation agencies;
(v) Leverage transportation and environmental resources, public and private, to multiply benefits and maximize results;
(vi) Support and stimulate applied research and training to remove barriers identified by partners and stakeholders.

CONCLUSIONS

The major advantages of using these approaches to develop new or expand existing operations or to establish public-industry partnerships are:

(i) The community has a clear long-range development master plan for a specific area with an increased tax and jobs base.

(ii) The mining company is assured of a long-term operation and increased profitability through the diversification and vertical integration of the operation.

(iii) The multi-purpose development planning and public-industry partnership activities are providing a solid foundation for the future growth of the aggregates industry.

ACKNOWLEDGEMENTS

The authors thank Jason C. Willett and Robert Callaghan for their help with this paper, particularly in the preparation of the graphics.

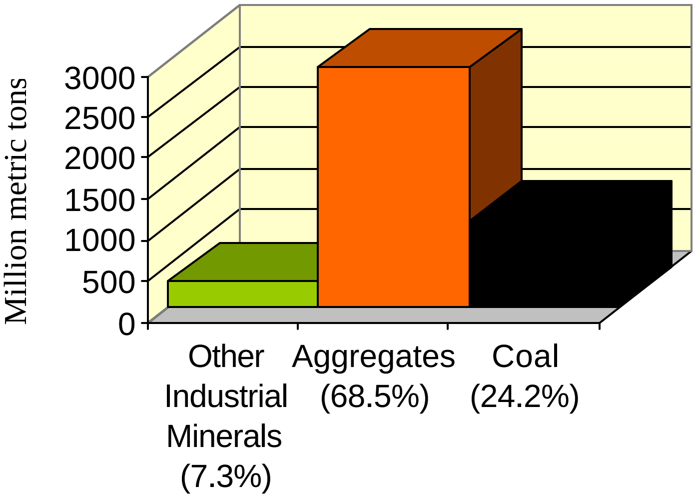

FIGURE 1 All U.S. Nonmetal Mining Production in 2005.

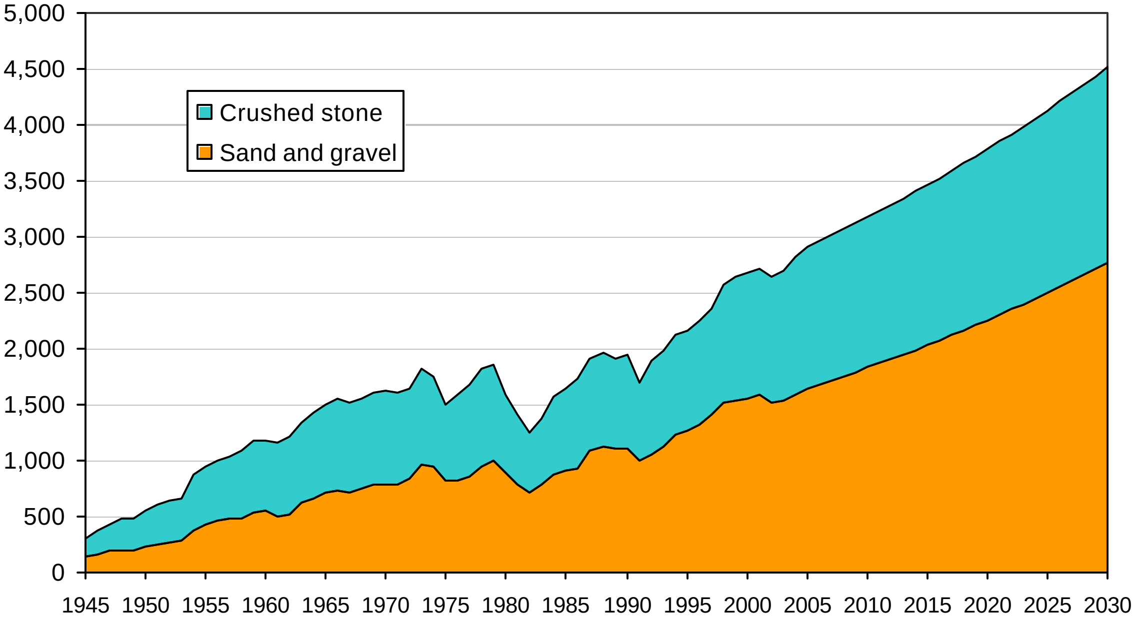

FIGURE 2 **U.S. Aggregates production (million metric tons).**

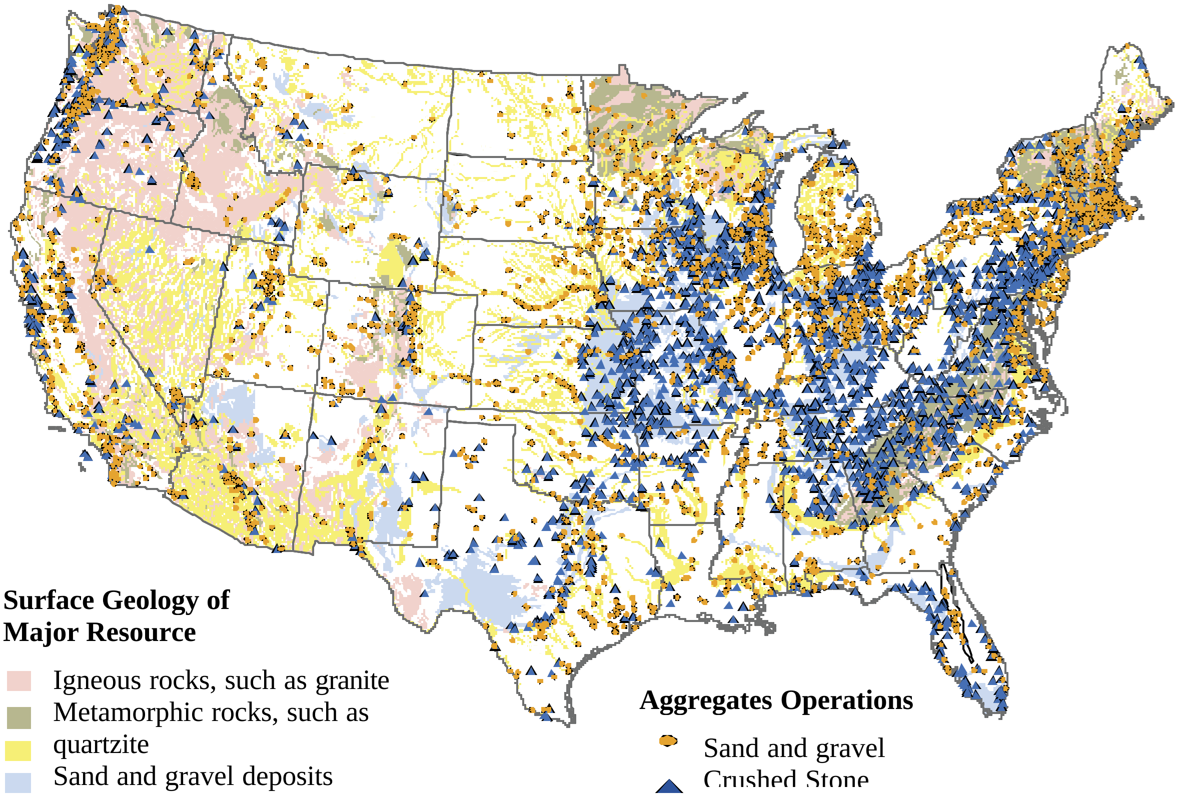

FIGURE 3 **Aggregates operations in the conterminous United States in 2004.**

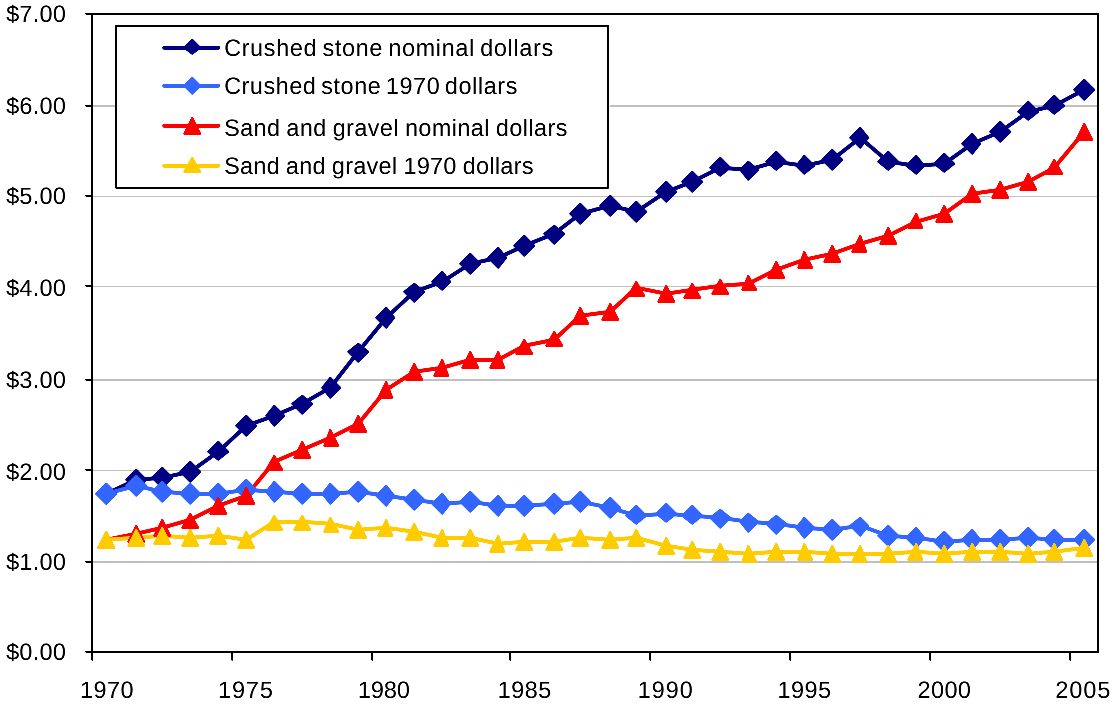

FIGURE 4 Aggregates prices over time (f.o.b. plant).

The North Carolina Granite Corporation: Dimension Stone, Mount Airy, Surry County, North Carolina

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ABSTRACT

The North Carolina Granite Corporation ("NCGC") was founded in 1889 in Mount Airy, North Carolina, site of the world's largest open-faced granite dimensional stone quarry. NCGC is the only integrated stone company founded by an architect for architects. The main quarry is a 50 acre white (salt and pepper) granite, and the company operates other granite quarries in Georgia (white/beige – 65 acres), South Carolina (pink – 44 acres), and Quebec Canada (Caledonia brown – 104 acres). Total quarrying capacity exceeds two million cubic feet per year.

Completely integrated manufacturing facilities are co-located at the Mount Airy site. NCGC can produce any stone product except 3/8" floor tile. In addition to granite, this facility also processes marble, limestone and sandstone. In association with local quarries, NCGC provides 25 standard granite colors plus an array of Brazilian and Chinese stones for countertops, and other interior products. NCGC also imports a number of finished stone products from various countries.

The principal products are raw blocks for export around the world, building components such as façades for high-rise office buildings, mausoleums, street curbing, landscape products, and many standard products such as pavers or crushed stone for road beds and asphalt. Specialty crushed products are produced for chicken grit and for exposed aggregate concrete pavers and engineered stone. Building components and street curbing have been part of the product line for over 100 years.

NCGC provides stone engineering, drafting, material selection, design, value engineering assistance, and complete fabrication. Production facilities totaling more than 180,000 sq ft under roof include slabbing, surface finishes (polished, textured, antiqued) cut-to-size, and installation features (anchor holes, slots). NCGC utilized the latest technology to produce cost-competitive products

Major projects include Amoco Headquarters (Chicago, Illinois), Wright Brothers Memorial (Kittyhawk, North Carolina), Pegasus Statue (Brookgreen Garden, South Carolina), World War II Memorial (Washington, D.C.), Bank of Jakarta (Indonesia), Singapore Subway, Arlington Memorial Bridge (Washington, D.C.), Hyatt Headquarters (Chicago, Illinois), and West Pradhammakaya Temple (Bangkok, Thailand).

NCGC is located in the Piedmont region of the US, encompassing the states of North Carolina, South Carolina, Georgia, Tennessee and Alabama. This region is experiencing rapid growth because of its business-friendly governments, quality of life and affordability. NCGC is the only integrated stone company within the Piedmont and is positioned to grow with the demand for stone products.

Ferris, Robert R., 2006, The North Carolina Granite Corporation: Dimension Stone, Mount Airy, Surry County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Stone has always been a preferred building material. Early man used it for maximum protection against the elements and predators. Since the Iron Age, it has been possible to work the stone and the aspect of design and beauty was added to the benefits of stone leading to the birth of the commercial stone business.

Primitive tooling limited early construction to the softer stones such as limestone and marble. While these stone structures far outlasted organic building materials, soft stones are vulnerable to air-borne erosion and acidic attack from ground water. Regardless, early edifices built to commemorate the progress of man were built of stone and many still stand today, albeit in various stages of decay (e.g., the Pyramids of Giza or the Coliseum of Rome).

As Europe developed, so did the use of stone for homes and state buildings. The great castles of Europe are testimony to the important role that stone played in construction of that time. The magnificent churches, parliaments, museums, and private residences of kings, czars and rulers were all built of stone.

When the settlers arrived in the New World, they brought their stone culture to America. From that evolved the stone mansions of New England and nearly every state capital building. Stone added the aurora of wealth and stability, leading to the construction of banks and universities of stone.

No other building material embodies protection, stability, longevity, beauty, luxury, elegance, majesty, and wealth like stone. Stone continues to shout these values today, but until the late 20th century the use of stone was limited to the very wealthy. That all began to change about 1980 with the introduction of new technology which was destined to drive the cost of stone products down to the level of the pocketbooks of the average person.

Available stone technology during the 19th century limited stone's use to products made from marble and limestone. These soft stones were easily fabricated and the use of marble and limestone spread throughout the US. Granite was so hard, it was difficult and expensive to process, so its usage was limited. Granite is the king of commercial stones. It is more than twice as hard and strong as marble or limestone. Its chemical resistance is far superior.

Because of its superior physical properties it was the material of choice for applications where the stone was exposed to the ground. It could resist the chemicals and acidic ground water so much better that it was usually the stone selected for foundations. Its superior abrasion resistance made it ideal for the early roads upon the introduction of the automobile. Many cobblestone highways still exist today. Grave stones migrated to granite because of their contact with the ground and the resistance to airborne erosion. Bridges, sea-walls, and dikes were often made of granite because of the attack from water, particularly salt water.

By the end of WWII, concrete became the material of choice for highways because of its lower cost and the rapidity with which new roads could be built. Of course, concrete will not hold up under these harsh conditions, but still roads are built of concrete today because of low initial cost. Street curbing was also made of concrete, but in some parts of the world, street cubing has returned to a granite application – particular in regions where salt is put on the roads in the winter. Today, there is a continuing shift back to granite for street curbing (even in regions where there is no snow) for its aesthetic characteristics as well as minimal maintenance.

Certainly there were many buildings made of granite, particularly when the granite was available locally and transportation costs off-set the higher processing costs. This was the case in 1889 when the first railroad was built to serve Mount Airy, North Carolina. Actually, this speaks to two significant issues relative to NCGC.

The architect, Mr. Thomas Woodroffe from England, chosen to design and build the stations along the railroad, elected to build them from the stone harvested from the massive stone formation located in Mount Airy. He founded NCGC, opened the quarry, and it has been in continuous operation since.

The second reason is why NCGC foresees another 100 years of operations. The railroad was built to transport the many people that wanted to come to Mount Airy to vacation or live. The railroad was the route to utopia. But we are getting ahead of ourselves and will come back to this very important subject in the evolution of NCGC.

For the first hundred years of NCGC's existence it supplied building components for architects throughout the region. NCGC began supplying the street curbing for Washington, D.C., the massive blocks for the buildings and monuments, and the stone for bridges of this great city. Even then, Washington could afford the very best.

The reputation of the Mount Airy White granite spread throughout the world, and today it can be found on buildings and structures in virtually every part of the world. With the advent of the skyscraper, exterior granite panels became the material of choice for the finest buildings. The ability of granite to hold its polish in exterior applications is one reason why marble and limestone are less frequently selected for outside applications.

Up to the late 20th century, granite was still considered too expensive for mass applications. When industrial diamonds became readily available the granite industry rapidly adopted this new technology. Industrial diamonds are the only substance in sufficient quantity and priced competitively that are harder than granite.

By the beginning of the 21st century, industrial diamond technology had begun a revolution in the granite industry. It was now possible to process granite as easily as limestone and marble. The entire cost structure of the stone industry was turned upside down. The king of stones could be supplied at the cost of lesser stones, so architects no longer had to compromise on performance.

As mentioned above, street curbing is a product that is increasingly being supplied in granite. Granite survives the salt and snowplow abuse in the north, but elsewhere concrete curbing fails from the dirt side due to the chemicals in the soil and acidic water. In parts of Europe, concrete is no longer used for curb, and increasingly in the US this is the case. The cost of granite curb has come down to be competitive with concrete curbing, so again, the architects and engineers no longer have to compromise performance.

Curbing is a highly engineered product. Every city has its own designs and specifications. NCGC manufactures over a hundred different designs. In addition to its technical requirements, NCGC also adds aesthetics such that the curb can communicate old world charm to sophisticated elegance. Granite curbing just looks better, and infinitely better than broken concrete. Once installed, granite curb lasts for centuries with virtually zero maintenance.

NCGC is a major producer of granite curbing, along with all the auxiliary products such as handicap ramps, detectable truncated dome pavers, sewer inlets, and driveway transitions. NCGC uses the latest diamond technology in its quarry operations as well as in its fabrication shops.

In the past few years, NCGC has invested millions of dollars to install the latest technology. In addition to diamond technology, the use of high pressure water for cutting granite is extensively used throughout NCGC's quarry and production activities. Modern equipment to supply fine streams of high pressure water (40,000 psi and higher) has improved the production speed of cutting high quality dimensional stone blocks from the mother rock, reducing waste, as well as to texture the surface of finished products.

NCGC's Mount Airy operations also posses three environmentally important aspects. There is zero waste from either the quarry of the fabrication shops. All trimmings are crushed on-site into usable aggregate. Even the dust from the air filters is sold for pottery applications. One hundred percent off all the stone taken from the mother rock is sold as a finished product. There are no chemicals or additives used in quarrying or fabrication. Mount Airy White granite is very clean and uncontaminated. This makes it ideal for high appearance applications such as terrazzo, tilt-up walls, exposed aggregate pavers, or chicken grit. High pressure water is used to texture finished products instead of the old flaming method of propane torches. This reduces the usage of imported oil and eliminates the hot-house gases.

Granite countertops are an example of what the new technology has provided. Stone countertops, and particularly granite countertops, were the first stone product to reach the mass market. Initially, reserved for the very expensive home, granite countertops can be found in almost any priced home today.

Granite countertops introduced stone to the entire population of the US. Only in the past few years has granite been economically available to everyone. The penetration of stone in the US is only beginning. An endless array of products for the residential market can be made from stone.

This brings us back to the second reason why the railroad to Mount Airy was so significant for NCGC. The railroad was built because people wanted to come to Mount Airy to live or relax. In general, this is true of the entire region represented by Mount Airy – Utopia. The *Reader's Digest* recently ran a story on the quality of life in Mount Airy – and they named the article "Utopia". NCGC refers to this region as the "Piedmont".

The Piedmont extends from the Atlantic Ocean to the Appalachia Mountains. It includes the states of North Carolina, South Carolina, Georgia, Tennessee and Alabama. Within this region are the Great Smoky Mountains and the Blue Ridge Mountains – from ocean fishing to clear trout streams around every bend in the road. It includes the sand hills so popular for great golf courses and Myrtle Beach that is one of the most popular surf and golf destinations anywhere in the world. You can work in one of the great cities like Atlanta, Charlotte, or Raleigh. You can live on 10 acres on a secluded mountain top or the edge of a lake. You can settle in a small town like Mount Airy.

The Piedmont is experiencing a booming economy, attracting new high-tech industry and retirees. Residential development is popping up everywhere. New condos are coming on the market every day. Vacation homes along the water are in strong demand. People and industry come here because it is the most desirable place to live in the US – and it is affordable. The weather is mild with four beautifully colored seasons.

The Piedmont is to the US what Switzerland is to Europe – what Shangri-La is to Asia. Interestingly, NCGC is the only integrated stone company in the Piedmont - standing ready and able to supply the growing demand for stone products.

The Piedmont is the reason NCGC has another 100 years ahead of it. Its extensive stone deposits and unmatched fabrication capability are vital to developing the stone market in the Piedmont. There is not another comparable facility within 1000 miles.

We hope you enjoy your site visit to our quarry and fabrication facilities (Figure 1). For more information on NCGC visit our web site www.ncgranite.com.

FIGURE 1 North Carolina Granite Corporation's quarry and fabrication facilities located at Mount Airy, North Carolina.

Assessing waste dump materials for construction aggregate resources

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ABSTRACT

This paper discusses resource assessment projects of waste dump materials from three different industrial mineral operations.

As communities are severely restricting the permitting of new construction aggregate projects, mineral resource suppliers have begun to seriously consider materials that have already been mined, and which, in some cases, simply need to be processed. Rigorous specifications often restrict the use of the waste minerals; however an assessment program can target and recycle wasted materials, and provide a community with an additional source of construction aggregate, and the mineral supplier with additional income.

The profiled projects were located at sites which mined calcium carbonate for cement resources, calcium carbonate for high grade calcium carbonate products, and several metamorphic and igneous rocks at an iron deposit. Discussed are the methods used to assess the quality and quantity of the materials, and the successes and the unanticipated pitfalls of each project.

Shumway, Dinah O., and Morton, Paul K., 2006, Assessing waste dump materials for construction aggregate resources, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

WHY EVALUATE WASTE DUMPS FOR CONSTRUCTION AGGREGATE?

Many factors will force or encourage the assessment of mine waste materials as potential construction aggregate resources. Waste dumps in California may host billions of tons of material that have the potential to provide the construction aggregate resources that our communities need. In California, for example, per capita consumption of construction aggregate is about 7 tons of construction aggregate annually, and the reserves currently permitted present a shortfall of future demands in most areas. California is experiencing state wide rapid growth and the currently permitted resources are not able to supply the demand in the many areas of new development. The expansion of urbanization into areas formerly mostly rural, and often the setting of mining operations, is only one of the factors that encourage mine operators to regard the waste materials at the mine site as potential resources.

Urbanization not only increases construction aggregate market demand but also encroaches on resource areas that were formerly located too far away from the aggregate market, but are now economic. Moreover, deteriorating infrastructure in markets where construction aggregate demands are exceeding supply creates opportunity for the identification of new local resources. Also, the development or planned upgrading of transportation routes allows more efficient and economic transport of aggregate materials to new or expanded markets. Other factors that drive the evaluation of waste dump/stockpiles include a limitation of space at existing mine sites for the placement of waste materials, a quest to enhance revenue by mine owners, and the costs of permitting, including habitat considerations that limit mine development.

CHALLENGES IN THE EVALUATION OF WASTE DUMP/STOCKPILES AS CONSTRUCTION AGGREGATE

Paul Morton and Dinah Shumway, of TerraMins, Inc. have undertaken several projects since 2003 that proposed to assess waste materials as potential construction aggregate resources. We discuss here our methodology and some of the problems and results using the 4 projects as examples. Each project presented a different set of challenges. Some of the challenges discussed here are obvious, but some were not anticipated and presented themselves during the investigation process.

TerraMins' approach to the evaluation of the waste dump/stockpiles has three primary parts: 1) ***identify***, sample and test the main lithologic units, 2)***identify*** any deleterious materials that affect the material's performance as construction aggregate resources, and 3) ***estimate*** the usable tonnage of the waste dumps as well as a waste factor for the waste/dump stockpiles. These tasks are discussed using as examples past TerraMins projects.

EVALUATION PROJECTS

The four projects that are used here to demonstrate TerraMins' evaluation approach are the Specialty Minerals, Inc. C-21 stockpile, Kaiser Steele's Eagle Mountain Mine, the Mesquite Mine, and Cemex White Mountain Mine site. All the project sites are located in Southern California.

The C-21 stockpile site (Figure 1) is the site of mostly carbonate dolomitic material or iron stained materials not suitable for high grade-high whiteness calcium carbonate resources.

The Mesquite Mine waste dump is composed of mostly metamorphic gneisses that hosted the gold deposit. The need for construction aggregate resources for specific applications at a regional landfill development which is under construction adjacent to the mine site prompted a study to asses the materials already at the mine site to fulfill the construction aggregate requirements. In Figure 2, an areal photo of the site, the waste dumps evaluated are located in the north western area of the site.

The White Mountain mine is the site of stockpiled carbonate conglomerate from the nearby Black Mountain Quarry and which is not suitable as cement resources. The out-of-spec material is used to reclaim the White Mountain site and is presently being reprocessed as construction aggregate using a portable plant. The site has recently been approved for a Conditional Use Permit for a permanent aggregate plant (Figure 3).

The Eagle Mountain Mine was opened in the early 1950's and closed in 1982. The iron deposit is a replacement deposit which produced over 228 million tons of iron and over 700 million tons of mine waste. The Eagle Mountain ore deposits extending over a strike length of 7 miles were developed from 5 pits and generated over 700 million tons of waste material. Figure 4 is an areal photo showing the extent of the workings and the waste dumps at the site.

EVALUATION PROCESS

The assessment of waste dump/stockpiles material characteristics is exactly analogous to the assessment of "ore deposits". The material in a waste dump is a reflection of the original or primary target for mine development. Although the materials placed on the waste dump/stockpile may be rejected from the mining operation they may nevertheless have characteristics that reflect the primary target. Some of these characteristics can be liabilities in assessing the waste materials for construction aggregate.

In a precious or base metal mining situation, for example, the materials that are placed on a waste dump stockpile can include alluvial overburden, igneous and metamorphic unmineralized materials that can be altered and unaltered. At least some of the waste materials can be expected to be affected by the processes in the environment of formation of the metallic deposits.

If the primary target is carbonate rock mined for its chemical or physical properties (e.g. color or CaO content), the material could be wasted because it does not meet the specific chemical or physical characteristics. If the primary target is a particular unit within a sedimentary series, the wasted materials could be the non-target unit. Such units could include quartzite, dolomite, or calc-silicate units. In many areas of the California Desert the wasted materials could also include a percentage of igneous rocks of various ages.

Because the initial sampling of stockpiles is limited to the surface exposures, or the material most recently placed, it is useful to know the "vintage" of the waste dump stockpile, i.e.: when did the waste dump/stockpile construction begin? Mining operations do not usually keep records on the types of materials placed on waste dump/stockpiles; however knowledgeable company representatives can sometimes provide that information about initial mining operations that can include details about the initial materials placed on the stockpiles. In the absence of persons with that specific knowledge, research into the geologic reports and access to initial mining reports can provide useful information. Educated assumptions can be made regarding the composition of the lower levels of the dumps based upon geologic records and reports. Although most mining operations have relatively accurate information regarding the volumes and tonnages placed on waste dump/stockpiles, one of our projects provided a particularly difficult challenge in this regard. Below we explain the details of the three major parts of our approach using examples from our projects:

1) Identify, sample, and test the lithologic Units

A basic goal in evaluating waste dump/stockpiles and assuring that there will be a uniform supply of high quality of resource is to demonstrate that the individual and possibly, widely varying, rock types present possess quality characteristics that have the potential to provide materials of uniformity high quality. More specifically, if the identified rock types are sampled individually, tested, and meet the specifications, then it can be assumed that all the rock types will be suitable. Therefore the first objective is to identify the various rock types, selectively sample each, and submit the samples (about 200 lbs +\-) to the physical testing required for construction aggregate.

Identification of the various rock types requires field examination, but access to geological reports and maps allows for some predictability in what rock types the investigator can expect to encounter. The areal photograph of the East End waste dumps at Eagle Mountain Iron Mine (Figure 5) illustrates the typical situation of various rock types which compose the waste dumps.

The rock types that were identified at the Eagle Mountain mine site are listed below in Table 1. The Eagle Mountain waste dump/stockpiles are composed of metamorphic and igneous rocks. At the West End the metamorphic rocks are the primary rock types, while the waste dump/stockpiles in the East End include a mix of igneous and metamorphic rocks. In the West End, although several of the lithologies are similar, every attempt was made to identify characteristics that might differentiate variations in the lithologies. For example, although there are two different dolomite and hornfels species identified, they were judged, based on slightly different accessory minerals to be sufficiently unique. The principal rock types in the West End of the Eagle Mountain site include altered quartzite, quartz monzonite, a dark gray hornfels, and dolomite. In the East End, where the igneous rocks were hopelessly mixed, we collected composite samples, reasoning that if the composite samples did not pass the testing, a subsequent sampling could be conducted to identify the unsuitable materials. The samples collected at Eagle Mountain, including the composite samples, all passed the physical testing.

TABLE 1 List of Rock Types Identified at the Eagle Mountain Site

Location	*Descriptions*
West End	**Quartzite**: greenish gray altered
West End	**Hornfels:** dark gray, fine-grained, porphyroblastic texture
West End	**Dolomite**: white altered, fine grained, siliceous, includes pods of yellow serpentine
West End	**Dolomite**: white, fine grained, includes pods of yellow serpentine (var. lizardite?)
East End	**Quartz-monzonite:** pink, highly altered, large porphyritic feldspars, abundant sericite, sheared, from contact zone
East End	Composite: **quartz-monzonite**: highly altered, large olive-green amphibole crystals and sericite (altered from feldspar?); **quartzite**: fine grained, white; dolomite: gray sericitic; **gneiss?** (or altered quartz monzonite)
East End	Composite: **hornfels**: gray, medium grained, **quartz-monzonite**: mostly unaltered, but some chlorite replaces biotite; **quartzite**: yellow, gray to white with alternating layers of sericite, and biotite: minor iron ore clasts

Figure 6 shows the C-21 stockpile in the San Bernardino Mountains showing several rock types placed on the dump. Unlike the Eagle Mountain mine site, geologic reports and interviews with knowledgeable company representatives clearly identified the rock types that were used to construct the C-21 dump. Since the stockpile is less than 10 years old, identifying the rock types by formation name was possible. The samples collected were white to tan coarse grained calcite and dolomitic marbles, dark gray and light gray medium to coarse marbles and fine grained calc-silicate.

Table 2 is a list of the samples collected at the C-21 site. Results of testing were mixed. However, it was observed that the materials determined as suitable for construction aggregate resources could be identified by formation and strategically mined and segregated for later processing.

TABLE 2 List of Samples Collected at the c-21 Waste Stockpile

Description	Member
Dark gray, fine –to –medium grained limestone/marble	Yellow Pine
White, fine grained siliceous limestone/calc-silicate; accessory garnet, wollastonite, tremolite? Chert nodules	Anchor
White, coarse grained marble; very friable	Bullion
Buff to tan coarse grained marble; very friable	Bullion

The extensive waste dumps at the Mesquite Mine consist of over 290 million tons of material in 10 dumps (see Figure 7). The materials consist of alluvial overburden as well as unaltered, mildly altered to severely altered gneiss, schist, granite, and volcanic rocks. The sampling of the waste dumps at Mesquite was conducted by bulk sampling in side hill and trenching excavations using a track mounted excavator, and bucket auger borings. The samples were screened over a grizzly and the minus 12” material recovered for testing.

Unlike the waste dumps at Eagle Mountain or the C-21 Dump, where the distribution is basically random, and the crude segregation of samples is limited to individual bucket loads, the distribution and segregation of the materials within the waste dumps at Mesquite is observed in larger areas (see Figure 8). This appearance of larger, more uniform lithologies indicated that the waste dumps may be suitable for bulk sampling and bypassing the initial lithologic segregation task.

The results of testing were satisfactory to marginally satisfactory. Although the sampling technique bypassed the identification of the various lithologies and went directly to bulk sampling, it is not known if selectively sampling for various lithologies would have been any more successful. Although collecting the composite samples at the East End Eagle Mountain was successful, the bulk sampling at Mesquite produced marginal results. After reviewing the testing results, the investigators concluded that the marginal results are associated with regional hydrothermal events, primarily affecting the feldspars.

Although the initial reconnaissance inspection gave the investigators no indication that would have precluded the sampling and testing of the material, the testing results clearly present a caution to preliminary conclusions, especially in hydrothermally altered areas.

TerraMins' experience at Mesquite underscores the necessity of applying a full battery of testing to the waste materials at sites that have undergone regional or local hydrothermal alteration. Initial inspection of the material that was placed on the waste dumps was assumed to have no precious metal values, and did not appear upon first inspection to have been greatly affected by hydrothermal alteration. Our experience is that ignoring the potential for widespread affects of ore- forming hydrothermal events can invite additional risk in the assessment for construction aggregate potential.

The White Mountain site (see Figure 3) is an example of homogenous material with no quality problems or issues. Unlike the other sites discussed above, the waste materials placed at White Mountain had the advantage in that the material was fairly uniform total tonnage was known and the. Variations in color were found to be irrelevant here because most of the material on the waste dumps is from the same lithologic unit. The material placed at White Mountain had chemical signatures (mostly silica and magnesium content) that made it unsuitable for cement manufacture.

2) Identify any deleterious materials

The materials placed on a waste dump are usually wasted because the materials do not meet the specifications for the primary ore deposit target. Excessively weathered or, in the case of hydrothermal deposits, deleterious minerals present such as pyrite or the weathered equivalent, iron oxide (a common hydrothermal mineral) must be identified. Issues that arise in carbonate environments range from alteration or metamorphism that forms coarse calcite or dolomitic marbles that do not hold up to the durability testing for construction aggregate. In carbonate environments, vigilance must be given to the potential for the formation of cryptocrystalline minerals such as chert, and, however minor, of the development of the asbestiform species of tremolite (and sometimes actinolite).

TerraMins' experience with the occurrence of amphiboles, even though very minor, has had two outcomes. Actinolite, a very common accessory mineral, was discovered in minor abundances at one study site. The mere mention of the mineral in a preliminary report was enough to end any negotiations for the mineral rights of the property. However, at another study site the identification of possible asbestiform tremolite prompted a consultation with a certified lab that performed an analysis that identified tremolite, but not the asbestiform species.

3) Estimate the tonnage of the waste dumps

Physical testing can provide the predictive physical characteristics for the material in determining its suitability as construction aggregate resources, but some estimate of the recoverable tonnage must be made as well. In order to permit a site for construction aggregate production, or to revise reclamation plan to allow the recycling of formerly waste materials for construction aggregate products, the recoverable tonnage must be known.

In our case studies, the C-21 dump and the White Mountain mine dumps were resources of known tonnage. The stockpiles both relatively recent, with a known and well documented tonnage. And, although the material sampling and testing at the C-21 stockpile was less than satisfactory, the tonnage was known, or at least documented by the owners. In addition, the source of the material and the tonnage were well documented by mine records and confirmed by knowledgeable mine personnel. The owners of the White Mountain mine recognized early in the process that the material being used for reclamation was suitable as construction aggregate, and maintained accurate production records. The Eagle Mountain Mine site however, provided a much more challenging problem in the determination of the tonnage of the waste materials at the site.

One might assume that the problem in determining the volume of materials placed at a site would be simple: If one assumes that the waste was placed on original topography, and the current topography is available, it is an easy volume calculation to figure the difference. Access to digital data and appropriate software makes the task easier, and maybe more accurate.

The conventional method of estimating volumes of materials consists of constructing cross-sections at consistent intervals determined by topography, constructing polygons that would allow a calculation of the area each cross section represents, and finally extrapolating over a reasonable horizontal distance, depending on the uniformity of the topography, that the cross sections would represent. A tonnage factor is applied to the volume for an estimate of the tonnages. This method was used to calculate the volumes at the East End, as the material was dumped on a fairly uniform slope.

Unfortunately, the variable and incised original topography at the West End was much less amenable to the application of conventional methods in a reasonable time frame. Figure 8, illustrates the varying topography of the West End and the sinuous nature of the waste dumps at the West End site at Eagle Mountain.

The situation at Eagle Mountain was further complicated by the fact that, although TerraMins has access to the final toe and crest contour maps circa 1981, no interim development plan maps were available. Waste was placed on sites that had undergone previous modification which included cuts, road building, grading and other modifications that had the ultimate result of reducing the original topography before placement of the waste/stockpiles and thereby making any volume determination difficult and inaccurate. Figures 8 and 9 show the waste dump/stockpiles are irregular, and also vary in elevation. In some cases the original topography actually exceeded the current waste dump/stockpile elevations.

Because of these issues, it was decided early in the project that the only efficient method of determining volumes for most of the West End area was in the use of GIS desktop technology. In addition to reducing the time to acquire the volume data, the numbers would likely be more accurate than conventional methods.

Stable Base hard copies of the original topography at a scale of 1”= 200’ were located for most of the area and discrete areas were assigned to individual Aggregate Resource Areas (ARAs) to facilitate tonnage determinations (Figure 9).

ArcView 8.3 was used to create digital files of all the ARAs within the West End. The original topography within the ARAs was digitized in topographic contours, while the 1981 topography was digitized as point data. Map data digitizing was performed by student technicians at Victor Valley College under the direction of Shumway and Curt James, adjunct Faculty in the Natural Resources Department at Victor Valley College. Figure 10 shows the various files for one ARA that were created for the project.

The final analysis required to determine volumes was performed using the 3-D analytical tools in ArcScene software (Figure 11). Curt James performed the final analysis.

Without the intermediate topography showing the final cuts before the placement of waste materials it is impossible to estimate the total amount of resources within those areas. The GIS software can only calculate the volume difference between the old and new topography. Over 165,463,000 tons of construction aggregate resources were identified in the waste dump/stockpiles at the West End of the Eagle Mountain Mine. Waste Material placed in the Pit in the West End was estimated using conventional methods.

CONCLUSIONS

Materials that are placed on waste dump/stockpiles are an important resource in areas that are experiencing rapid urbanization, decreasing reserves, and difficulties in permitting new construction aggregate reserves.

We identified three major tasks in the process of assessing waste dump/stockpiles as construction aggregate resources: the identification of the various rock types on the waste dumps, the identification of deleterious minerals, and the determination of recoverable tonnage. TerraMins’ experiences at 4 project areas identified some challenges facing investigators in assessing waste dump/stockpiles:

- Identification, sampling and testing of the various rock types requires field examination and access to relevant geologic reports, maps and if possible knowledgeable company representatives. The identification of potentially deleterious minerals can be facilitated with a careful consideration of the geologic environments of formation of the primary target of the mine development. This can be especially meaningful in assessing materials from precious and base metal mining waste materials when there is high potential for alteration and the formation of other undesirable minerals.

- Although bulk sampling will be necessary prior to any decisions regarding the suitability of the waste materials, it may be unwise to attempt bulk sampling before identifying and sampling the discrete rock types that may be hosted in the waste dump/stockpiles.

- Knowledgeable company representatives and mining documents can provide more accurate information about materials and tonnages. The tonnage available on the stockpiles is usually the most accessible, especially for recent or well documented waste dumps.

- Where tonnages are unknown, or where the necessary data to determine available tonnages is difficult to acquire, the use of GIS technology and software can provide reasonable accurate tonnage numbers.

Recycling already mined materials into a product that growing communities need can be a selling point for companies that plan to manufacture construction aggregate from waste. Our investigations identified some strategies that mining companies may consider in deciding whether to evaluate mining waste materials as construction aggregate resources:

- If mine planning activities can identify units or areas of mine development that may have some construction aggregate potential, a sampling and testing program can identify those materials with potential, and those materials can be selectively segregated leading to more efficient processing of the waste materials.
- Early identification of waste materials with construction aggregate potential can also mean that monitoring activities can proceed which accurately document tonnage placed on the stockpiles, which can aid processing and marketing, and shorten any necessary permitting timeframes.
- Early assessment of waste materials can also identify any potential issues, such as the presence of deleterious materials that can make reprocessing of the waste materials problematic.

ACKNOWLEDGEMENTS

We extend our thanks to the mining company owners, and the company representatives at the projects we used as examples for this paper. Thanks to Google for making great areal photos available online.

FIGURE 1 Photo of Specialty Minerals C-21 Stockpile (2004)

FIGURE 2 Areal photo of the Mesquite Mine site

FIGURE 3 Areal Photo of the Eagle Mountain Mining Site (1882)

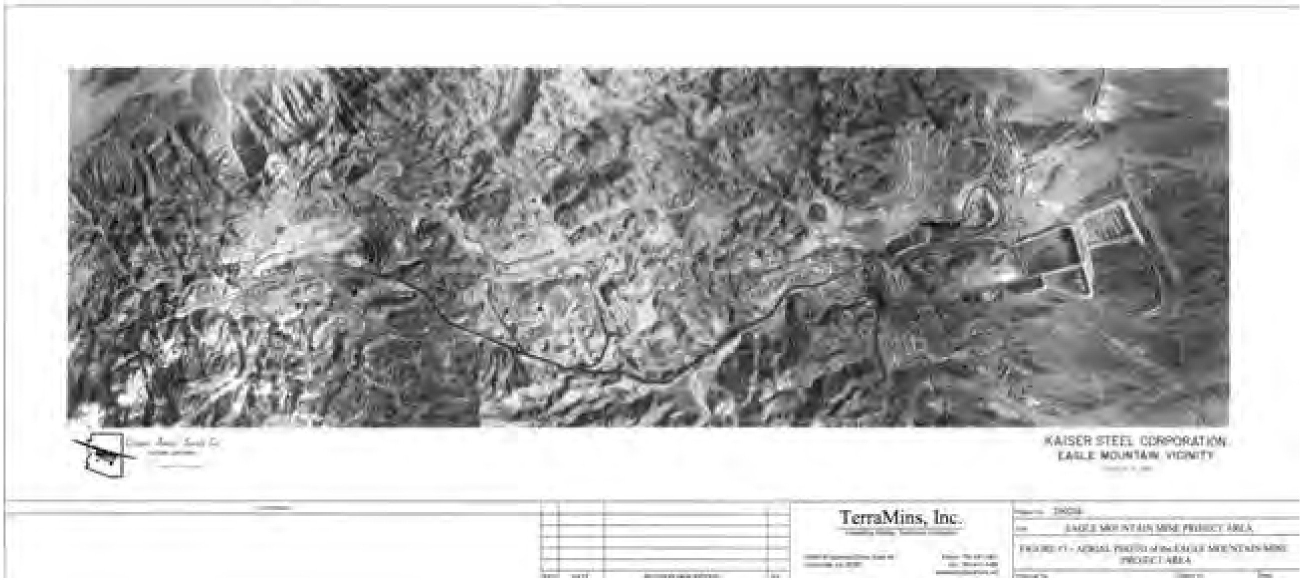


FIGURE 4 Areal photo of the Eagle Mountain Site (1982)

FIGURE 5 Variety of rock types at the East End Eagle Mountain Mine

FIGURE 6 Photo of the C-21 Stockpile showing varying rock types at the site

FIGURE 7 Areal photo of a waste dump at the Mesquite Mine site

FIGURE 8 Areal photo of the West End Eagle Mountain Mine site

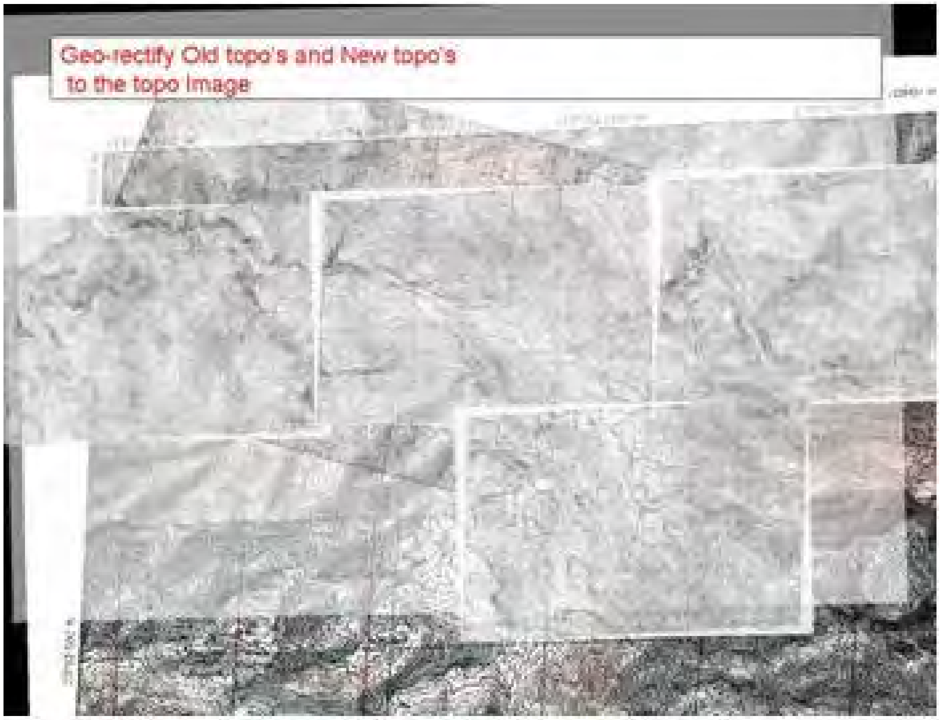


FIGURE 9 Stable base hard copies of original topography were georectified to current topography

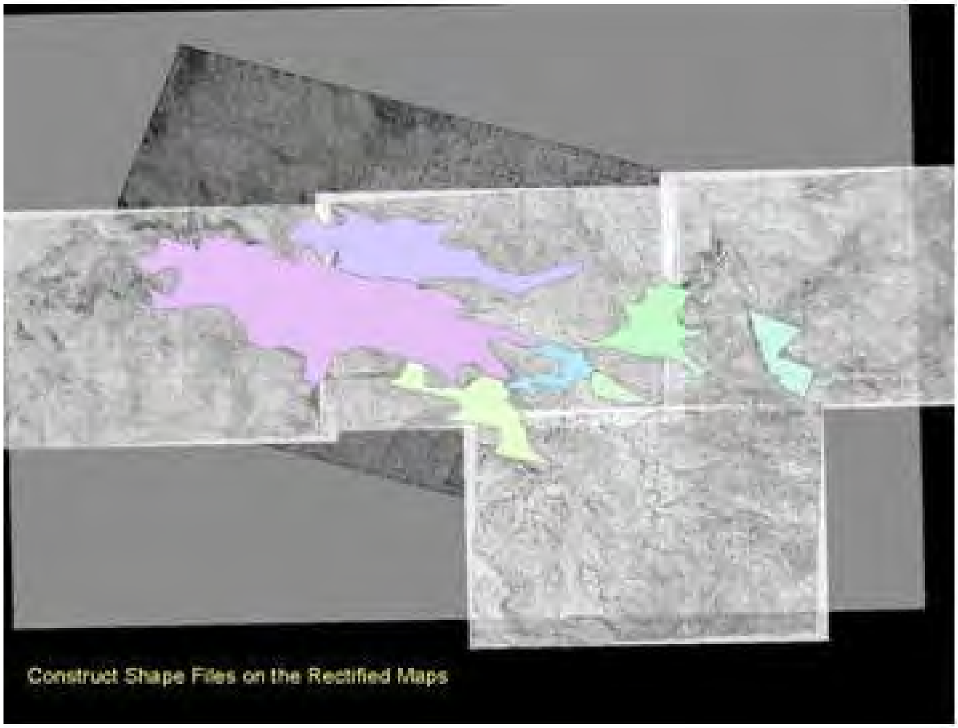
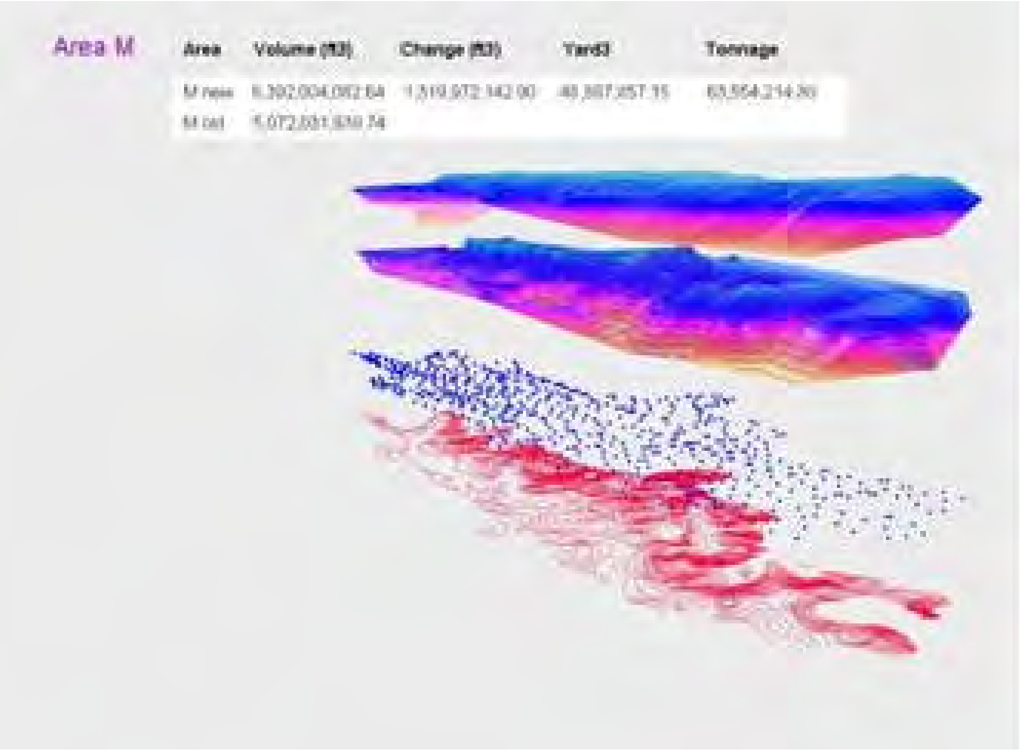


FIGURE 10 Areas were assigned to individual Aggregate Resource Areas (ARA's)



Area	Volume (ft3)	Change (ft3)	Yard3	Tonnage
M new	6,392,004,082.64	1,319,972,142.90	48,887,857.15	63,554,214.30
M old	5,072,031,939.74			

FIGURE 11 Final topographic modeling provided volume estimates

Coal as an industrial mineral

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ABSTRACT

More than a billion tons of coal is produced annually from 26 states. While most coal is burned to produce electricity or heat, it is also important as an industrial mineral. As much as 10 % of coal production is used for nonfuel applications. These uses are: 1) as process aids to produce iron and steel; 2) as feedstock to coal gasifiers or liquefiers and chemical feedstocks resulting from such processing; 3) as combustion byproducts; and 4) as filtering agents and other uses. Different processes have very different coal quality requirements, and many of them result in high-value products. The potential for improved coal and byproduct uses is great.

The metallurgical industry has utilized coal to produce coke as a material to inject into blast furnaces. Coal has been used as a metallurgical agent to assist in the reduction of iron ore to elemental iron since the thirteenth century. Upon heating in special ovens, coal forms coke, which acts as a reducing agent, supplies heat energy to the iron ore, and supports the weight of the charge during the smelting process. During coking, the coal softens, fuses, and resolidifies to form a strong, porous material. Medium-volatile bituminous rank coals usually have the best coking properties; coals of lower rank are less effective.

Direct injection of pulverized coal (PCI) into blast furnaces gained importance by replacing costly coke with cheaper coals. Direct injection became popular in the United States after its successful application in Japan and Europe and is now a common practice in most steel plants. Some plants use semi-pulverized or granular coal to replace coke. For this application, high-, medium-, or low-volatile coals can be used. Low-volatile bituminous coal has more carbon and can replace more coke. High-volatile bituminous coal is usually harder than low-volatile bituminous coal so more energy is needed to pulverize it. However, high-volatile bituminous coals can react faster, thus allowing more injection without affecting the blast furnace burden permeability. For a coal to be considered for use in a blast furnace, it should have high combustibility and a high replacement ratio. The replacement ratio is defined as the ratio of mass of coke saved to the mass of coal needed to replace it.

Gasification of coal produces gas (Syngas) and chemicals that can be used as fuels or as feedstocks for further chemical processing. Many chemicals currently produced from petroleum and natural gas could easily be obtained from coal, and as petroleum and gas costs rise, coal is becoming an attractive alternative. In industrial gasification, coal reacts with an oxidant (air or oxygen) and steam. The sulfur in coal is transformed into hydrogen sulfide and nitrogen into ammonia. Syngas, composed of CO and H_2, may be used directly as a fuel, as an intermediate in the production of methane, in the production or upgrading of coal-derived liquid fuels, and in the chemical industry. Methods of gasification include fluidized-bed gasification, fixed-bed gasification, entrained-flow gasification, and molten bath-gasification; each method requires a somewhat different gasifier unit and produces different byproducts. Coal liquefaction, a

process that provides liquid fuel as a substitute for crude oil, is also gaining momentum. Re-forming coal into oil has been performed commercially for almost 100 years. While commercial production of coal-derived synthetic liquid fuels is still very limited in the U.S., it is expected to grow rapidly. Liquefaction provides coal tar which is the precursor to thousands of organic chemicals.

All coal processing results in solid byproducts, commonly called ash or slag. Many tons of ash or slag components are used as aggregate, cement components, construction materials, and other large-volume uses that compete with conventional earth materials. Scrubber residue is converted to synthetic gypsum and this product is becoming available in large amounts. A number of high-value components, such as cenospheres, are currently recovered; many more ash components have potential uses. Byproducts from gasifiers and liquefiers will soon available in larger amounts and research is needed to characterize those new materials.

A myriad of other unconventional uses for coal currently exist: filtering water and processing fluids, making electrodes, producing graphite and other carbon materials, and producing cement, fertilizers, and a host of other chemicals. Biotechnology is another field in which coal and its byproducts can find application. Coal is a venerable material long used as fuel, but also a most useful industrial mineral.

- **Note**: Paper not available at time of publication.

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Session Four

North American diamonds – History, deposits, exploration and gemology

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ABSTRACT

Numerous diamonds have been found in North America during the historical past. The discoveries led to developments of small diamond mines in Murfreesburo, Arkansas (Prairie CreeK) and the Colorado-Wyoming State Line district (Kelsey Lake) in the US. Later, world class diamond deposits were found in Canada that led to that nation becoming a major source of gem-quality diamonds. Canada now ranks as the world's third largest producer of diamonds following the development of their first mine (Ekati) in 1998. Since 1998, a second mine (Diavik) has been placed into production with three addition mines currently being developed. Hundreds of additional discoveries have been made in Canada in recent years, several of which are significant and may lead to additional diamond mines.

Even though similar Precambrian basement rocks extend southward under large portions of the United States, exploration in the US has been minor compared to the Canadian activity. With reports of hundreds of diamonds along with many kimberlitic indicator mineral anomalies, kimberlites, lamproites, lamprophyres and some district geophysical anomalies, one would expect that additional exploration in the US and Canada will lead to many more discoveries.

The geology of the North American craton is very favorable for discovery of diamondiferous kimberlite, lamproite, lamprophyre and some unconventional host rocks. The North American craton is predicted to be a major source of gem and industrial quality diamonds for decades to come.

Hausel, W. Dan, and Sutherland, Wayne M., 2006, North American diamonds – History, deposits, exploration methods and gemology, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

DEDICATION

This paper is dedicated to our two colleagues and friends: Robert Lyman (coal geologist) and Ray Harris, (uranium and industrial minerals geologist) who passed on before their time. Both will be greatly missed.

INTRODUCTION

Commercial diamond deposits are rare. In the richest primary mines, diamond is found in concentrations considerably less than 1 ppm (Lampietti and Sutherland, 1978). The few commercial deposits are hosted by kimberlite, rarely by lamproite, and in placers assumed to have been derived from primary host rocks. Most primary diamond deposits are found within thermally stable Archean cratons that have thick cratonic keels (referred to as Archons), and in cratonized Proterozoic belts found along the margins of these Archean basements (referred to as Protons). However, the discovery of several unconventional host rocks in recent years requires a new philosophy in diamond exploration, as some potentially contain economic amounts of diamond (Hausel, 1996; Erlich and Hausel, 2002).

The world's natural diamonds are mined from a small group of primary and secondary deposits that mostly have operating lives of 10 to 30 years. A notable exception is the South African Premier mine, the source of some of the largest gem diamonds ever found including the largest diamond - the 3,106 ct Cullinun. The Premier mine has operated for more than 100 years. Another exception is the marine placers along the western coast of Africa, which have been productive for decades.

Diamond production statistics indicate that the top world producers (total carats) of natural diamonds (gems plus industrial stones) are: (1) Botswana, (2) Australia, (3) Canada (4) Congo, (5) South Africa, (6) Russia and (7) Angola (Hausel, 2006a). Notably absent from this list is the US, even though large regions are underlain by cratonic basement terrains favorable for the discovery of diamond. Canada, which became a major diamond producer in 1998, will remain in the forefront of diamond production and exploration for decades to come. Not only is the terrain and geology of much of Canada favorable for discovery of significant diamond deposits, but various Provincial and Territorial governments have provided exploration and investment incentives. This is unlike the US, which instead provides a negative business climate for exploration for diamonds and other natural resources and provides little to no support for research. As a result, nearly all North American exploration activity and investment is occurring in Canada. This philosophy has led to the discovery of more than 500 kimberlites and several unconventional host rocks in Canada over the past 10 to 15 years - nearly half of which are diamondiferous (Kjarsgaard and Levinson, 2002).

North American Craton

The North American Craton is very favorable for the discovery of diamonds and the largest craton in the world (Figure 1). The cratonic basement that underlies large regions of Canada protrudes south into the US extending under large regions of Montana, Wyoming and the Great Lakes region, where the craton has been subdivided into smaller provinces. Even with these favorable extensions of cratonic basement into the US, the political climate has stymied exploration south of the Canadian border. For example, investment in exploration and research in Wyoming Province – the most favorable extension in the US, has amounted to much less than 0.001% of research and exploration investments in Canada.

In Canada, hundreds of kimberlites have been discovered with dozens containing commercial quantities of diamond. Exploration projects in Canada are very well funded and significant discoveries have been made in nearly every province and territory. Over night, Canada became a world power in the diamond industry.

South of the Canadian border, a similar basement terrain extends into Montana and Wyoming (Wyoming Province) and also into the Great Lake Region (Superior Province). However, no significant discoveries have been made to date – but very little investment has been made to search for diamond deposits. Even so, many detrital diamonds, hundreds of kimberlitic indicator mineral anomalies, dozens of vegetation anomalies, circular geomorphic and vegetation anomalies, geophysical anomalies, known kimberlites and the largest group of lamproites in North America, it is anticipated that the US cratonic projections enclose a large number of diamond deposits. Many additional diamonds and diatremes have been discovered scattered throughout various regions of the US, both within the cratonic environments, and also in unconventional terrains (Hausel, 1996, 1998). Some of the more notable terrains include the Appalachian Uplift, the Arkansas Protonic terrain, the Superior Province, the Wyoming Craton and the California abducted belt.

Diamond Mineralogy and Geochemistry

Both gem and industrial diamonds have been created in the laboratory (Hazen, 1999) but the value of synthetic gem diamond falls short of natural gem diamond. Some natural diamonds represent the most valuable commodity on earth based on price per unit weight (Hausel, 2006a).

Native carbon may occur as one of three polymorphs: diamond, graphite and lonsdaleite (Erlich and Hausel, 2002). The physical differences between these are due to the bonds between carbon atoms. The crystalline cell of diamond approximates a cube with sides of 3.56Å and the coordination of carbon atoms in diamond is tetrahedral such that each atom is held to four others by strong covalent bonds resulting in the extreme hardness, incompressibility and thermal conductivity associated with diamond.

In the simplest form, diamond forms a cube, but natural diamonds are also found in a variety of habits. Cubic habits are relatively uncommon for diamond, but when found, they are often frosted industrial stones. Many diamond cubes have been found in placers in Brazil, and a significant percentage of diamonds recovered from the Snap Lake kimberlites in Canada also have cubic habit (Pokhilenko and others, 2003).

One of the more common habits for diamond is that of an octahedron (Figure 2). Partial resorption of the octahedron can result in a rounded (12-sided) dodecahedron with rhombic faces. Many dodecahedrons develop ridges on the rhombic faces to produce a 24-sided crystal known as a trishexahedron. Four-sided tetrahedral diamonds are distorted octahedrons (Bruton, 1978; Orlov, 1977; Shafranovsky, 1964). A tetrahedron by definition is a four-faced polyhedron in which each face forms a triangle (Bates and Jackson, 1980). These have four faces, four edges, and six apexes (Erlich and Hausel, 2002). Twinning in diamond commonly follows the spinel law and yields a flat triangular macle.

Diamonds recovered from lamproites often exhibit resorbed habits as such, octahedrons are uncommon in lamproites. The many resorbed diamond textures associated with lamproitic magmas are a result of the instability of diamond in lamproite as compared to many kimberlites. In particular, the slower rate of rise of lamproite magma through the graphite stability field, coupled with high magmatic temperatures in an oxygen-rich environment provides conditions that favor diamond resorption. Similar resorbed habits occur in diamonds in lamprophyres as well as in some kimberlites that exhibit geochemical evidence of eruption in an oxidizing magma.

In addition to resorbed textures, known diamondiferous lamproites tend to produce a large percentage of industrial to gem diamonds.

Industrial stones may be classified as bort (a poor grade diamond that is used as industrial abrasive) and carbonado (an opaque, black to grayish, fine-grained aggregate of microscopic diamond, graphite, and amorphous carbon with or without accessory minerals) (Erlich and Hausel, 2002).

Even though diamond is extremely hard, it is brittle and will break yielding a conchoidal to hackly fracture along with smooth cleavage surfaces. Diamond exhibits perfect cleavage in four directions parallel to the octahedral faces: thus an octahedron can be fashioned from an irregular shaped diamond simply by cleaving the stone (Kukharenko, 1954; Orlov, 1977). Natural diamonds contain tiny mineral inclusions along cleavage planes. These provide important data on the origin of diamond, and some can be used for age determinations. The mineral inclusions typically form assemblages characteristic of peridotite or eclogite. Some rare inclusions have been identified that are characteristic of very deep mantle sources and interpreted as ultra-high pressure diamonds originating in the lower mantle (Erlich and Hausel, 2002).

The specific gravity for diamond (3.516 to 3.525) is high enough that it will concentrate in stream, river or marine placers with *'black sand'* heavy minerals. This density is surprisingly high given the fact that diamond is composed of such a light element (carbon). Compared to graphite (2.2), diamond is twice as dense due to the close packing of atoms from high pressures within the earth's mantle (Harlow, 1998).

Diamond has greasy to adamantine luster. This luster is due to high refractive index resulting in a gemstone of unparalleled beauty with extraordinary fire. Diamonds also occur in a variety of colors from white to colorless, gray to black, and shades of yellow, red, pink, orange, green, blue, violet and brown. Strongly colored diamonds are termed fancies and many have extraordinary beauty that sell for premium prices. As an example, in 1989 a 3.14-carat Argyle pink diamond sold for $1,510,000. More recently, a 0.95-carat fancy purplish-red Argyle diamond sold for nearly $1 million.

The color in most other gemstones is due to trace impurities of transition elements. However, the color in diamond is often caused by trace nitrogen, boron or to structural defects. Diamonds may be red, pink, purple, orange, yellow, green, blue, white, black, gray or brown.

The most common color in diamond is brown. Prior to the development of the Argyle mine in Australia in the 1980s, brown diamonds were considered unattractive and were typically classified as industrial stones. But due to Australian marketing strategies, some brown stones are now highly prized gems. Lighter brown diamonds are quite variable and have color tones that range from very light brown, light (champagne) brown, medium brown, dark brown to very dark brown. Color saturation is also variable, resulting in bright brown and deep (cognac) brown colors. In particular, the champagne and cognac diamonds are now in demand.

Pink, red and purple diamonds are rare and the color in these is concentrated in tiny lamellae in an otherwise colorless diamond. The color lamellae are interpreted to be the result of micro-deformation possibly resulting from stresses applied to the diamond while crystallizing within an active subduction zone. At any rate, pure pink diamonds are extremely rare, and potentially may be more common in deposits that have distinct links to present or past subduction (i.e., a strong eclogitic signature).

Most green diamonds have only a thin surface coat that is removed during faceting – thus natural faceted green diamonds are rare. The green color results from natural irradiation, while others may result from the presence of hydrogen. The rarest color in diamond is orange, for which the coloring agent has yet to be identified. The range of orange color tone is quite variable in lightness and saturation resulting in pale orange, bright orange, dull orange, and deep orange. One of the most exquisite of all orange diamonds is a pumpkin orange color.

Black diamonds result from the presence of numerous graphite inclusions, which not only color the diamond, but also make the diamond an electrical conductor. Individual black colors can vary from pale (charcoal) black, dull (ink) black and bright (gun metal) black, all having weak saturation. Gray diamonds are hydrogen rich and their color is related to absorption of a portion of the light spectrum by hydrogen defects. Opalescent or fancy milky white diamonds are the result of numerous mineral inclusions (and possibly nitrogen defects) (Harlow, 1998).

Diamond's high index of refraction (IR=2.4195) is a result of density. Such high density in a mineral diminishes light velocity in the crystal such that it will slow light to only 77,000 mi/sec in diamond, or less than half the velocity of light in a vacuum (Harlow, 1998). Diamonds are thermal conductors and are four times as thermally conductive (5 to 25 watts/cm/^{o}C) as copper at room temperature. Unlike copper, diamond is also an electrical insulator (0 to 100 ohm/cm at 300^{o}K). Because of its high thermal conductivity, diamond will feel cool and the gem will conduct heat away from the lips, which is why diamonds are sometimes referred to as *"ice"*. Diamond detectors are designed to measure the unique thermal conductivity of a diamond's surface.

Diamonds are relatively unaffected by heat except at high temperature. Without the presence of oxygen, diamond will transform to graphite residue at 1900°C. When heated in oxygen, diamond will burn to CO_2 at much lower temperatures ($\geq$690^{o}C). Diamonds are unaffected by acids.

Diamonds repel water and are therefore hydrophobic (nonwettable) and will attract grease. Even though they are 3.5 times heavier than water, diamonds can be induced to float. Water will adhere to materials that contain oxygen making them wettable, since the oxygen atoms in the water and in the materials will link. Hydrocarbons such as grease have affinities for material without oxygen – such as diamond. This property is used in grease tables. Such tables are coated with grease to attract non-wettable diamonds, while wettable oxygen-bearing minerals tend to wash over grease plates on the tables (Erlich and Hausel, 2002).

GEMOLOGY

There are four general types of commercial natural diamonds: (1) *gem* (well-crystallized, transparent, flawless to nearly flawless), (2) *bort*, (3) *ballas* (spherical aggregates formed by many small diamonds), and (4) *carbonado* (opaque, black to gray, tough, and compact industrial diamond). Gem diamonds may be further subdivided into *gem* and *near-gem* (lower-quality gemstones).

Rough gem diamonds have values as much as 10 to 100 times greater than industrial diamonds. Gem diamonds, when cut and polished, will often fetch values that are 5- to 100- times that of the rough stone particularly when they are dressed in jewelry. The extreme value of diamond as a gemstone is due to its mystique, rarity, extreme hardness, gem preparation, marketing practices, beauty and high refractive index and dispersion that produce brilliant faceted gems with distinctive “fire”.

Top cutters in the world produce beautiful gems from rough material and may require considerable pragmatic crystallographic research to determine location of cleavage, fractures, pits, curves, protrusions, inclusions, and color inconsistencies. In some cases, valuable diamonds have been studied and mapped by cutters for as much as a year prior to faceting. Preparation for conventional faceting can take place over a considerable amount of time and require mathematical models to calculate the greatest potential yield of dispersion for the gem. Since 1981, lasers, and since 1988, computer modeling and scanning, have become an integral part of diamond fashioning. A rough diamond can now be modeled with a scanner and computer and determine the optimum faceted stone using a virtual 3D model displaying positions of mineral inclusions and virtual saw planes.

The size and shape of rough diamond, the number and location of imperfections and inclusions, and the direction of cleavage (referred to as “grain” by cutters) are considered prior to creating a gemstone. Large diamonds may be pre-shaped by cleaving with the cutter selecting the octahedral cleavage to cut a small groove in the octahedral plane with a sharp-edged diamond chip or laser. The diamond mounted on a dop holder with a steel knife placed in the groove may be cleaved by striking the back of the knife. Laser kerfing may instead be used to mark a small notch burned into the stone. If cleavage is improperly identified, the diamond may shatter into pieces. Most conventional primary shaping is done by cutting the stone with a diamond saw. After the stone is placed in a clamp and the cleavage is marked, the diamond is either cut parallel to the cube or to the dodecahedron with a rapidly rotating blade impregnated with diamond powder. Because of hardness, it may take 4 to 8 hrs to complete a cut through a 1-ct diamond of only 6 to 8 mm in diameter by using conventional cutting methods (Hurlbut and Switzer, 1979)! The process is sped up using a laser with the diamond mounted in a dop on an x-y platform. With the desired cut preprogrammed in a computer, the platform moves the diamond through the laser. At the point where the beam is focused, the temperature is extremely high and the molecular structure of diamond is converted to graphite on the first pass, and then the graphite is "burned off" on the return pass. Diamond combustion occurs at 690^{o}C to 875^{o}C. Representative cutting time with a laser would be approximately eight hours for a 10-ct. crystal (Baker, 1981).

Faceting is done by grinding and polishing on a revolving horizontal lap impregnated with diamond powder, or with a laser. The diamond is held at various angles and polished. In a standard, round, brilliant diamond, as many as 58 facets may be cut and polished. The optimum directions for conventional polishing are those parallel to the crystallographic axes. Because the cubic faces of the diamond are parallel to axes, they are easiest to polish. Those that lie nearly parallel to an axis are also more favorable to polish because of lower hardness.

Dodecahedral faces lie parallel to a crystallographic axis, and each face has one optimum conventional polishing direction. The octahedral face is the hardest on the diamond since it lies at the greatest angle from the crystallographic axis. It is nearly impossible to saw or facet using conventional methods if the plane of the cut or facet varies more than a few degrees from that of a cubic face. In this case, a laser is necessary to produce cuts and facets.

Tiny inclusions of diamond may be randomly scattered within a host diamond. Using conventional methods, the diamond inclusions are avoided during sawing since vibrations produced when the blade contacts the included diamond can cause the host to shatter. Even if the stone does not shatter, the cutting time may increase 2 to 3 times and extend cutting into many days or even weeks. With laser technology, this problem is resolved and may take only a matter of hours. The laser also includes an ability to produce new fancy shapes that were not formerly possible, such as horse-heads, oil wells, stars, butterflies, initials, etc. Many diamonds that had distorted growth, such as twinning, were virtually impossible to cut by conventional means because of changes in cleavage and crystallographic axes. However, these stones can now be cut by a laser without regard for the grain (Baker, 1981).

The value of the finished gem is judged by *"four Cs"*—cut, clarity, carat weight and color. The cut of a diamond can increase its value enormously - the better proportioned, polished and faceted, the greater its value. For diamonds of similar quality, those of greater size can dramatically increase in value with increased carat weight. When the girdle (base) and table of the diamond are proportioned correctly, the diamond will exhibit greater fire and brilliance. Gem diamonds include fancy (colored) and white (colorless) stones. Colorless diamonds range from colorless (white) and blue-white to pale yellow (Bruton, 1978). One of the more common systems for evaluating diamonds is the Gemological Institute of America's (GIA) color grading system, which ranges from D (colorless) to X (light yellow). Each letter of the alphabet from D to X shows a slight increase in yellow tinge (Hurlbut and Switzer, 1979).

A visual appraisal is done in a well-lighted room using natural north window light. Such appraisals compare the stone to a master set of instrument-graded diamonds. The instrument used in color grading is a colorimeter, which quantitatively measures the degree of yellowness (Hurlbut and Switzer, 1979). Clarity is determined by the presence or absence of blemishes, flaws, and inclusions. Many of the grading systems in use have descriptive terms such as flawless or imperfect, and terms denoting intermediate grades such as very slightly imperfect.

GEOLOGY

Commercial concentrations of diamond have only been found in rare magmatic rocks and placers presumably derived from these magmatic (igneous) rocks. The only host rocks containing commercial deposits are kimberlite and lamproite. Diamonds have been identified in other igneous rock types (i.e., alkali basalts, lamprophyres, ultramafics, etc) as well as in some ultra-high pressure metamorphic rocks (Hausel, 1996; Erlich and Hausel, 2002). Commercial host rocks so far have been restricted to ancient stabilized cratons and craton margins that include Archons (cratons of Archean age) and Protons (cratonized belts of Early to Middle Proterozoic age). Nearly all exploration ventures focus on diamondiferous kimberlite in classical cratonic terrains.

Diamonds of Igneous Association

Primary magmatic diamond deposits are limited to a few rock types that originally formed under extreme pressure and temperature at great depths beneath the lithosphere. The most notable magmatic deposits are associated with kimberlite, lamproite and some lamprophyres. Many diamondiferous kimberlites, lamproites and lamprophyres tend to occur in small or large clusters of a few to more than 100 individuals. The emplacement of clusters in most cases can be related to structural control - as a result, more than one intrusive is often found along the same fracture or orientation, or along parallel or cross fractures. Several structural orientations are often recognized within a given district and many individual structures (faults, shear zones, etc) responsible for control have limited strike lengths. Larger, more distinct structures may occur that are thought to be related in some way to kimberlite emplacement (Hausel and others, 1979). Even so, the evidence is not always convincing.

Detailed mapping of smaller linear structures responsible for the orientation of kimberlites may lead to the discovery of additional hidden to poorly exposed kimberlite (Hausel and others, 1979; Hausel and others, 1981; Hausel and others, 2000). The emplacement of kimberlite in the Iron Mountain district of Wyoming is thought to have had an association with the nearby Cheyenne Belt suture zone (Hausel and others, 2003). This suture is interpreted to represent a paleo-benioff zone marking the break between the Wyoming (>2.5 Ga) Province from the Colorado (1.8 -1.6 Ga) Province to the south (R.S. Houston, personal communication, 1996). The suture lies 8.5 km (6 mi) north of the known kimberlites at Iron Mountain while the Iron Mountain kimberlites tend to occur along fractures that parallel the suture. However, 85 km (60 mi) further south, kimberlites of the State Line district show primarily north-northwesterly trends with some east-west cross-trends and no evidence of control by major structures (Hausel and others, 1981).

Kimberlite magmas tend to erupt as diatremes (pipes) at the earth’s surface. These contain considerable latent energy and forces generated by the erupting magma that disrupt and incorporate blocks of country rock to produce a distinct pipe breccia. The breccia, referred to as diatreme facies kimberlite, will exhibit fragments of kimberlite along with xenoliths of crustal and country rock and cognate mantle nodules within a serpentinized peridotite matrix. Kimberlite diatremes typically exhibit more than one episode of magma intrusion and often suggest several episodes of intrusion within the same pipe as well as within the same district. For instance 6 different kimberlite facies were mapped within the Sloan 1 and 2 kimberlite complex in Colorado (McCallum and Mabarak, 1976).

Diatremes appear as vertical pipes that taper at depth to steeply inclined cylindrical bodies. The average angle of wall inclination at the Wesselton, DeBeers, Kimberley, and Dutoitspan pipes in South Africa is 82° to 85°. Ideally, the pipes form circular or ellipsoidal cross sections in the horizontal plane and are filled with kimberlitic tuff or tuff-breccia. In a vertical plane, the ideal cross-section is carrot-shaped. Most pipes continue from the surface to depths of 1 to 3 km (0.6 to 2 mi) where they pinch to narrow root zones that originate from a feeder dike beneath the root (Kennedy and Nordlie, 1968). At the feeder dike complex, the kimberlite is porphyritic (root-zone or hypabyssal facies) rather than brecciated.The porphyry may have considerable olivine or serpentinized olivine phenocrysts with minor pyroxene in a fine-grained serpentine matrix typical of peridotite.

Diamondiferous kimberlite was identified in 1870 at the Jagersfontein and Dutoitspan pipes in South Africa. Diamonds were initially recovered from deeply weathered, oxidized kimberlite (referred to as *'yellow ground'*). Less intensely weathered kimberlite (referred to as 'blue ground') located under the yellow ground consisted primarily of carbonated montmorillonite clays with scattered rounded boulders of country rock and mantle nodules. As the kimberlite was mined to greater depth, hard, serpentinized rock was intersected. H.C. Lewis introduced the term *"kimberlite"* in 1887 for the rock at the type locality near Kimberley, South Africa, and was defined as a porphyritic mica-bearing peridotite.

The magma temperature is hot at depth, but at the point of eruption is strikingly cool. Watson (1967) suggested a magma temperature of <1100°F (<600°C) was necessary to produce coking effects on coal intruded by kimberlite. A lower temperature of emplacement is supported by the absence of visible thermal effects on country rock adjacent to most kimberlite contacts. Davidson (1967) suggests that the temperature of emplacement may be as low as 390°F (200°C) based on the retention of argon. Hughes (1982) argues that near-surface temperatures of the gas-charged kimberlite melt may even have been as low as 32°F (0°C) owing to the adiabatic expansion of CO_2 gas during eruption at the surface. He also supports that the emplacement velocity of gasses and magma that form the diatreme at the surface could be as high as Mach 3!

Lamproite, another important host for diamond, became of major interest following the discovery of a world-class diamond deposit in olivine lamproite in the Kimberley region of Western Australia in 1979. This discovery led to the development of the Argyle mine. Several other diamondiferous lamproites have been identified or recognized in Australia, Canada, Zambia, Ivory Coast, India, Russia, and the United States.

Lamproites have been found in more than 25 provinces or fields in the world (Mitchell and Bergman, 1991; Coopersmith and others, 2003). Altered diamondiferous leucite lamproite had been described as early as 1967 near Seguela, Ivory Coast (Dawson, 1967). More than a century earlier (in 1827), diamonds had been recovered from the Majhgawan lamproite in India. Diamonds had also been identified in the Prairie Creek lamproite in Arkansas (US) as early as 1906 (Scott-Smith, 1986, 1989). Olivine lamproites, to date, have yielded higher ore grades than leucite lamproites, but for the most part are very low grade such as the Mahjgawan olivine lamproite (1.14 Ga) (10 cts/100 t). The Prairie Creek olivine lamproite is reported to average about 11 cts/100 t. Lamproites in the Zhenyuan field of the Yangtze craton, China, have grades of only 25 cts/100 t (Mitchell and Bergman, 1991). Even though these and others have very low grades, the Argyle olivine lamproite was very rich with an average grade of 750 cts/100 t!

The morphology of lamproite contrasts with the typical kimberlite pipe. Instead of pipes with steep walls that slowly diminish in width with increasing depth like kimberlites, lamproites are characterized by "champagne-glass" vents filled by tuffaceous rocks often with massive volcanic rocks in the core. Many lamproites form distinct cinder cones, flows, and or maar-like volcanoes (Mitchell and Bergman, 1991). A qualitative correlation between diamond and olivine in lamproite is supported by the Ellendale and Kapamba districts, where diamond grades are consistently higher in olivine lamproites than in adjacent leucite lamproites. Thus any deposit of olivine lamproite is of exploration interest.

Because of a slow magma ascent rate, diamonds in lamproites often show a variety of morphologies suggestive of resorption and large diamonds are uncommon. At

Argyle, for instance, more than 60% of the recovered diamonds were irregular in shape and include macles, polycrystalline forms, and rounded dodecahedrons (Shigley and others, 2001). Some diamonds also exhibit evidence of shearing or deformation. Where found, ore grades are essentially restricted to preserved pyroclastics in a given vent, where magma temperatures declined rapidly following eruption (Scott-Smith, 1986).

Where lamproitic vents flare into large craters, a potential for substantial ore tonnage exists. At the Argyle lamproite, early reserve estimates of 94 million tons of ore at an average grade of 750 cts/100 t led to its classification as a world-class deposit. Many fabulous gemstones were recovered, but a large portion of the diamonds were graphitized and partially resorbed, and the largest diamond only weighed 42.6 cts. The overall average size of the diamonds was <0.1 carat. Even so, at one point, Argyle's annual production totaled 40% of the world's production, and by the end of 2000 the mine had produced an extraordinary 558,400,000 cts (Shigley and others, 2001) unmatched by all other *in situ* diamond deposits.

Many lamproite-derived diamonds are relatively small and have *'fancy'* colors. Overall, diamonds from Argyle and Ellendale lamproites are smaller than those in many kimberlites. This difference can be explained by strong diamond resorption in the hot lamproitic magma and lower emplacement velocity. Macrodiamonds (>1 mm) from Ellendale lamproites are dominantly yellow dodecahedra, whereas microdiamonds (<1 mm) are colorless to pale-brown, frosted, unresorbed step-layered octahedra. The Argyle diamonds are mostly irregularly shaped, fractured, strongly resorbed dodecahedra or combinations of octahedra and dodecahedra. Almost 80% of Argyle diamonds are brown and many of remaining 20% are yellow or colorless. Significant, but rare, are economically important pink diamonds.

NORTH AMERICAN DEPOSITS

Until 1998, North America produced very few diamonds. But due to extraordinary exploration efforts, Canada is now a world power in diamonds with value of production ranking number 3 in the world. It is easy to predict that Canada will soon become the number 2 producer based on the number of discoveries and the exploration expenditures and investments. And even though large regions of the United States have potential to host significant diamond deposits, the US will remain essentially unproductive unless effort is made to devote research funds (on the State Government level) and the Federal Land Agencies change their demeanor and provide assistance to the State Governments and exploration groups.

Exploration over the past several years resulted in the discovery of more than 500 kimberlites (including some unconventional host rocks) in Canada of which nearly half are diamondiferous (Kjarsgaard and Levinson, 2002). Some unconventional host rocks include actinolite schist (metamorphosed komatiite) at Wawa, Canada, as well as several lamprophyres found elsewhere. The geochemistry of the Wawa deposits is comparable to the immobile geochemistry of relatively well-preserved komatiites.

Cratonic basement rocks underlie large parts of Canada, and continue south into the US extending under large regions of Montana, Wyoming and also the Great Lakes region. Many detrital diamonds and a few hundred kimberlite and lamproite intrusives have been found in these regions. Many diatremes have been found in the US, both within the cratonic environments, cratonic margins and also in unconventional terrains (Hausel, 1996, 1998).

Within the Wyoming Province (>2.5 Ga) and portions of the Colorado Province (<2.5-1.6 Ga), collectively referred to as the Wyoming Craton, nearly 150 kimberlites along with several lamproites and lamprophyres have been found surrounded by hundreds of kimberlitic indicator mineral anomalies. The Wyoming Craton underlies nearly all of Montana and Wyoming, and a large part of northern Colorado. A few dozen kimberlites and lamprophyres have also been found in the Superior Craton in the Great Lakes region of Michigan, Wisconsin and Illinois.

Approximately 30% of kimberlites found in the Wyoming Craton are diamondiferous, although many others have yielded favorable geochemistry and many of the remaining have not been tested. Twenty-two *in situ* diamond deposits have been identified in Wyoming; 20 diamondiferous kimberlites have been found in Colorado (Hausel, 1998) and one diamondiferous kimberlite has been described in Montana (Ellsworth, 2000). Diamondiferous host rocks have been found in the Great Lakes region, where as many as 26 kimberlitic and lamprophyric intrusives were discovered in the Michigan-Wisconsin-Illinois region. Eight (or approximately 30%) kimberlites yielded diamonds (Cannon and Mudrey, 1981; Carlson and Floodstrand, 1994). A diamondiferous lamprophyre (melonite) was also discovered in southeastern Wisconsin (Carlson and Adams, 1997) and a small group of diamondiferous lamproites have been known in Arkansas for nearly 100 years (Hausel, 1995).

Diamonds have been mined on a very small scale at two US localities – one in Arkansas, and the other along the Colorado-Wyoming border. The pipe at Murfreesboro, Arkansas was initially mined in the early 1900s. The host is olivine lamproite but results indicated that the lamproite was too low grade to sustain a commercial operation. Along the Colorado-Wyoming border, a small group of kimberlites were mined in 1995-96 and the pipes produced some attractive diamonds, but the grade was low. Numerous other detrital diamonds have been found scattered throughout the US with very little to no follow-up studies. Additionally, many kimberlites, lamproites and lamprophyres have been described in the US (Hausel, 1998).

Arkansas

Portions of the Gulf Coastal region of Arkansas and Texas are underlain by Early to Middle Proterozoic basement rocks and considered to have moderate to low favorability for discovery of diamondiferous lamproite and kimberlite. The Prairie Creek intrusive consists of olivine lamproite and occurs along the edge of the Ouachita Mountains. This intrusive has been one of the two most productive deposits in the US for number of diamonds recovered. The lamproite was the site of North America's first diamond mine following the discovery of diamonds in 1906 near the mouth of Prairie Creek, 4 km (2.5 mi) southeast of Murfreesboro. The pipe yielded more than 90,000 diamonds including the largest diamond in the US (40.42 cts). The property was later incorporated into the Crater of the Diamonds State Park after it was assumed the deposit was uneconomic.

Diamonds from Prairie Creek have included 30% gems and 70% industrial stones and no attempt has ever been made to recover microdiamonds (Sinkankas, 1959). The ore grade is low. Some large diamonds recovered from the property include the Uncle Sam (40.42 cts), the Star of Murfreesboro (34.25 cts), the Amarill Starlight (16.37 cts) and the Star of Arkansas (15.24 cts). Most diamonds are white, yellow or brown, and the most common habit is a distorted hexoctahedron with rounded faces (Bolivar, 1984; Kidwell, 1990). The area is characterized by Cretaceous age sedimentary rock that dip gently to the south (Meyer and others, 1977). The age of the pipe, based on geological evidence and age dating is Late Cretaceous (106 Ma) (Gogineni and others, 1978). This region of Arkansas, including parts of Texas and Oklahoma, was subjected to alkalic igneous activity during the Cretaceous.

The pipe covers an area of approximately 29.5 ha (73 ac) and contains breccia, tuff, and hypabyssal olivine lamproite (Miser and Ross, 1922; Bolivar, 1984). Nearly all diamonds were recovered from breccia facies in the lamproite, whereas the other facies are diamond poor. Gogineni and others (1978) report pyrope analyses with compositions equivalent to G9 calcic-chrome pyropes and Fipke and others (1995) identified only one sub-calcic G10 pyrope. None of the chromite analyses yielded diamond inclusion geochemistry.

At least five other lamproites have been recognized in the region and due to very thick vegetation and erosion the probability of other undiscovered lamproites in the region is likely. These were found 3.8 km (2 mi) north of the Prairie Creek intrusive and include the Kimberlite, American, Black Lick, Twin Knobs, and Twin Knobs 2 intrusives (Krol, 1988; Mike Howard, written communication, 1996). Both the Kimberlite and American lamproites have yielded some diamonds (Miser, 1914; and Miser and Ross, 1922).

Other ultramafic rocks of lamproitic or lamprophyric affinity have been reported a few miles east of Prairie Creek and about 4.8 km (3 mi) south of Corinth. Another intrusive of possible interest is the Blue Ball kimberlite 38 km (24 mi) southwest of Danville (Salpas and others, 1986).

Wyoming Craton (Colorado-Wyoming-Montana)

Diamonds were found *in situ* in the Colorado-Wyoming region in 1975 in a Wyoming kimberlite (McCallum and Mabarak 1976). Since 1975, essentially every kimberlite in this district has yielded diamond. Even so, some have not been bulk sampled and several geophysical anomalies interpreted as blind diatremes remain inexplicably unexplored and untested. Of the bulk samples taken, ore grades range from <0.5 ct/100 t to 135 ct/100 t with 30 to 50% gemstones. The kimberlites (Early Cambrian and Early Devonian) extend 4.8 km (3 mi) north into Wyoming and about 16 km (10 mi) south into Colorado.

Some target areas within the district and large areas immediately north, east, west and south of the district remain unexplored:

(1) A group of distinct INPUT geophysical anomalies were identified within the Wyoming portion of the district that is interpreted as blind diamond pipes – these have never been drilled. Similar anomalies were identified by the same INPUT survey and were not followed up in 1981. *These later became part of the Kelsey Lake diamond mine*. The southern portion of the district and adjacent areas has not been explored by airborne geophysical surveys!

(2) Some kimberlites have been found in the district in recent years that remain unsampled.

(3) Some very strong indicator mineral anomalies have also since been found within the district that indicates the presence of undiscovered kimberlite.

A second major kimberlite district lies to the north of the State Line, 75 km (45 mi) north of Cheyenne near Chugwater. This district, known as Iron Mountain includes the nearby Indian Guide district and contains a very large cluster of kimberlite dikes, sills and blows (and structurally controlled depressions) that intrude the Sherman granite (1.4 Ga) and the Laramie Mountains anorthosite batholith (1.5 Ga). The kimberlites form continuous anatomizing (Early Devonian) dikes with some eroded pipes. Portions of the dike complexes were mapped over a strike length of 8 km (5 mi) prior to the kimberlite disappearing under Phanerozoic and Quaternary sediments at both ends of the complex. This indicates that the complex extends for an unknown distance along both extremities under younger sedimentary rock (Hausel and others, 2000).

Due to lack of funding and support by the past two Wyoming State Geological Survey directors, the region to the north remains unmapped as well as to the west and essentially all of the kimberlites remains untested for diamond. All of these kimberlites and related rocks (with the exception of a small carbonated breccia along the southern margin of the district) have yielded a distinct sampling of diamond stability indicator minerals (pyrope and chromite) (Hausel and others, 2003). Past bulk sample tests have been minimal with one sample of kimberlite along the northwestern margin of the district yielding a macrodiamond (0.3 ct) and some microdiamonds (Coopersmith and others, 2003).

Between the Iron Mountain and State Line districts, as well as north, >300 kimberlitic indicator mineral anomalies were discovered by the Wyoming State Geological Survey, but only a half dozen or so were ever traced to their source due to lack of funds available from the State (Hausel and others, 1988). Numerous other kimberlitic anomalies were identified by Cominco American in the same region (Howard Coopersmith, personal communication). Only a small sampling of the indicator minerals was tested for geochemistry (due to lack of funding). Of those tested, a relatively high percentage yielded diamond-stability geochemistry (Hausel and others, 2003).

Kimberlitic indicator mineral anomalies are widespread in the Wyoming Craton, even though only a very small percentage of the craton has been explored. These have been identified in the Laramie, Hartville, Sierra Madre and Seminoe Mountains in southeastern Wyoming, in the Greater Green River Basin in southwestern Wyoming, in the Bighorn Basin and the southern Bighorn Mountains and Owl Creek Mountains and also in the Powder River Basin of northern Wyoming, in the Front Range of northern Colorado, in the Uintah Mountains of northeastern Utah, and in the Sweet Grass Hills of Montana. The presence of several hundred kimberlitic indicator mineral anomalies, several diamonds, along with some geophysical and remote sensing anomalies in limited regions support that *the Wyoming Craton has been intruded by major swarms of kimberlitic and related intrusive*s, suggesting that the Wyoming Craton could be a major diamond province. Because a large part of the Wyoming Craton remains unexplored for diamonds, additional discoveries are expected (Hausel, 1998).

One diamond mine was developed along the Colorado-Wyoming border in 1995-96. Commercial production began in 1996 at a rate of 25,000 cts/yr after Redaurum Ltd. placed two of the Kelsey Lake kimberlites (KL1 and KL2) into production. These deposits were initially mapped as the Schaffer 1, 2, 6, 7, 8, and 9 by Eggler (1967). Years later, additional kimberlites were apparently discovered by Coopersmith (1991), and the new discoveries along with the earlier Schaffer pipes were designated as the Kelsey Lake pipes. The kimberlites are irregular-shaped pipes and fissures containing diatreme facies kimberlite with zones of hypabyssal facies and minor crater facies kimberlite as xenoliths. An apparent Devonian age on the Kelsey Lake kimberlites is in agreement with

Early Devonian isotopic ages for most other pipes found in the Colorado-Wyoming kimberlite province (Coopersmith, 1993, 1997).

The property yielded many high-quality diamonds >1 ct. Some of the larger recovered stones have included 6.2-, 9.4-, 10.48-, 11.85-, 14.2-, 16.9-, 28.18-, and 28.3-ct gemstones. One broken fragment was estimated to have come from a larger stone of 80 to 90 cts (Howard Coopersmith, personal communication). The diamonds have predominantly octahedral habit and are colorless with some honey-brown gemstones (Coopersmith and Schulze, 1996).

The 28.18-carat diamond was cut to produce the largest faceted U.S. diamond. The finished stone weighed 16.8 carats, and had an estimated value of more than US$250,000 (Denver Post, September 25, 1997). A 28.3-carat diamond, also recovered from Kelsey Lake, was cut into a 5.39-carat gemstone that sold for US$87,000 (Paydirt, 1996).

The mine consisted of two open pits of only 39 m (125 ft) deep. The kimberlites, previously known as the Schaffer kimberlites (Eggler, 1967) were also detected by a later geophysical survey (Paterson and MacFadyen, 1984). The mine ore averaged only about 5 to 15 cts/100 t (Coopersmith and others, 2003) and operations terminated due to legal problems and the property was reclaimed in 2005. The kimberlites were not mined out and considerable unmined ore remained on the property. Resources were established at 16.9 million tonnes to a depth of 100 m (320 ft) (Coopersmith, 1997).

Most kimberlites in the State Line district surrounding the Kelsey Lake mine show distinct structural control. Thus exploration for additional kimberlites is enhanced by field mapping of structures and trends. The kimberlites have been deeply eroded such that diatreme and some hypabyssal facies are exposed at the surface. This implies that a very large diamond budget was transported downstream. The possibility of several overlooked placers is supported by the discovery of a placer diamonds (from very limited sampling) including a > 6 cts diamond recovered in Fish Creek and smaller diamonds elsewhere. There has been very little exploration of placers or paleoplacers in this district.

A very large kimberlitic indicator mineral anomaly was identified in southwestern Wyoming (McCandless and others, 1995). Five diamonds were found in the early 1980s in a drainage running from the flank of Cedar Mountain along the western edge of this anomaly. Ten mafic to ultramafic breccia pipes and dikes (Richard Kucera, personal communication, 1995) were discovered in this drainage. The pipes lie along a 7 to 14 km (5 to 10 mi) long, northerly-trending lineament in the Bridger Formation (Eocene). Samples recovered from the pipes yielded some diamonds (Hausel and others, 1999) and Guardian Resources later reported the discovery of two additional breccia pipes nearby (Guardian Resources press release, Nov. 24, 1997). Several alluvial diamonds were also recovered from a nearby drainage (Guardian Resources press release, Sept. 24, 1996). The Cedar Mountain pipes and dikes host 'kimberlitic indicator' minerals that are geochemical similar to those found in the Bishop Conglomerate and in anthills to the north. The presence of these minerals in the pipes provides a source rock for a portion of the detrital minerals found in the anthills and Bishop Conglomerate (Oligocene); however, the pipes only account for a small portion of the indicator minerals in this region. Thus, the possibility of numerous undiscovered pipes in basin and the Unitah Mountains are necessary to account for the widespread anomaly.

The largest lamproite field in North America is found northeast of the Cedar Mountain pipes, just north of the towns of Superior and Rocks Springs. In this area, 22 lamproites have been mapped. The field remains relatively unexplored for diamonds even though numerous gem-quality olivines have been found in the area as well as two diamond-stability chromites (Hausel, 2006b). The possibility of hidden, diamondiferous olivine lamproites in the field is considered to be very high. However, the district remains relatively unexplored for hidden lamproite. Many other strong anomalies have been identified Wyoming including indicator mineral anomalies in the Seminoe Mountains, the Bighorn Basin, and many vegetation anomalies along with diamonds and indicator minerals in the Medicine Bow Mountains.

Detrital diamonds have been found in Montana in the northern portion of the Wyoming craton, along with numerous potential host rocks (alnöite, peridotite, monchiquite, lamproite and kimberlite). Several potential hosts are found within the central alkalic province in eastern Montana, and a few lamproites are reported in western Montana, including the Ruby Slipper lamproite (Pete Ellsworth, personal communication, 1996). Two diamonds were found in gravels of the Etzikom Coulee in the Milk River drainage north of the Sweet Grass Hills in northern Mountana. The diamonds weighed 0.14 and 0.17 cts (Lopez, 1995). The occurrence lies near a buried magnetic anomaly aligned with presumed lamproitic and kimberlitic rocks in Alberta, Canada.

An extensive field of lamproites, lamprophyres and kimberlites occur in eastern Montana. Some of these have minor diamond stability minerals (Fipke and others, 1995) suggesting a possible sampling of the diamond stability field. Within this field are some interesting targets including a belt of ultramafic lamprophyre and kimberlite diatremes within the Grassrange Field in east-central Montana. The area was highly recommended by the senior author (Hausel, personal field notes, 1994) as having very high potential for the discovery of diamonds and a few years later, the Homestead kimberlite was discovered in this field and proved to be diamondiferous (Ellsworth, 2000). The Homestead kimberlite sits near an extensive breccia pipe known as Yellow Water Butte. This breccia consists of massive to brecciated olivine-phlogopite-diopside-carbonate lamprophyre with massive hypabyssal olivine lamprophyre facies (Doden, 1996). The breccia should be considered as a potential host for diamonds (Hausel, personal field notes, 1994).

Hypabyssal facies kimberlites are also found near Landusky north of the Grassrange Field. These are four closely spaced diatremes in the eastern part of an east-northeasterly trending swarm of ultramafic alkalic diatremes, dikes, and plugs (46 to 51 Ma) in the Missouri Breaks area of north-central Montana referred to as the Williams kimberlites. The available analyses of peridotitic garnets from the kimberlites indicate compositions equivalent to G-9 (Hearn and McGee, 1983). However, P-T estimates from co-existing orthopyroxene-clinopyroxene pairs in some of the peridotite nodules indicate some nodules may have originated from the diamond stability field (Fred Barnard, personal communication, 1994).

California-Oregon-Washington

Many diamonds were found as by-products of gold placer mining in the California, Oregon, and Washington. The source for the diamonds is unknown, although the presence of diatremes containing diamond-stability signature minerals and some peridotites with similar high-pressure minerals have been identified in the region. Some historical hydraulic gold placer mines north of Oroville in the Round Mountain area produced diamonds as a by-product between 1853 and 1918. About 400 diamonds and

600,000 ounces of gold were recovered from the mining operations on the Feather River (Hill, 1972).

Kunz (1885) described diamonds in all the northern counties in California drained by the Trinity River; in the vicinity of Coos Bay, Oregon; and on the banks of the Smith River of Del Norte County, California. Five diamonds were also recovered from a tributary of the South Fork of the Trinity River known as Hayfork Creek. One found in 1987 weighed 32.99 cts (Kopf and others, 1990). Countless numbers of small diamonds have also been reported in the black sands of the Trinity River. Sinkankas (1959) reported that microdiamonds were found in the black sands of the Trinity River near its junction with the Klamath River. Pyrope garnet and chromian diopside were also described from the Trinity River (Kopf and others 1990) and chromian diopside-bearing serpentinites were also identified in this area (Hausel, personal field notes ,1995).

The presence of an active benioff zone along the coastal region provides a mechanism for obduction of slices of mantle material, or over-pressurized magmas that erupted from the benioff zone at depth resulting in breccia pipes or diatremes. Such possible breccia pipes have been described at Leek Springs and also in the Sierra Nevada of California. Both pipes contain minerals with diamond-stability geochemistry.

One diamondiferous diatreme was reported by the Northern Miner (January 29, 1996). Diadem Resources reported the discovery of a cluster of dikes including a 1,875 by 188 m (6000 x 600-ft-wide) ‘dike’ after following an indicator mineral train upstream from a historic diamond placer at Leek Springs. The drill cuttings from 38 m (120 ft) of what was described as a lamproite(?) yielded 235 diamond fragments (Northern Miner, May 20, 1996).

At another breccia pipe to the south at an undisclosed location, a diatreme consists of clasts of serpentinite along with a large number of indicator minerals typical of mantle peridotite. The geochemistry of the indicator minerals included both diamond-stability and graphite-stability minerals. The pipe has not been tested for diamond.

Great Lakes Region

A group of kimberlites are reported in the Michigan-Illinois area in the Great Lakes region of the US. Parts of the Great Lakes region are underlain by the Superior Province, which is an Archean craton underlying much of Minnesota and eastern South and North Dakota and extends north into Canada. The Superior Province is bounded on the west by the Trans-Hudson Orogen and a Proton of Early to Middle Proterozoic basement rocks to the east and south suggesting that the region to have moderate potential for discovery of diamond deposits.

The Early to Middle Proterozoic basement along the eastern and southern margin of the Superior Archon underlies much of the Great Lakes region. This basement is bounded by Late Proterozoic rocks of the Grenville Tecton further to the east. The Grenville Tecton extends into eastern Michigan and Indiana.

Several diamonds (including some fairly sizable stones) have been recovered from the Great Lakes region (Hausel, 1998). Historically, these were thought to have been transported from Canada by continental glaciers during the last ice age. This assumption may be questioned particularly following the discovery of several post-Ordovician kimberlites in Michigan. A few dozen kimberlites and lamprophyres have now been described in the Superior Craton of the Great Lakes region of Michigan, Wisconsin, and Illinois. Eight kimberlites yielded diamond in the Michigan area (Cannon and Mudrey, 1981; Carlson and Floodstrand, 1994) and a diamondiferous lamprophyre diatreme (melonite) was also discovered in southeastern Wisconsin (Carlson and Adams, 1997).

At least 26 kimberlites were identified in the Michigan, Wisconsin, and northern Illinois area. In addition, eleven magnetic anomalies were detected that are suggestive of buried kimberlite pipes. Michigan also hosts Paleozoic outliers completely surrounded by Proterozoic age rocks that are interpreted as cryptovolcanic structures potentially related to kimberlite.

One of the diamondiferous kimberlites near Crystal Falls, Michigan lies one mile west of Lake Ellen near the Wisconsin border. The intrusive, known as the Lake Ellen kimberlite, is poorly exposed but produces a strong positive magnetic anomaly indicating it has a circular plan about 200 to 300 m (650 to 950 ft) in diameter covering a surface area of about 8 ha (20 ac). The kimberlite was emplaced in Proterozoic age volcanic rocks and contains abundant Ordovician(?) dolomite xenoliths. Diatreme facies kimberlite at Lake Ellen is described to contain olivine, pyroxene, mica, pyrope, and magnesian ilmenite in a fine-grained serpentine matrix (Cannon and Mudrey, 1981). A few small diamonds were recovered from the kimberlite at a diamond extraction plant in Crystal Falls. Another kimberlite, known as the Michgamme kimberlite, lies a short distance northwest of the Lake Ellen intrusive along the Michgamme Reservoir shoreline (Carlson and Floodstrand, 1994).

Northwestern Wisconsin is also underlain by basement rocks of the Superior Province, while Proterozoic rocks underlie much of the remainder of the state. Since 1876, approximately 25 diamonds were found in southern and central Wisconsin. All of the diamonds were found in Pleistocene glacial deposits or Holocene river gravel and a diamondiferous ultramafic lamprophyre (melnoite), known as the Six-Pak diatreme, was discovered by Ashton Exploration using airborne magnetic surveys in this region. The diatreme was drilled and covers approximately 20 ha (50 ac). The pipe is formed of hypabyssal facies and contains a typical kimberlitic mineral assemblage including calcic pyrope garnets typical of G9 lherzolitic paragenesis. Several small diamonds were recovered from the intrusive. The instruive lies in the outskirts of Kenosha in southeastern Wisconsin (Carson and Adams, 1997).

Many other kimberlites, lamproites and lamprophyres have been identified in the US. Many were tested by cursory sampling in the past. The reader is recommended to refer to Hausel (1998) for information on these.

Canada

Kimberlites and other potential host rocks have been identified over large regions of the North American Craton in Canada. Most discoveries have been made since the early 1990s.

In Eastern Canada, several kimberlites and related rocks have been discovered in Quebec including: (1) Abloviak kimberlite along the edge of Ungava Bay in extreme northern Quebec, (2) the Wemindji kimberlite on the shoreline of Hudson Bay, (3) Renard and Indicator Lake kimberlites in central Quebec, (4) a kimberlite cluster at Bachelor Lake north of Val-Dor, (5) the New Liskerd cluster on the western border of Quebec north of Sudbury, and (6) an unconventional host (alnöite) at Ile Bizard near the US border along the St. Lawrence River east of Ottawa (Erlich and Hausel, 2002; DeBeers, 2003).

An area of considerable interest is the Renard kimberlites on the Foxtrot property in the Otish Mountains of LaBelle Province east of James Bay in central Quebec. In this area, a 459-ct parcel of diamonds was recovered from a 664-t sample collected from four kimberlites. The largest diamond from the pacel weighed up to 4.3 cts. Another property along the coastline of northern Quebec, known as Torngat, yielded some high quality diamonds in low grade ore. The property includes a series of diamondiferous kimberlite dikes (Cumming, 2006).

North of the Great Lakes in Ontario, kimberlites discoveries have included (1) the Attawapiskat cluster, which includes several well-mineralized kimberlites including the Victor pipe in the tundra near Hudson Bay, (2) the Kyle Lake kimberlite cluster about 100 km (60 mi) west of the Attawapiskat cluster, (3) the Kirkland Lake cluster along the eastern Ontario border adjacent to Quebec, (4) the Keith Township kimberlite, and unconventional host rocks of great interest known as (5) the Wawa cluster metakomatiites located on the northeastern shore of Lake Superior.

The Wawa cluster of metakomatiites are very intriguing in that they are represent metamorphosed ultramafic lavas erupted at very high temperatures and represent some early formed magmatism related to greenstone belt evolution during the Archean when the earth's atmosphere was reducing. The presence of diamonds in such rocks will result in new exploration concepts and terrains for diamonds in greenstone belts, particularly since other metakomatiites outside of Canada have been found to contain diamond in recent years (Erlich and Hausel, 2002).

The Victor Project, in the James Bay Lowlands near Attawapiskat, encloses 18 kimberlite pipes, 16 of which are diamondiferous. The Victor Main pipe and Victor Southwest pipe consists of two pipes that coalesce at the surface and have a combined area of 15 ha (37 ac), The pipe includes both pyroclastic crater and hypabyssal facies kimberlite and has highly variable diamond grades. When a decision is made to put the property into production, the open pit mine is expected to have a mine-life of 12 years and total project life of 17 years. The mine would be supported by a processing plant designed to process 2.5 million tonnes/yr.

To the west of Ontario, exploration in Manitoba resulted in the discovery of the Wekusko kimberlite north of Lake Winnepeg. There are some other reports of discoveries in the province. Further west, many kimberlites and clusters have been identified in Saskachewan and Alberta north of Montana and Wyoming.

In Saskachewan, a major kimberlite district known as Fort a la Corne was discovered near the town of Smeaton east of Prince Albert. This district has attracted considerable attention due to the number of kimberlites and the large size of the intrusives. At the Star kimberlite project, a small bulk sample yielded a grade of 18 cts/100 t. The Fort a la Corne project, 50 km (30 mi) northeast of Prince Albert, includes more than 70 large kimberlites ranging in size from 2.7 to 250 ha (6 to 318 ac) that lie under 100 m (320 ft) of glacial cover (Robertson, 2004). The kimberlites are thought to have laterally extensive subhorizontal lenses of crater facies kimberlite that are as much as 2000 m (6400 ft) in diameter and in some cases crater facies as much as 100 m (320 ft) thick. Kimberlites were discovered in this region by follow-up drilling projects into circular to sub-circular complex magnetic anomalies.

In neighboring Alberta, kimberlites have been identified at (1) Mountain Lake northeast of Grande Prairie, (2) in the Buffalo Hills cluster, where 38 kimberlites have been found northeast of Mountain Lake, and (3) the Birch Hills cluster located southwest of Lake Athabasca. One kimberlite (K252) in Buffalo Hills yielded a test grade of 55 cts/100 t (Cummings, 2006). In neighboring British Columbia, lamprophyric pipes are found near the Alberta border just north of Montana. These are known as the Cross diatremes.

In the Canadian far north several other kimberlites have been discovered at: (1) Darnley Bay along the shoreline of the Beauford Sea (Northwest Territories), (2) Victoria Island cluster (Northwest Territories - Nunavut), (3) Somerset Island cluster (Nunavut), (4) Jackson Inlet kimberlite on the Brodeur Pennensula of Baffin Island (Nunavut), (5) Kim Lake kimberlite on Baffin Island (Nunavut), (6) the Aviat kimberlites on the Melville Peninsula (Nunavut), (7) the Thirsty Lake intrusive along the northwestern margin of Hudson Bay (Nunavut), and kimberlites in the Lac De Gras region (Northwest Territories) (DeBeers, 2003).

A major kimberlite district was discovered within the Slave Province northeast of Yellowknife in the Northwest Terrritories in the early 1990s. Within this region, several commercial diamond pipes and a dike have been identified. The clusters include; (1) the Ekati group, (2) Diavik group, (3) Snap Lake group, (4) Gahcho Kue (formerly Kennady Lake) and (5) Jericho kimberlites, all very important diamond deposits (Figure 4). Portions of the first three clusters are currently producing diamonds. Other kimberlites are found south of Yellowknife on the shoreline of the Great Slave Lake.

One of the great exploration success stories in history was the discovery of diamonds in the Canadian Northwest Territories, which sparked the largest claim staking rush in history (Krajick, 2001). Within a few years following the discovery, the capitalization of the *Ekati mine* resulted in the first Canadian diamond mine in 1998. Since the mine began operations, other commercial properties have been identified in the Northwest Territories that include the Snap Lake dike and the Diavik pipes. A fourth commercial diamond prospect in Canada, *Jericho,* is located in Nunavut, 170 km (100 mi) north of Ekati and 420 km (250 mi) north-northeast of Yellowknife. Of the four commercial operations Ekati is by far the largest operation.

(1) Kimberlites at *Ekati* are located nearly 300 km (180 mi) northeast of Yellowknife. Several of the pipes were found lying under a group of shallow lakes in the Lac de Gras region in the early 1990s. Within a few years following the discovery, Canada's first diamond mine was commissioned by BHP in late 1998. This is a world-class mine. The property includes a cluster of 121 kimberlite intrusives (52 Ma), and to date, commercial mineralization has been identified and reserves established and/or mined at the Fox, Leslie, Misery, Koala, Koala North, Panda, Beartooth, Sable and Pigeon kimberlite pipes: the other kimberlites on the mine property are being evaluated and the mine is anticipated to have a minimum life of 25 years.

In 2001, Ekati produced 3.7 million carats totaling about 6% of the world's diamond value. In 2003, production increased to 6.96 million carats (EMJ, 2004). The open pit operation on the Panda kimberlite reached maximum economic depth in 2003, five years after mining was initiated. However, declining production from the Panda open pit was replaced by production from the nearby Misery and Koala open pits.

Evaluation showed that the Panda kimberlite mine life could be extended using underground mining techniques, thus the remaining kimberlite is being developed using sublevel retreat mining. Underground mining was previously initiated at the adjacent Koala North pipe in 2002. The Panda underground mine is expected to produce 4.7 million carats over an operating period of 6 years, with production scheduled in 2005 followed by full production in 2006. The Ekati production for the first quarter of 2004 totaled 1.27 million carats, which was a 40% decline from the previous quarter. For the first 9 months of fiscal year 2004, the Ekati produced more than 5.3 million carats.

On June 30th, 2003, the Ekati mine reported 47.7 million tonnes of ore reserves at 80 cts/100 t (36.6 million carats of recoverable diamonds) based on a 2 mm cutoff size. Measured, indicated, and inferred kimberlite resources stood at 127.9 million tonnes of ore containing an estimated 171.2 million carats (Robertson, 2004)! As exploration continues on the property, these reserves will increase (Hausel, 2006a).

(2) Production at the *Diavik mine* began in 2003. *Diavik* is estimated to host 102 million carats of diamond and anticipated to yield 6 million cts/yr when in full production. The Diavik pipes are located in the Lac de Gras region in the Slave Province west of Ekati and are being mined by Diavik Diamond Mines. Diavik Diamond Mines is a subsidiary of London-based Rio Tinto and is a joint venture between Rio Tinto (60%) and Toronto-based Aber Diamond Mines (40%). Rio Tinto assumed operating responsibility from their subsidiary Kennecott Canada Exploration.

Fifty-five kimberlites have been found on the property of which 25 are diamondiferous and at least four have commercial mineralization. The mine is estimated to host 138 million carats of diamond in four of the kimberlites (A154S, A154N, A418, A21). The A154S kimberlite is one of the richest in the world with a reserve of 11.7 million carats at an average grade of 520 cts/100 t. The mine is currently focusing on development of both the A154S and A154N and is anticipated to yield 6 to 8 million cts/yr when in full production. It has resources to sustain the operation for 16 to 22 years. In 2004, the mined produced 7.6 million carats including some large stones up to 151 cts. The property lies on a 20 km^2 island known as East Island 300 km (180 mi) northeast of Yellowknife The Diavik kimberlites (55 Ma) intrude the Precambrian Slave basement complex (2.5 to 2.7 Ga) with several lying beneath lakes. Capitalization costs to initially open the mine were on the order of $1.3 billion.

(3) The *Snap Lake mine* is scheduled to begin diamond ore recovery from a kimberlite dike about 100 km (60 mi) south-southeast of Ekati and 220 km (130 mi) northeast of Yellowknife. The Snap Lake sill dips under adjacent Snap Lake. It has a strike length of 3.2 km with a dip of 15° and dip length of at least 3.1 km (1 km deep). DeBeers anticipates to begin construction in 2006 with full production scheduled in 2008. The kimberlite will be mined entirely underground. The rock is estimated to contain 38.8 million carats in 22.8 million tonnes of ore with an average ore grade of 146 cts/100 t (Robertson, 2004). The mine life is anticipated for 22 years. Snap Lake is one of three properties that are being developed by DeBeers. The other two deposits scheduled for mining by DeBeers are Gahcho Kue east of Snap Lake, and the Victor in the James Bay Lowlands of northern Ontario.

(4) The *Jericho mine* lies south of Carat Lake in Nunavut Territory, 420 km northeast of Yellowknife, about 170 km north of the Ekati mine near Echo Bay's Lupin Gold mine. The Jericho kimberlite is a multiphase intrusive measuring 300 m by 100 m (960 ft by 120 ft) that was found on dry land. The pipe has an indicated and inferred resource of 7.1 million tonnes of ore averaging 84 ct/100t for an estimated resource of 6 million carats to be produced over 9 years. During bulk sampling of the pipe by Tahera Exploration, a decline was driven to obtain a 9,435 t bulk sample which yielded 10,539

cts at a cut off grade of 1 mm. The stones included 44 diamonds weighing between 5 and 10 cts and 23 stones larger than 10 cts. The largest stone weighed 40 cts.

This property includes six diamondiferous kimberlites. Reserves of 2.6 million tonnes of ore averaging 120 ct/ 100 t have been established. Mine construction began in 2005 and production scheduled for March 2006 (EMJ, 2004).

(5) The *Gahcho Kue* (formerly Kennady Lake) property lies south of Lac de Gras, 80 km southeast of Snap Lake near Ft. Defiance and 300 km northeast of Yellowknife. At least 8 diamondiferous kimberlites occur on this property including sills and dikes. Inferred and indicatred resources of the three pipes are 31.4 million cts averaging 148 cts/t. Estimates suggest a potential tonnage of at least 20 million tonnes of ore in the 5034, Hearne, and Tuzo pipes. The ore averages 167 ct/100 t. Gahcho Kue is currently being explored by a joint venture between Mountain Lake Resources and DeBeers. Development is expected to take 3 years (EMJ, 2004) and will produce 3 million carats annually when in full production over 15 years.

Many other deposits have been found in Canada since the 1990s in the Northwest Territories, Nunavut, Alberta, Ontario, Quebec, and Saskatchewan (Olson, 2001, 2003). According to EMJ (2004), Canada is currently supplying about 15% of the world's diamonds and is expected to show dramatic increases in the future. In 2002, the Canadian diamond industry produced nearly 5 million carats. In 2003, production increased to 11.2 million carats, and it is estimated that essentially 50% of the world diamond exploration funding is focused on Canada.

In addition to the commercial properties, many other successes have been made. DeBeers alone reported the discovery of more than 219 kimberlites in 12 different regions of Canada, of which more than half are diamondiferous. Typically, only one in every 200 kimberlites will contain sufficient amounts of diamonds of high enough value to result in a commercial mine (Hausel, 2006a).

The current focus of DeBeers is on the Slave Craton of the Northwest and Nunavut Territories, and also the Superior Craton covering parts of Manitoba, Ontario and Quebec, and the Churchhill Province of Nunavut. The company currently has several advanced stage projects including Gahcho Kue in the Northwest Territories and Fort a la Corne in Saskatchewan.

DIAMOND GENESIS

The majority of diamonds are interpreted to represent xenocrysts derived from disaggregation of mantle fragments trapped within the magma. Kimberlites often contain rounded diamondiferous hand-specimen to boulder-size nodules of peridotite (garnet and chromite harzburgites and less commonly lherzolites) and eclogites. It is thought that these are residual fragments of a diamondiferous mantle that were sampled by kimberlite (and related) magmas. During transport to the earth's surface, many were disaggregated and their diamond and kimberlitic indicator mineral content scattered throughout the hybrid magma with mantle nodules that survived in tact. Some diamondiferous eclogite nodules recovered from kimberlite have been diamond-rich yielding average ore grades estimated at 20,000 to 30,000 cts/t. Some diamondiferous peridotite nodules have yielded grades 2 to 4 orders of magnitude less than the richest eclogites. These are still as much as 3 orders of magnitude greater than the host kimberlite ores. Bulk samples of kimberlite and lamproite have ranged from 15 to 2000 cts/100 t.

Peridotite is thought to be the most common rock type in the upper mantle in cratonic keels, and pyrope garnets from many diamondiferous peridotites have unique geochemistry. These pyropes are designated as G10 and have chemical affinities for subcalcic harzburgite and have relatively low Ca/Cr ratios compared to lherzolitic pyropes (Gurney, 1989). Calcic chrome-rich pyrope garnets designated as G9 have affinity for lherzolite. Lherzolite is thought to have less potential for diamond, even so, some lherzolites are diamondiferous!

Eclogite occurs as nodules in kimberlite and is interpreted to represent xenoliths unrelated to kimberlite. They are assumed to either be cumulates of garnet peridotite melts or of subducted oceanic crust. Mantle garnets of eclogitic paragenesis have been designated as either Group I or Group II. Diamondiferous eclogites belong to Group I which contain almandine-pyrope with =0.07% Na_2O, low levels of Cr_2O_3 (<0.05 wt.% Cr_2O_3) and CaO in the range of 3.5 to 20 wt.%. Group II eclogitic pyropes have <0.07% Na_2O. Low-Cr garnets with less than 3.5% CaO are probably derived from crustal rocks (Helmstaedt, 1993).

Many diamonds in kimberlite and lamproite formed at depth within the diamond-stability field defined by a unique set of high P and T within the earth’s lithosphere (non-convecting uppermost portion of the mantle). The top of this zone corresponds to graphite transition to diamond: the bottom corresponds to the maximum thickness of the lithosphere. Graphite transforms to diamond at a depth of 150 to 200 km (90 to 125 mi) (45 to 55 kbar) and 1920-2190^{o}F (1050°–1200°C) within cratonic keels.

There is also a very minor contribution of diamond from sub-lithospheric depths within the convecting portion of the mantle to depths of 700 km (420 mi). These ultra-high pressure diamonds are transported to the lithosphere by convection within the earth’s asthenosphere and contain mineral inclusions suggestive of very high pressure and temperature. (Erlich and Hausel, 2002). Such ultra-high pressure diamonds contain mineral inclusions that support derivation at depths of >300 km where garnet and pyroxene are unstable and transform to stable sub-Ca, high Cr majorite garnet (Stachel, Brey and Harris, 2005).

Other diamond deposits have been recognized that do not fit traditional models. These unconventional deposits include rare metamorphics, meteorites, lamprophyres, peridotites and eclogites (Hausel, 1998; Erlich and Hausel, 2002). Unconventional deposits would also include those formed above subduction zones. In such deposits, diamond is postulated to form within cold subducting slabs along some continental margins. Some research has postulated that such diamondiferous slabs may be generated at depths of only 80 to 90 km (50 to 56 miles) at 22 to 25 kbar and 390-750^{o}F (200°–400°C).

Some interesting unconventional source rocks include Archean rocks of komatiite affinity. One komatiite in South America is described as a diamondiferous lamprophyre of komatiitic affinity. Ayer and Wyman (2003) suggest the South American rocks originated at only 50 miles (80 km) depth. Similar hosts are under investigation in an Archean greenstone belt in the Wawa area, Ontario, Canada (Ayer and Wyman, 2003; Kaminsky and others, 2003). Another similar diamond occurrence was discovered in volcaniclastic komatiite in the Dachine region of the Inini greenstone belt of the Guyana shield of French Guiana (Capdevila and others, 1999). This komatiite was suggested by Capdevila and others (1999) to have originated at depths of >250 km (>155 mi). Bulk samples of the rock yielded <1 to 35 diamonds/lb. Using a cut-off size of 1 mm, sample grades varied from 0.06 to 10.48 cts/100t. The largest stones ranged from 1.7 to 2.36 mm across. Colors varied from white to light brown and rarely greenish/yellow and were translucent to transparent but often masked by large quantities of inclusions. The dominant shapes are irregular with few cubic and octahedral stones. The diamonds are for the most part intensely reabsorbed (Global Infomine press release, 10/12/2000).

Indicator minerals associated with komatiites are rare, and are essentially restricted to Mg-Cr garnets and chromite. The garnet population is characteristic of lherzolite with some subcalcic harzburgitic (G10) pyrope and eclogitic garnet. Other kimberlitic indicator minerals (Mg-ilmenite, chromian diopside, and perovskite) are absent. Chromite cores are poorer in Ti and richer in Mn that those typically associated with kimberlite and lamproite. These are similar to spinels found in similar rocks in other greenstone belts.

When found, the komatiites are highly altered and form finely foliated albite-carbonate-chlorite-talc schists, actinolite-chlorite schists, and primary volcanic textures are preserved in some outcrops. Concentrations of immobile elements are very low, similar to other komatiites, yet distinct from kimberlite and lamproite. It is thought that the komatiite formed by melting of a hot, deep, mantle source, and the diamonds were transported as xenocrysts from depths >150 km (>95 mi). Capdevila and others (1999) suggest a depth of genesis for the Al-depleted magma at >250 km (>160 mi).

In one test, samples from 8 outcrops of metakomatiite at Wawa Ontario, Canada yielded 231 diamonds. The diamonds were found in a narrow 1 to 10 m (3 to 30 ft) wide actinolite-rich ultramafic dike crosscutting metasedimentary and metavolcanic rocks of a greenstone belt. In another sample, 164.7 kg (363 lbs) of rock were taken from a road cut along the Trans-Canada Highway north of Wawa and yielded 95 diamonds. The samples suggest an average grade of 25 cts/100 t, potentially within limits of a commercial deposit, depending on the size and clarity of the stones!

Diamonds were also discovered in 2.67 Ga lamprophyres in the Michioicoten and Abitibi greenstone belts. These apparently represent the oldest known primary host rocks for diamonds. They were intruded late in the evolution of the greenstone belts and the chemistry of the lamprophyres suggest that the diamonds originated from spinel lherzolite mantle at depths of less than 80 km (<50 mi), whereas the diamond stability field is interpreted to lie at >150 km (>95 mi). The probable absence of a thick cratonic root beneath the Michioicoten, Abitibi and Wawa greenstone belts at the time of eruption indicates a variant of a subduction diamond model applied to Phanerozoic terrain in southeastern Australia may be appropriate. Most likely these diamonds formed at relatively shallow depths (80 km; 48 mi) in a subduction zone and were generated in a low-temperature environment located in a subducted or underplated oceanic crust (Ayre and Wyman, 2003). These are notable discoveries since most greenstone belts in the world have thin to thick successions of komatiites and very few have been sampled for diamond.

EXPLORATION METHODS

Diamond exploration requires use of a number of tools. First, a region is selected to have good potential for the discovery of commercial diamond deposits. Since kimberlite and lamproite have been important sources for diamond, most prospecting focuses on finding these types of rocks. Typically, Archons (cratonic areas older than 2.5 Ga) have highest priorities. In these regions, the areas are examined by aerial photography for vegetation and topographic anomalies that might be indicative of kimberlite. This data is examined along with stream sediment sampling designed to find kimberlitic indicator mineral anomalies (chromian diopside, pyrope garnet, picroilmenite, diamond and chromite). Once these are identified, additional surveys are conducted to find the source of the indicator minerals and to investigate any aerial photo anomalies.

Airborne geophysical surveys are typically flown over regions where kimberlites have been identified, or where distinct indicator mineral anomalies have been identified. INPUT surveys (combined EM and magnetics) are used to focus on geophysical anomalies. These may be drilled or dozed depending on the depth of the anomaly. Once a kimberlite is discovered, structural mapping and aerial photo mapping may reveal controlling structures that can lead to the discovery of additional kimberlite pipes. For additional information on exploration techniques used for kimberlite, see Erlich and Hausel (2002).

Cost figures for annual diamond exploration amounts to tens of millions of dollars. Regional circumstances will dictate which exploration method will need to be used; however, when an exploration program is initiated, priority is given to areas of favorability for finding 'traditional' diamondiferous host rocks. For example, commercial diamondiferous kimberlites are considered to be restricted to cratonic regions that have been relatively stable for about 1.5 Ga. Janse (1984, 1994) suggested that cratons be separated into areas of favorability known as Archons, Protons and Tectons. This method for outlining regions of favorability provides an excellent first option priority list.

Archons (Archean basement stabilized >2.5 Ga ago) are considered to have high potential for discovery of commercial diamond deposits hosted by kimberlite and possibly by lamproite and lamprophyre. Protons (Early to Middle Proterozoic [2.5–1.6 Ga] basement terrains) have moderate potential for commercial diamond deposits in kimberlite and high potential for commercial diamond deposits in lamproite and possibly lamprophyre. Tectons (Late Proterozoic [1.6 Ga–600 Ma] basement terrains) are considered to have low potential for commercial diamondiferous host rock. Unconventional diamond deposits (such as high-pressure metamorphic complexes, astroblemes, subduction-related complexes and volcaniclastics) may occur in tectonically active terrains, but the methods for exploration for these, are not well defined.

Following selection of a favorable terrain, topographic and geological maps, aerial and satellite imagery, and aerial geophysical data are examined. Unusual circular depressions, circular drainage patterns, noteworthy structural trends and vegetation anomalies are noted. Geophysics is used to search for distinct ("bull's eye") conductors and magnetic anomalies. Geochemical data are examined for Cr, Ni, Mg, and Nb anomalies.

Stream sediment sampling

One of the primary methods used in diamond exploration is stream sediment sampling programs designed to search for 'kimberlitic indicator minerals' (pyrope garnet, chromian diopside, chromian enstatite, picroilmenite, chromian spinel, and of course diamond). Diamond targets are small and may range from diatremes of several acres to narrow dikes and sills. Diamond-bearing kimberlites and lamproites typically contain abundant soft serpentine with resistant mantle-derived xenocrysts and xenoliths. The serpentine matrix tends to decompose releasing distinct mantle-derived 'kimberlitic indicator minerals' into the surrounding environment. The indicator minerals may be carried downstream for hundreds of yards, or a few or many miles depending on the climatic and geomorphic history of the region. Diamonds however, are thought to be carried considerable distances – in some cases, hundreds of miles. The indicator minerals may provide a trail leading back to the source.

In the planning stages of stream-sediment sampling, proposed sample sites are initially marked in prominent drainages on a topographic map using a sample spacing designed to take advantage of the region. In arid regions, sample spacing should take advantage of relatively short transport distances of the indicator minerals. In subarctic to arctic areas (i.e., Canada, Sweden, Russia, etc) sample density may be considerably lower owing to the greater transport distance and the logistical difficulties of collecting samples. Anomalous areas are then re-sampled at a greater sample density.

The traditional kimberlitic indicator minerals are rare to non-existent in lamproite, thus other minerals (zircon, phlogopite, K-richterite, armalcolite, priderite) may be considered that unfortunately have low specific gravity, poor resistance, or are potentially difficult to identify. The better indicators for diamondiferous lamproite have been diamond and magnesiochromite.

To take advantage of the dispersion of kimberlitic indicator minerals, the size of samples are determined based on the environment. For example, where there is a general lack of active streams, much larger samples are taken compared to regions with active drainages. In areas with juvenile streams, samples are often panned on site to recover a few pounds of sample concentrates. Recovered indicator minerals are tested for chemistry using an electron microprobe to identify those that have higher probability of originating from the diamond stability field. The data are plotted on maps to facilitate evaluation.

Geomorphology

Kimberlite and olivine lamproite are often pervasively serpentinized, making outcrops the exception rather than the rule. In many cases, geomorphic expressions of pipes are subtle to unrecognizable. The Kimberley pipe in South Africa was expressed as a slight mound, but nearby pipes (i.e., Wesselton pipe) were expressed as subtle depressions. Others produced subtle modifications of drainage patterns (Mannard, 1968). In the subarctic, where glaciation has scoured the landscape, some kimberlites produce noticeable depressions filled by lakes. In the semi-arid region of Wyoming and Colorado, a few kimberlites are expressed as slight depressions, but most blend into the surrounding topography and may or may not have a subtle vegetation anomaly.

In the Ellendale field, Western Australia, serpentinized diamondiferous olivine lamproites lie hidden under a thin layer of soil in a field of well-exposed leucite lamproite volcanoes. The Argyle lamproite and diamondiferous lamproites in the Murfreesburo area of Arkansas were also hidden by a thin soil cover

Lineaments

Many kimberlites and lamproites are structurally controlled (Hausel and others, 1979; 1981; Erlich and Hausel, 2002). Controlling lineaments and fractures may be indicated by alignment of a cluster of intrusives or by the elongation of a pipe. In Lesotho, South Africa, Dempster and Richard (1973) reported a close association of kimberlite with lineaments: 96% of kimberlites were found along WNW trends, and many pipes were located where the WNW trends intersected WSW fractures.

Lamproites in the Leucite Hills, Wyoming are found on the flank of the Rock Springs uplift where distinct E-W fractures lie perpendicular to the axis of the uplift (Hausel and others, 1995). In the West Kimberley province of Western Australia, some lamproites are spatially associated with the Sandy Creek shear zone, a Proterozoic fault. In the Ellendale field, several lamproites lie near cross faults perpendicular to the Oscar Range trend, even though the intrusions do not appear to be directly related to any known fault. The Argyle lamproite to the east has an elongated morphology suggestive of fault control, and intrudes a splay on the Glenhill fault (Jaques and others, 1986).

Remote Sensing

Kingston (1984) reported remote-sensing techniques are widely used to search for kimberlite: these include conventional and false color aerial photography, LANDSAT multispectral scanner satellite data, and airborne multispectral scanning.

Many pipes and dikes possess distinct structural qualities or vegetation anomalies that may allow detection on aerial photographs (figure 5). Many kimberlites have been identified on aerial photographs on the basis of vegetation anomalies, circular depressions or mounds, and/or tonal differences (Hausel and others 1979, 2000, 2003).

Geophysical Surveys

Geophysical exploration has been used successfully in the search for hidden kimberlite and lamproite (Barygin, 1962; Litinskii, 1963a,b; Gerryts, 1967; Burley and Greenwood, 1972; Hausel and others, 1979, 1981; Macnae, 1979, 1995; Woodzick, 1980; Patterson and MacFadyen 1984), particularly in districts where kimberlites have previously been discovered. Contrasting geophysical properties are often favorable for distinguishing kimberlite, lamproite and minette from country rock.

INPUT™ airborne surveys are effective in identifying both serpentinized and weathered kimberlite owing to the combination of conductivity and magnetics used in INPUT™. Rock exposures of kimberlite may yield magnetic signatures but are poorly conductive, while deeply weathered kimberlites are conductive but poorly magnetic.

Because of the relatively small size of the diamond host rock, close flight-line spacing is necessary. In an airborne INPUT™ survey over the State Line district, Wyoming, a flight-line spacing of 640 feet (200 m) effectively detected several kimberlites and identified distinct magnetic anomalies interpreted as blind diatremes (Patterson and MacFayden, 1984). An aeromagnetic (200–400m line spacing) survey flown over parts of northeastern Kansas identified several anomalies, some of which were drilled resulting in the discovery of previously unknown kimberlites (i.e., Baldwin Creek, Tuttle, and Antioch kimberlites) (Berendsen and Weis, 2001). Flight line spacings of 160 to 320 feet (50-100 m) were used for INPUT™, magnetics and radiometrics in the Ellendale field, Australia (Atkinson, 1989; Janke, 1983; Jaques and others, 1986). The olivine lamproites yielded distinct dipolar magnetic anomalies.

Most kimberlites in the Colorado–Wyoming State Line district yielded small complex dipolar anomalies in the range of 25 to 150 gammas, with some isolated anomalies of 250 and 1,000 gammas (Hausel and others, 1979). Blue ground kimberlite tends to mask magnetic anomalies. In the Iron Mountain district, where much of the kimberlite is relatively homogeneous, massive hypabyssal-facies kimberlite, only weak to indistinct magnetic anomalies were detected (Hausel and others, 2000).

Resistivity of weathered lamproite may be lower than that of country rock, owing to the conductive nature of smectitic clay relative to illite, kaolinite and other clay minerals (Gerryts, 1967; Janke, 1983). However, the Argyle olivine lamproite yielded moderate to strong resistivity anomalies (40-100 ohm/m) compared to the surrounding country rock (200 ohm/m) (Drew, 1986).

Biogeochemical and Geochemical Surveys

Kimberlite and lamproite are potassic alkalic ultrabasic igneous rocks with elevated Ba, Co, Cr, Cs, K, Mg, Nb, Ni, P, Pb, Rb, Sr, Ta, Th, U, V and light rare earth elements (LREE). The high Cr, Nb, Ni, and Ta may show up in nearby soils (Jaques, 1998), but dispersion of these metals in soils is not extensive.

Bergman (1987) suggested that olivine lamproites are generally enriched in compatible elements relative to leucite lamproites as a result of the abundance of xenocrystal olivine in the former. Barren lamproites contain elevated alkali and lithophile contents (K, Na, Th, U, Y, and Zr) relative to diamondiferous (olivine) lamproites. Diamondiferous lamproites possess twice the Co, Cr, Mg, Nb, and Ni, and half the Al, K, Na and as barren lamproites (Mitchell and Bergman, 1991), and lamproites have anomalous Ti, K, Ba, Zr, and Nb compared to most other rocks. These components may favor the growth of specific flora or may stress local vegetation (Jaques, 1998). The Big Spring vent, West Kimberley, Australia, is characterized by anomalous faint pink tones that reflect the growth pattern of grass on the vent (Jaques and others, 1986).

Many kimberlites in the Colorado–Wyoming State Line district will not support growth of woody vegetation resulting in open parks over kimberlite in otherwise forested areas. These same kimberlites may support a lush stand of grass delineating the limit of the intrusive. Distinct grassy vegetation anomalies over kimberlites in the Iron Mountain district were used successfully to map many intrusives (Hausel and others, 2000). The anomalies are especially distinct following a few days of rain in the late spring.

Vegetation over the Sturgeon Lake kimberlite in Saskatchewan was tested for 48 elements; the kimberlite showed a consistent spatial relationship with Ni, Sr, Rb, Cr, Mn and Nb, and to a lesser extent with Mg, P and Ba, and relatively high Ni concentrations occurred in dogwood twigs. In hazelnut twigs, Cr levels were greater than 15 ppm near the kimberlite but only 5 to 8 ppm elsewhere, and Nb was higher in hazelnut twigs. Sr and particularly Rb were relatively enriched in some plant species on kimberlite. The Sr was probably derived from the carbonates associated with the kimberlite, whereas the Rb was derived from phlogopite. Ni, Rb and Sr distribution and Cr enrichment associated with Mn depletion in the twigs could be used to identify nearby kimberlite (Gregory and Toomes, 1969).

CONCLUSIONS

With the current trend of investment, exploration and progressive pro-mining atmosphere, it is anticipated that Canada will be a leading diamond producer for decades to come. The shear size of the North American Craton allows one to predict Canada to become the world's number 2 source for diamonds in the future. Unless there is a major change in attitude of the US government and population, little is expected to be produced in the US, even though parts of the US (i.e., Superior and Wyoming Provinces) are underlain by this craton. The importance of the North American Craton in the future of the diamond industry has resulted investments of hundreds of millions of dollars in exploration in North America.

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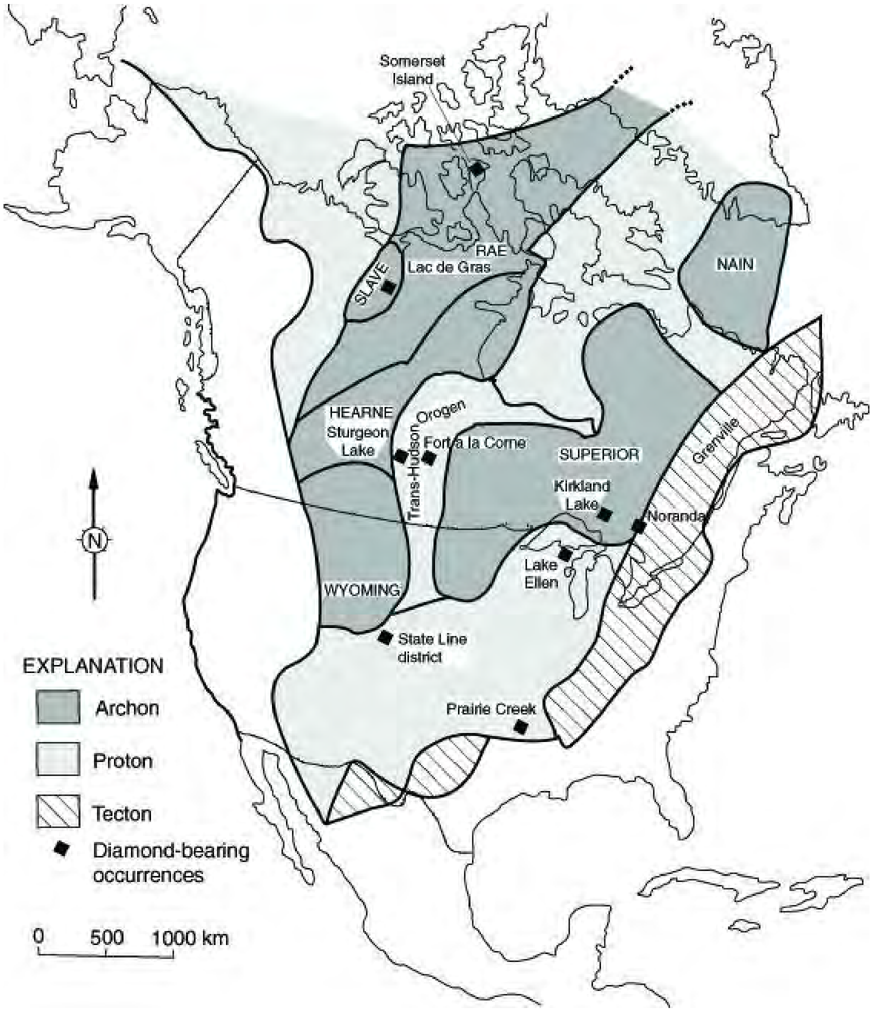

FIGURE 1 The North American craton.

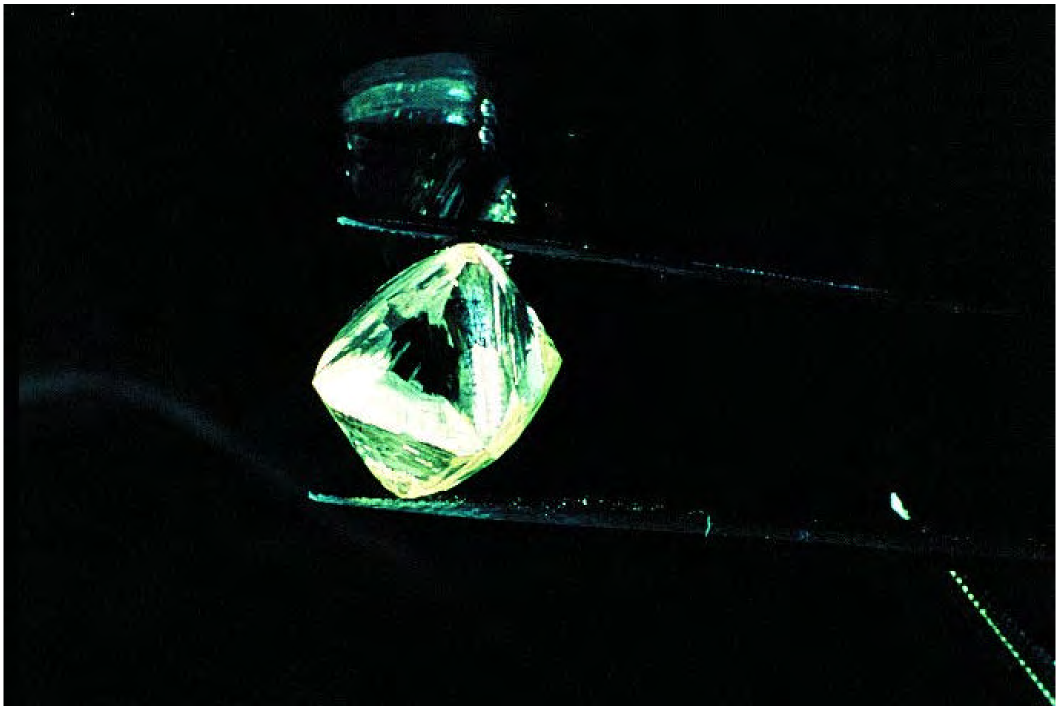

FIGURE 2 A flawless 14.2-carat diamond from the Kelsey Lake diamond mine, State Line district, Colorado-Wyoming, showing characteristic octahedral habit (photo courtesy of Howard Coopersmith).

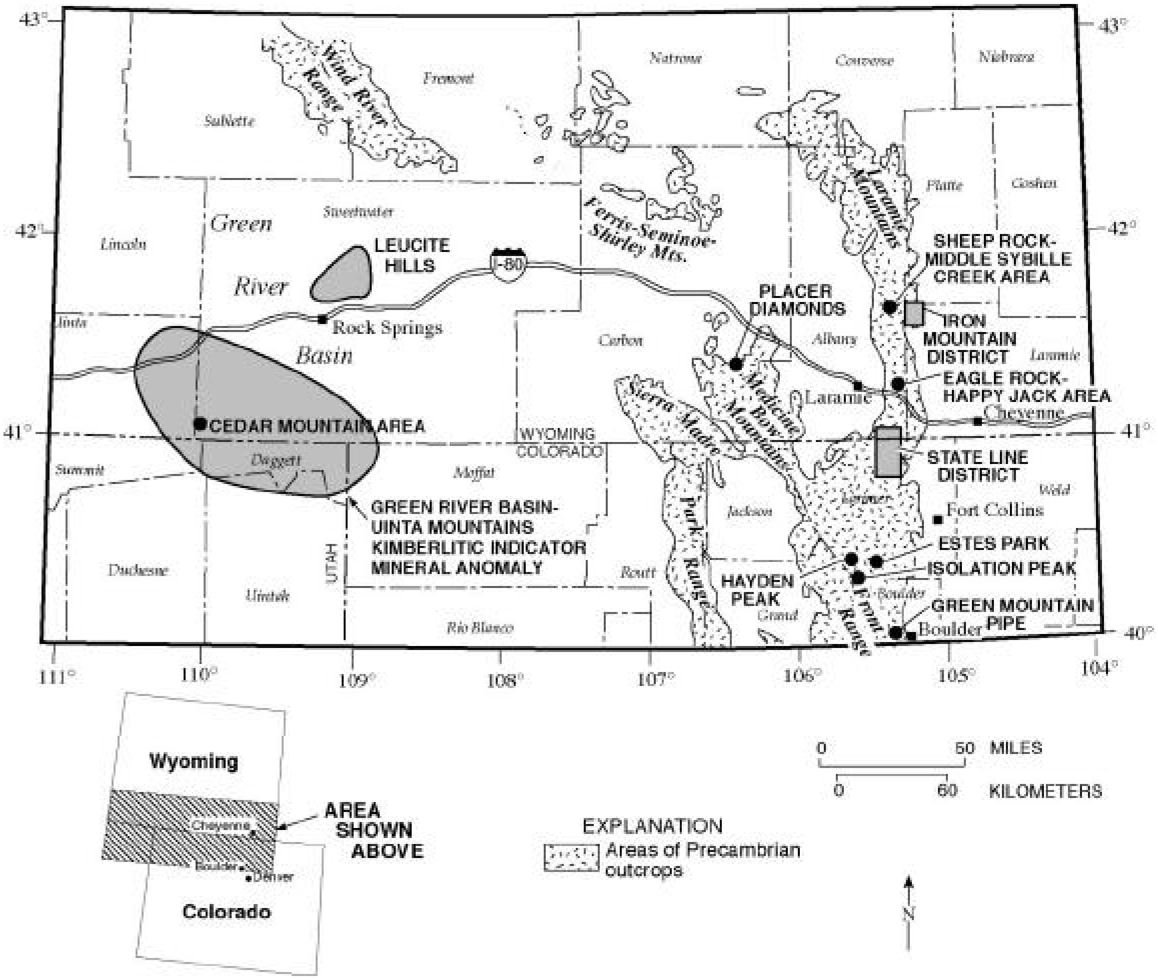

FIGURE 3 Southern Wyoming showing locations of kimberlites, lamproites and anomalies (from Hausel 1998).

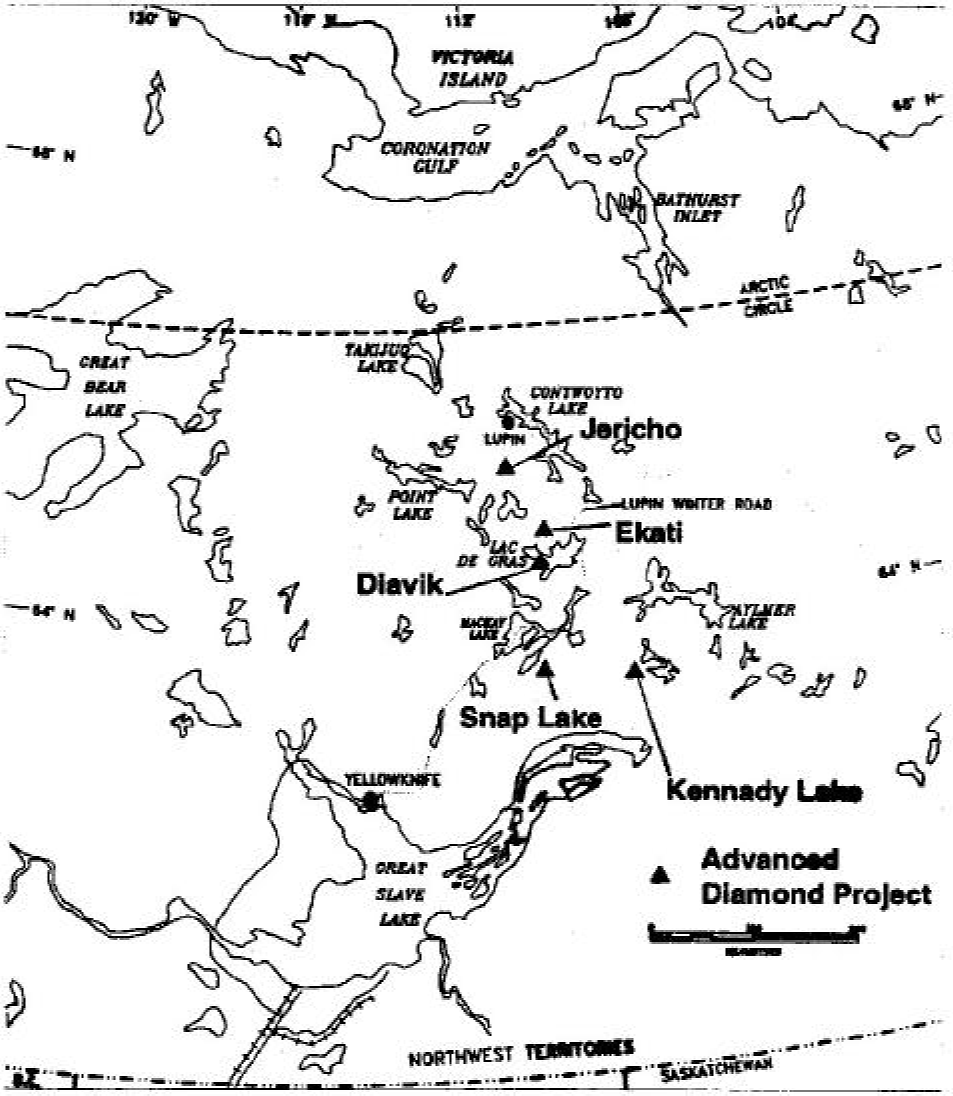

FIGURE 4 Northwest Territories and Nunavut kimberlite and diamond mine localities.

Figure 5 Aerial view of the Sloan 5 kimberlite, Colorado-Wyoming State Line district, showing distinct vegetation anomaly (high growth of grass and no trees) along a distinct lineament (photo by Hausel).

Quarrying history and use of Berea Sandstone in northeastern Ohio

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ABSTRACT

The Late Devonian Berea Sandstone is one of the best known and most studied sandstones in the world. It has been widely used as a dimension stone and for grindstones, and in the subsurface it is a source of water, oil, and gas. It is also a permeability and compression-strength standard.

Berea Sandstone has been quarried, beginning in the 1820s, from a number of northeastern Ohio counties, including Cuyahoga, Erie, Summit, and Lake Counties. Berea Sandstone continues to be quarried today in small amounts in eastern Erie County. Some of its historic quarries in northeastern Ohio have been illustrated and described in geological publications and works on local history, but other quarries have been poorly documented or not documented at all. It is difficult to find information on the earliest quarries. Some of the best information is available for late nineteenth and early twentieth century quarries: the extent, as well as the location, of historic quarries is depicted in atlases published in the later 1800s and the first decade of the twentieth century; and production statistics and other information can be gleaned from the non-population schedules of the 1880 census.

The historic quarries vary in terms of both geographical aspect and geological facies. Quarry types range from shallow quarries developed in a lowland wetland in western Cuyahoga County, to much more extensive, and very deep quarries developed in extremely thick Berea deposits in Lorain County associated with subsidence of a Devonian delta located in that area.

Most, but not all buildings that have been identified in historic works, and even corporate literature, as being made of Berea Sandstone are actually made of this stone. The stone used for buildings has in some cases been confused with various other rock units of northeastern Ohio. In many cases, Berea Sandstone used for buildings and other structures can be identified by one or more of the following: fine- to medium grain size; modal clast composition; small ferruginous spots; distinctive planar and color delineated horizontal bedding; microfaulting; and a variety of ripple marks characteristic of both unidirectional and oscillatory flow.

Hannibal, Joseph T., Saja, David B., Thomas, Sabina F., and Hubbard, Dennis K., 2006, Quarrying history and use of Berea Sandstone in northeastern Ohio, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

The Berea Sandstone (also known historically as the Berea grit) is one of the most famous rock units of North America, primarily because of its long quarrying history, its use for historic structures in major American cities, and its use in a variety of studies of rock properties. The Berea was one of the most important sources of grindstones in the 1800s and early 1900s. Indeed it may have produced more grindstones than any other locality in the United States or even in the world (Van Horn, 1931, p. 111). It was also one of the most highly desirable dimension stones used in the nineteenth century and early twentieth century (Bates, 1969, p. 104), and contains water, oil, and gas in the subsurface. The Berea, because of its relative homogeneity, has become a standard for various kinds of analysis involving rock cores and slabs. These analyses include, for example, studies of porosity and permeability, and rock strength (Menéndez and others, 1996). It has also figured in studies of weathering by Winkler (1997) and others.

GEOLOGY OF THE BEREA SANDSTONE

The Berea Sandstone extends from Pennsylvania and West Virginia into Kentucky and Ohio. It overlies the Bedford Formation (shale to fine sandstone) and deeper-water dark shales (Figure 1). Sediments were delivered from the uplifted ancestral Appalachian Mountains to the east. The age of the sandstones remains contested, but the Berea and associated rocks separate the thicker Catskill (Devonian) and Pocono (Mississippian) siliciclastic sequences of similar origin (Ettensohn and Barron, 1981). Many geologists, however, now consider it to be Late Devonian (Famennian) in age (Pashin and Ettensohn, 1995). Determining the precise environments of deposition is hampered by the same characteristic that makes the Berea Sandstone so valuable— its uniform texture. Grain size usually decreases with falling energy level. However, for reasons that remain unclear, sediments that were delivered from the eastern source were of uniform size, and sediment characteristics remain constant throughout the Berea. Nevertheless, other useful indicators are well represented in ample outcrops and have been used to constrain a possible scenario for the deposition of the Berea Sandstone in the vicinity of the quarries that are the topic of this contribution.

Sedimentary environments grade from coastal plain in the east to a restricted basin in the west, crossing a shoreline somewhere in Cuyahoga and Lorain Counties. These environments shifted westward as sea level fell, creating a vertical sequence that grades from nearshore near the bottom to flood plain near the top. Paleocurrent directions (that is, the direction water was flowing as reflected by sedimentary structures such as ripples) vary, but generally infer open water to the west and north.

In north-central and northwestern Ohio, the Berea Sandstone thickens dramatically (Figure 1), the result of subsidence as Berea sands were deposited on weaker and more fluid Bedford muds. The quarries are sited to take advantage of this local thickening. Within the western quarries well-developed channels can be seen, especially near the tops of the walls (Figure 2). On a smaller scale, unidirectional ripples are ubiquitous and reflect flow to the north and west (Figures 3, 4C). The planar bedding that is the hallmark of the Berea Sandstone often reflects past beaches (Figure 4B).

HISTORIC QUARRIES

Berea Sandstone was one of the first sandstones to be quarried in Ohio, and this stone was used for important early historic structures in south-central Ohio (Wolfe, 2004). These structures include the first Ohio statehouse, constructed in 1801. The very earliest history of the quarrying of Berea Sandstone in northeastern Ohio is difficult to pin down, but some accounts date the activity as beginning perhaps as early as the 1820s. Records from the 1880 census (U.S. Census, 1850–1880), however, date quarries still operating at that time back as far as the 1830s and 1840s, with additional quarries opening in northeastern Ohio later in the nineteenth century (Table 1).

TABLE 1 Examples of Berea Sandstone quarries in operation in northern Ohio, between 1 June, 1879 and 31 May, 1880, from 1880 products of industry reports of the census (U.S. Census, 1850–1880)

Name	Location	Year opened	Stone type (census name)	Mode of transportation	Principal market(s)
Berea Stone Company	Berea, Cuyahoga Co.	1830	sandstone	railroad	U.S. and Canada
J. McDermott Co.	Berea, Cuyahoga Co.	1830	sandstone	railroad	U.S. and Canada
Baldwin Quarry Co.	Berea, Cuyahoga Co,	1874	sandstone	railroad	U.S. and Canada
Murpheys works	Middleburgh, Cuyahoga Co.	1858	sand stone	rail	Cleveland
Lake Abraham Quarry no. 1	Middleburgh, Cuyahoga Co.	1874	sand stone	rail	Cleveland
Lake Abraham Quarry no. 2	Middleburgh, Cuyahoga Co.	1870	sand stone	rail	Cleveland
J. R. Hurst	Independence, Cuyahoga Co	1840	sand stone	wagon & canal	Cleveland
J. Kinzer	Independence, Cuyahoga Co	1848	sand stone	wagon & canal	Cleveland
T. Smith	Independence, Cuyahoga Co.	1871	sand stone	wagon & canal	Cleveland
G. A. Baillie	Berlin Township, Erie Co.	1872	sand stone	rail & water	New York, Detroit, and Chicago
J. S. Lowry	Berlin Township, Erie Co.	1877	sand stone	rail	Detroit, Cleveland, and Toledo

[1] Unfortunately the census data for Lorain County, the site of important nineteenth-century quarries and the center of the industry for much of the twentieth century, does not seem to have been preserved.

There may be up to one hundred or more historic Berea Sandstone quarries in northeastern Ohio. Many of these were small and have never been mapped. Most, but not all of the quarries, are located along streams or near the Berea escarpment and Berea highlands. A prominent exception to this are the historic quarries located in Bradley Woods Metropark in southwestern Cuyahoga County. These quarries are not developed along a major stream or a Berea high, but instead are located in a lowland wetland between two raised glacial lake ridges. Figure 5 shows the distribution of representative quarries throughout the region. The actual number of individual quarries is much higher than that shown.

Documentation of historic quarrying activity can be found in a wide range of publications, including Orton's (1884) report on sandstones and Bownocker's classic 1915 *Building stones of Ohio*, which devoted more space (47 pages plus several plates) to the Berea Sandstone than to any other building stone. The Berea Sandstone is also noted in most classic works on building stone such as those of George Merrill (1891) and Oliver Bowles (1917, 1939). The quarrying industry is featured prominently in a number of local histories, such as those for northwestern Cuyahoga County (Holzworth, 1970), the towns of Independence (Miller and others, 1979) and Amherst (Paschen, 2000), and the quarries at Berea (Sego, 1996). Recent work by organizations interested in preservation of historic structures have also added to the body of information on these quarries (Anonymous, 2004). Regional geologic reports, for instance that of Cushing and others (1931) on the Cleveland region, also note Berea quarrying, as do recent guidebooks (Hannibal, 2006). Data in addition to that listed on quarrying activity in Table 1 can be found in census schedules of the 1880 census (U.S. Census, 1850–1880). Quarries also appear in the 1850 non-population schedules, but these schedules provide less information than those for 1880.

The location of late nineteenth-century quarries can be found on topographic maps and in county atlases (see, for example, Lake, 1874a, 1874b). The atlases show quarry locations as well as landowners. Some atlases and histories also illustrate quarry scenes that allow one to see the technology used at the time (Stewart and Page, 1874, p. 24; Williams, 1879). Quarries that have remained active are noted in the yearly reports of the Ohio Division of Geological Survey (see, for instance, Wolfe, 2002).

EXAMPLES OF BEREA SANDSTONE QUARRIES

Since the number of Berea Sandstone quarries is so large, it is impossible to include detailed information on each of them in this article. Instead we describe the "type area" of the Berea first, in more detail, and then provide information on the important Amherst area quarries.

The quarries at Berea

Berea, Ohio, the type locality of the Berea Sandstone, is located just southwest of Cleveland. Because it was close to a rapidly growing city, Berea was the site of the first really large-scale quarrying of Berea Sandstone. Here the rock unit was first quarried for use as grindstones, and, soon thereafter, for building stone. The beginning and development of quarrying activity at Berea are recounted in a number of historical sources.

John Baldwin described his discovery (made ca. 1833, but sources vary on the date) of the sandstone at Berea as follows:

> …Something impelled me, I knew not what, to return to my home, by way of a new route and a longer way that would take me across the river on my farm. Obeying the impulse, I soon found myself across the stream, which at that time was very low, and I could pass over on exposed rocks. Suddenly I noticed a piece of rock that had but recently been broken off. I picked it up and examined its texture and quality of grit. I took from my pocket my knife [and sharpened it]. 'This,' I said to myself, 'will make superior grindstones'. (Webber, 1925, p. 45)

This, however is just one version of the story describing the discovery of the Berea Sandstone. Other accounts claim that the 28-year-old Baldwin discovered the sandstone while digging for the cellar of his house (Hatcher, 1949, p. 199), or that the Berea Sandstone had already been known to be a useful grindstone (Baldwin, 1874) and that Baldwin was just the one with enough entrepreneurial spirit to make a business out of the outstanding sharpening qualities of this local geologic gift.

While watching Jonathan Vaughn's log mill in Berea, John Baldwin conceived of the idea of using a rotating shaft and lathe and the hydropower of the Rocky River for cutting the sandstone into grindstones. Not much later, he walked to a Cleveland foundry with a whitewood pattern for a mold to a shaft and mandrel for his new stone-cutting enterprise at Vaughn's log mill. His construction worked and eventually the grindstone production began expanding. Contemporaries compared the frantic land purchases and leases for the purpose of quarrying in the following years to the Gold Rush in the West. Hundreds of acres of land were acquired and held in the form of stocks. Tracts contained lots of one-quarter acre each or anywhere from one to ten acres. Remaining parcels were sold to mechanics, gardeners, and "other respectable moral persons" (Sheldon, 1935). In Berea the area of quarrying operations extended a mile in northern, southern, and western direction from the center of the city.

At Berea the sandstone is very close to the surface, gently dipping towards the south at a rate of twenty feet to the mile. The average range of thickness of the sandstone "veins" is between twenty and sixty-four feet. The pebble-free "Berea ten foot sheet" (at its minimum only six inches thick) was by far the most valuable of the area's building stones, yet it lay about 26 feet below the surface, under layers of soil, and the Orangeville Member of the Cuyahoga Formation.

Rock chosen for the fabrication of grindstones had an even texture with just the right hardness, and was free of flaws such as cracks or impurities. The Berea was also noted for its resistance to glazing when used for dry grinding (Orton, 1880, p. 582). Inferior rocks, that is those that could not be easily split or sawn or that contained pebbles, were used for building purposes, paving blocks, and flagging for sidewalks and driveways, or for bridges, culverts, and foundation stone (Holzworth, 1986; Sego, 1996). Despite one negative geological evaluation in 1858 (Brainerd, 1874), sandstone from Berea become a very popular and valued dimension stone.

The quarrying processes in the Berea area started with the "stripping" of the overlying layers by steam shovels (Figure 6). Soil and shale were loaded onto trains and transported to exhausted quarries as landfill. Train tracks had to be shifted frequently. The railroads, originally financed by John Baldwin and drawn by oxen and later "pony" engines, crisscrossed the Berea area between the quarries and the depot between 1876 and 1886. Finally, in 1862, the Cleveland, Columbus, Cincinnati, and St. Louis Railroad companies added switches to the Berea quarries. Ox-drawn wagons were an additional mode of transportation to Cleveland. Boats from the Cleveland docks also carried stone to its destination.

Early quarrying involved trenching: Narrow slits were cut manually into sandstone, to a depth of eleven feet. The introduction of the steam engine in 1888 increased efficiency and accuracy of the process, which then was called channeling. Light blasting or pneumatic drilling broke the blocks free. Yet the work remained dangerous. Not only was there the potential for a boiler to become overheated and explode, but steam shovels did tip over and workers were scalded to death. Due to the ever-changing work areas within and around the quarries, structures were often carelessly put together. Wires and cables frequently snapped or slipped; derricks collapsed (Figure 7).

"Grit consumption" or "grindstone consumption" (silicosis) was common among the workers and often ended fatally (Howe, 1908, p. 525). John Baldwin's son, John Baldwin Jr., remedied the problem by blowing the rock dust out of the range of the quarrymen (Figure 8A). In addition, there was always the potential of being injured during the blasting of the rock, first with gunpowder and later with dynamite. Mickey Sego (1996) gives a lively account in "Life as a quarryman" in his history of the quarries.

After the trenching or channeling, the sandstone was lifted and transported to the mills where saws cut grindstones, whetstones, gravestones, bases for gravestones, curbstones, and building blocks. Holes for grindstones were cut and squared by hand until David E. Stearns introduced a saw for that purpose in 1846. During the peak of production, 65,000 cubic feet of dressed stone were shipped out on a monthly basis.

In February 1871, the Berea Stone Company formed from a merger of several quarry companies. The company owned 37 acres of land, had dozens of derricks, and employed around 100 men. In 1873 James McDermott & Co. pulled away to found an independent company in Berea (Figure 8B). After incorporated in July, 1886, the Cleveland Stone Company took over the McDermott enterprise, consolidating all remaining Berea quarries and several in Amherst, about twenty miles away. Later, in 1898, the McDermotts founded the McDermott Stone Company. (A "Timeline of quarry operations in Berea" can be found in Sego's history (Sego, 1996).)

During the last few decades of the 19th century, the reputation and use of the Berea Sandstone increased (see, for example, Newberry, 1873, and Peebles, 1908). Soon the Berea Sandstone replaced building stones and, especially grindstones, from France, England, and Nova Scotia. Berea once provided 85 percent of all the grindstone production in the United States (Bownocker, 1915, p. 116). "Grindstones were shipped throughout the United States, to Canada, to South America, to Europe, and even as far as Australia and Japan" (Hannibal, 1985). Yet Berea also produced fashionable building material, and even President Theodore Roosevelt was said to have been familiar with Berea and its quarries. But, as F. Holzworth (1970) pointed out, most of the financial support for the Cleveland Stone Company came from outside of Berea, and that the city of Berea was constantly forced to change its face. Neither houses, regardless of the exclusiveness of the district, nor streets, stores, cemeteries, or the Rocky River itself, could compete with the quarrying activities and the interests of the directors and stockholders of the Cleveland Stone Co. (Figure 9). Some buildings of historic importance, such as John Baldwin's original dwelling and the entire Baldwin University campus (founded by John Baldwin), were carefully taken apart and moved to different locations.

In 1893, the Cleveland Stone Company, now the only quarry operator in Berea, reduced wages, claiming that this measure would enable them to keep the quarries open. The company promised that wage levels would come back once the recession was over (Sego, 1996). Yet in 1896, after recognizing that sandstone orders had actually been steady and not decreasing, workers became restless and finally organized a six-week strike. The strike led to confrontations between workers and the local officials. After arbitration hearings the strike ended by mid-July. Wages eventually returned to the rate of 1893 (Sego, 1996). The quarries remained the key employer in Berea into the early twentieth century, with an estimated three quarters of the town's population directly or indirectly owing their livelihood to the quarries (Peebles, 1908).

During the 1920s, the signs of decline for the quarrying industry started to emerge. In 1922, the Cleveland Stone Company acquired the Sterling Grinding Wheel Company of Tiffin, Ohio, anticipating that artificial abrasives like carborundum would eventually be a more profitable substitute for natural sandstone. Concrete became increasingly popular as building material for roads and sidewalks. Other competitors for the natural-stone market were Indiana limestone (making up the facing on Cleveland's Terminal Tower), limestone from western Ohio, and Euclid bluestone from northeastern Ohio (Hannibal, 1985).

A few months prior to the stock market crash in October of 1929, the Cleveland Quarries Company appeared from the merging of the Cleveland Stone Company and the Ohio Quarries Company. Only a year later test borings indicated that the best sandstone in the active Berea quarry areas was gone for good, but a valuable 65-foot-thick deposit was located to the northeast, but was never exploited.

During the following five years, the quarrying activities in the city of Berea died down. Many thought that this development was actually for the better because they felt that the town had lost so much of its charm and character to the exploiting quarrying companies. One evening in 1936, "Old Jumbo," the large steam whistle announcing the end of the workmen's day, fell silent. Minimal quarrying continued until 1939 and a grindstone and curbing factory kept operating until October 21, 1946 while "ironically working on sandstone imported from the Cleveland Quarry Company's Amherst operations" (Sego, 1996).

A year later, the Cleveland Metropolitan Park Board purchased some of the old quarries and gave it back to Berea and the public, albeit at a cost to the citizens of Berea. Now part of the Metropark system, Baldwin Lake and Wallace Lake serve recreational purposes and as Berea's primary water reservoir.

The Amherst quarries

Lorain County has enormous deposits of sandstone located at or near the surface. Various geological reasons have been given for the great thickness (to > 200 feet) of Berea here (Figure 1). Pashin and Ettensohn (1995, Figure 29) called this the quarrystone facies of the Berea. "The story of sandstone and the Cleveland Quarries Company," a pamphlet of the Cleveland Quarries Company, claimed that the company was the world's largest producer and fabricator of sandstone (Cleveland Quarries Company, ca. 1954).

Henry Warner first opened a quarry near Brownhelm Township in Lorain County in the 1840s. John Worthington, a contractor from Toronto, soon purchased this operation and expanded the business. Other quarries were opened in the area in the 1840s and 1850s (Paschen, 2000). In 1869, the renowned Gray Canyon Quarry, Quarry No. 6 (Figure 2), was opened. In 1871, a railway connection was made between Brownhelm and Lake Erie at the port of Vermilion. Quarry No. 6 grew to what was, allegedly, the largest single sandstone quarry unit in the world (Amherst Historical Society, 2005; see also Anonymous, 1912). Quarry No. 6 has produced close to half a billion cubic feet of quality sandstone over the last 100 years. The dimension blocks weighed up to twenty, and sometimes forty tons. In 1903, John H. Walsh acquired land for the nearby Buckeye Quarry, which was quarried 240-feet deep and which grew to a size subequal to that of Quarry No. 6 (see Figure SA-1 in Potter and others, 1983). By the end of the nineteenth century, the Cleveland Stone Company had bought out the interests of the major northeastern Ohio quarries, including most of those in the Amherst area. By the early part of the twentieth century, stone from the Amherst area was considered superior to other Berea deposits as a source of dimension stone (Hannibal, 1985). The last great consolidation was in 1929, when the Cleveland Quarries Company purchased the Ohio Quarries Company, the owner of the Buckeye Quarry. At that time the newly expanded company became the Cleveland Quarries Company. The history of the Amherst quarries in many ways has mirrored that of the Berea quarries. Paschen (2000) has recently provided a detailed survey of the quarrying history of the Amnerst area and its influence on the growth of Amherst.

The list of uses for the Amherst Sandstone (Cleveland Quarries Company, ca. 1954, ca.1970) is impressive: It was used for building stone, cut stone, house ashlars, cupola blocks, soaking-pit linings, chemical vats, sidewalk stone, grindstones, curbing, garden stone, flagging, breakwater, silica sand, ladle linings in connection with the manufacture of steel (Pugh type), in foundries for cupola lining, for sand in refractories, Bessemer converter linings, laboratory table tops, and highway aggregate.

Like the Berea quarries, the Amherst quarries experienced a history of successes and setbacks. Mobile cranes began to replace guy derricks in the late 1950s (Anonymous, 1958). Despite cost savings due to more efficient technology, however, the economic situation became acute towards the end of the twentieth century. (A timeline of the sandstone industry in the Amherst area can be found in the *Chronicle-Telegram*, March 8, 1992, as part of the article asking, “How can it be over?” (Hicks and LeVeck, 1992)).

In March of 1992, the Cleveland Quarry Company announced that the firm would cease operations on April 30, 1992. The decision became necessary because the company was “unable to continue to operate without incurring substantial losses.” The downturn was blamed on construction and changes in the materials used. Most architects of the time were using glass, steel, limestone, and granite when designing factories and buildings, and sandstone was used mostly to replace stone in existing structures. Carborundum replaced sandstone as a hard material for grinding. Synthetic materials were lighter-weight, less expensive, more easily sculptured than natural stone. In addition, sandstone was more expensive to cut.

Soon after that announcement, American Stone Industries Inc. of Toronto (then called Slate & Stone Corp. of America) bought the quarries. Headlines from April 22, 1992 read: “South Amherst quarries to remain operating” because of a sudden increase in customer orders.

In spite of American Stone Industries’ promise to revitalize the operation, the quarry almost closed again at the end of 1995. There was a dispute between American Stone and the municipalities where part of the quarries’ 1,100 acres are located. Finally, new management, and increased demand, instituted changes that resulted in 43 workers cutting sandstone again in 1996. In March of 1998, American Stone Industries Inc. of Amherst reported a fourth-quarter improvement from the net loss for the same period one year previous.

A list of sandstone products of the Amherst Quarries can be found at Cleveland Quarries’ current website (2004). Dimension stone continues to be produced. Various types of landscape stone, and even grindstones are still available (Cleveland Quarries personnel, personal communication, 2006).

The Berea Sandstone quarries in the Amherst area, consisting of about 900 acres, were sold recently to a developer who was to begin work on a large complex of housing, hotels and recreational facilities in June of 2006 (Sangiacomo and Matzelle, 2005). The project, however, has been delayed (Sangiacomo and Matzelle, 2006). The Cleveland Quarries Company continues to quarry the Berea in its Birmingham quarries in eastern Erie County. Manufacturing facilities are located in South Amherst.

BEREA SANDSTONE BUILDINGS, OTHER STRUCTURES, AND CORES

A great number of buildings and other structures (Williams, 1879, p. 336; Orton, 1884; Cleveland Stone Company, ca. 1890; Masten, 1900) have utilized Berea Sandstone from northeastern Ohio. These include the Michigan State Capitol and a multitude of buildings in Ohio and other eastern states and provinces. Trim of Berea Sandstone is also common in the same region. Examples of buildings that are made with the Berea are listed in Table 2. Care must be taken, however, in identifying a structure as being composed of the Berea. Not all buildings that have been identified in historic works, as being made of Berea Sandstone are actually made of this stone, however. The Berea used for buildings has in some cases been confused with various other rock units of northeastern Ohio (see examples in Table 3).

TABLE 2 Examples of buildings and other structures constructed mainly of Berea Sandstone

Name	City	Year completed or dedicated	Quarry location
Old Stone Church[1]	Cleveland, Cuyahoga Co.	1854	Lorain Co.
Cleveland Viaduct	Cleveland, Cuyahoga Co.	1878	Berea, Cuyahoga Co.
Soldiers and Sailors Monument	Cleveland, Cuyahoga Co.	1894	Amherst area, Lorain Co.
Lindsay-Crossman Chapel	Berea, Cuyahoga Co.	1872	Berea, Cuyahoga Co.
Peters Hall	Oberlin, Ohio	1885	Amherst area, Lorain Co.
City Hall	Cincinnati, Ohio	1893	Amherst area, Lorain Co.
Michigan State Capitol	Lansing, Michigan	1879	Amherst area, Lorain Co.
Carnegie Building	Pittsburgh, Pennsylvania	1895	Amherst area, Lorain Co.

[1] According to Williams, 1879, p. 248. Some other sources do not agree on this quarry location.

TABLE 3 Examples of buildings and other structures said to be constructed mainly of Berea Sandstone but actually constructed of other stone or vice versa.

Name	City	Year completed or dedicated	Stone used
Old Stone House[1]	Lakewood, Cuyahoga Co.	1838	siltstone from the Ohio Shale
St. Vincent de Paul Church[2]	Akron, Summit Co.	1867	Sharon Formation
Squier's Castle[3]	North Chagrin Metropark, Cuyahoga Co.	1890s	Berea Sandstone, but identified as Euclid bluestone

[1] Identified as Berea Sandstone by Butler (1949).

[2] Identified as Berea Sandstone by McGovern (McGovern, 1996).

[3] Identified as Euclid bluestone on a plaque outside of the building.

Berea Sandstone has been produced and sold under various names, including Ohio sandstone, and has just been called sandstone and sand stone (see Table 1). Census reports for Ohio sandstones only distinguish sandstone from flag-stone and blue-stone. Traditionally, as is the case with many other building stones, some stone has been named for the township or city which produced it. Berea Sandstone from the Amherst area had been called Amherst Sandstone. In recent years the Cleveland Quarries Company has sold two main varieties of stone, Amherst gray (also called Berea gray) and Birmingham buff. These two main color varieties of stone continue to be available.

As a final note, the place of origin of cores used in studies of porosity, fluid flow, and fractures is not always, or is misleadingly, noted in studies. Most slabs and core of Berea Sandstone utilized in recent studies have been from the Cleveland Quarries' Birmingham quarries, located in Erie County.

IDENTIFYING BEREA SANDSTONE USED FOR HISTORIC STRUCTURES

In many cases, Berea Sandstone used for buildings and other structures can be identified by one or more of the following features: fine to medium grain size (using the standard geological sand-size classification); modal clast composition; and small ferruginous spots. More information on composition can be found in a number of works (see, for example: Pepper and others, 1954; Potter and others, 1983; Pashin, 1990; Pashin and Ettensohn, 1995; Menéndez and others, 1996). The stone may have distinctive planar and color-delineated horizontal bedding; microfaulting; and a variety of ripple marks characteristic of both unidirectional and oscillatory flow (Figure 3).

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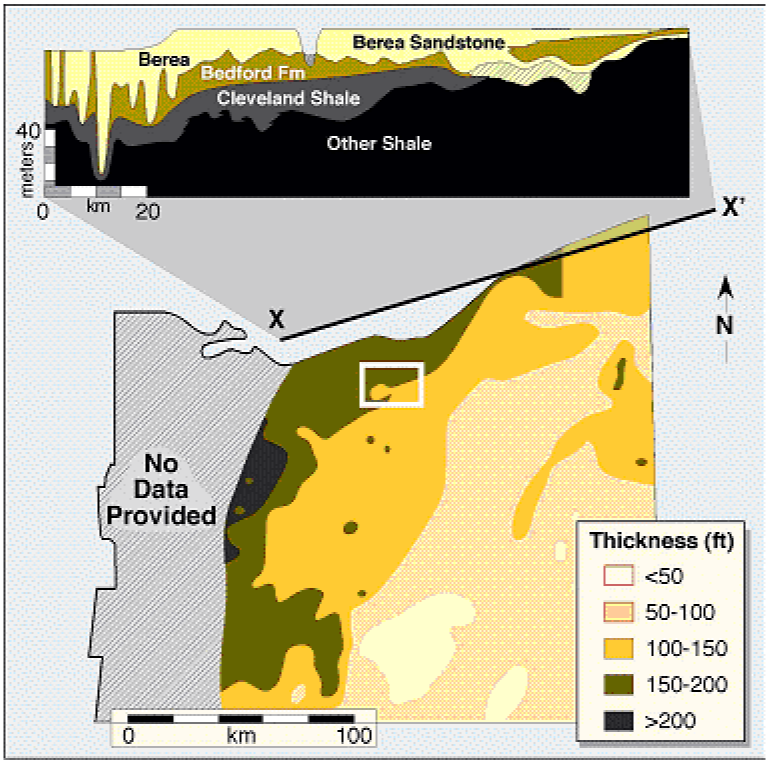

FIGURE 1 **Thickness of the Berea Sandstone across northern Ohio. The thickest (darkest) deposits are probably related to subsidence during deposition of coastal deltas, a pattern similar to the present-day Mississippi Delta. The pattern in the southern half of the state is the same. The quarries (white box) occur in areas where the sandstone exceeds 125 ft in thickness. The profile at the top shows a simplified cross section from west to east along the north shore. The quarries take advantage of the westward thickening that results from subsidence as Berea sands were deposited on more fluid Bedford muds beneath. Map and cross section after Pashin and Ettensohn (1995).**

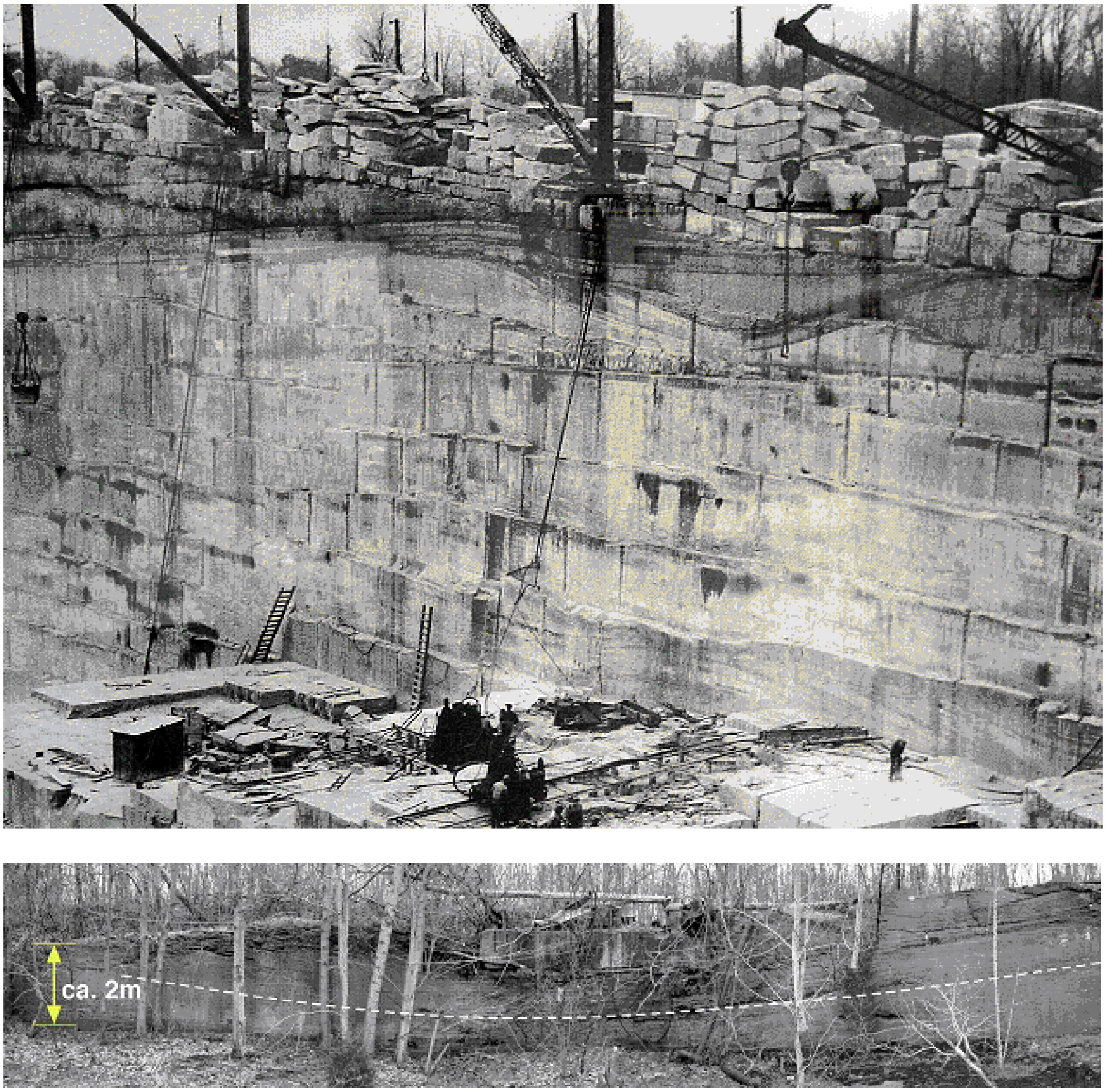

FIGURE 2 (Top) Wall of the Cleveland Quarries Company's Quarry No. 6, ca. 1950. Note the channel near the top of the wall. This and similar features (delineated by dashed line in bottom illustration from south wall of a quarry just to the south) were probably associated with the westward migration of fluvial environments over coastal and nearshore sediments as sea level fell. Photograph courtesy of Cleveland Quarries.

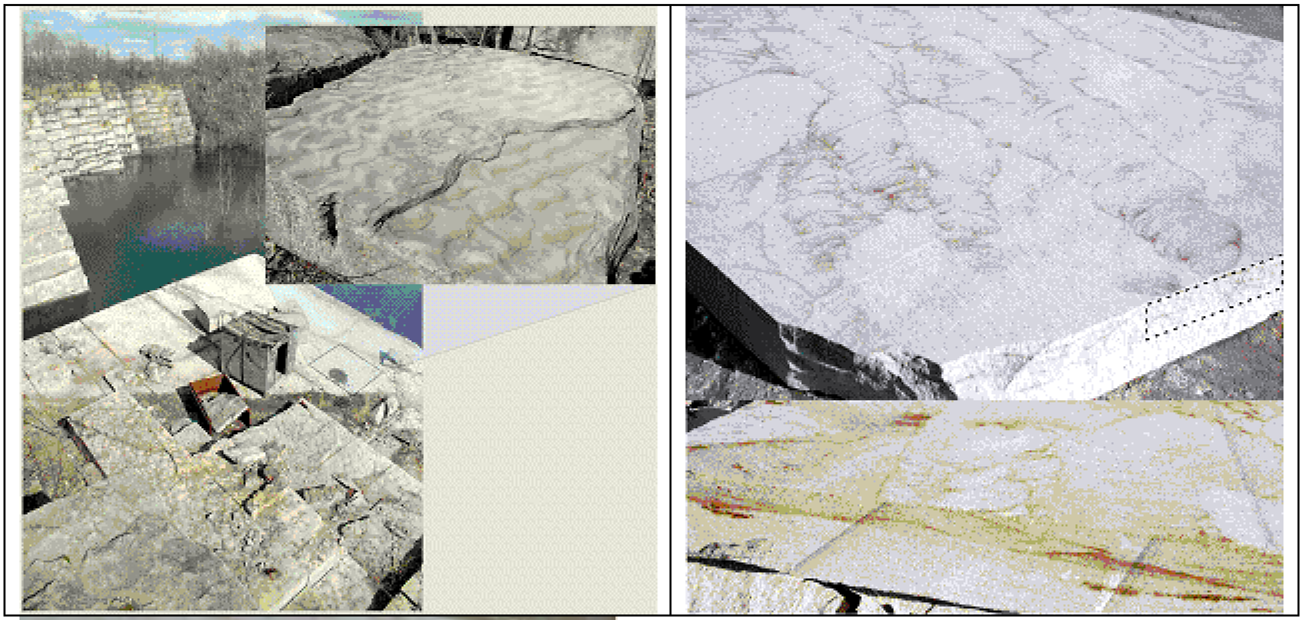

FIGURE 3 Photos of smaller-scale ripples in the Amherst quarries. On left, unidirectional ripples (inset) occupy entire bedding planes, such as the one exposed in the larger photo. These ripples reflect flow to the NW. The scalloped pattern on the bedding plane in the right photo is probably caused by the intersection of these ripples as they migrate in the currents, in this case toward the lower right. Features delineated by dashed box on vertical face in the right photo are seen enlarged in the lower portion of image.

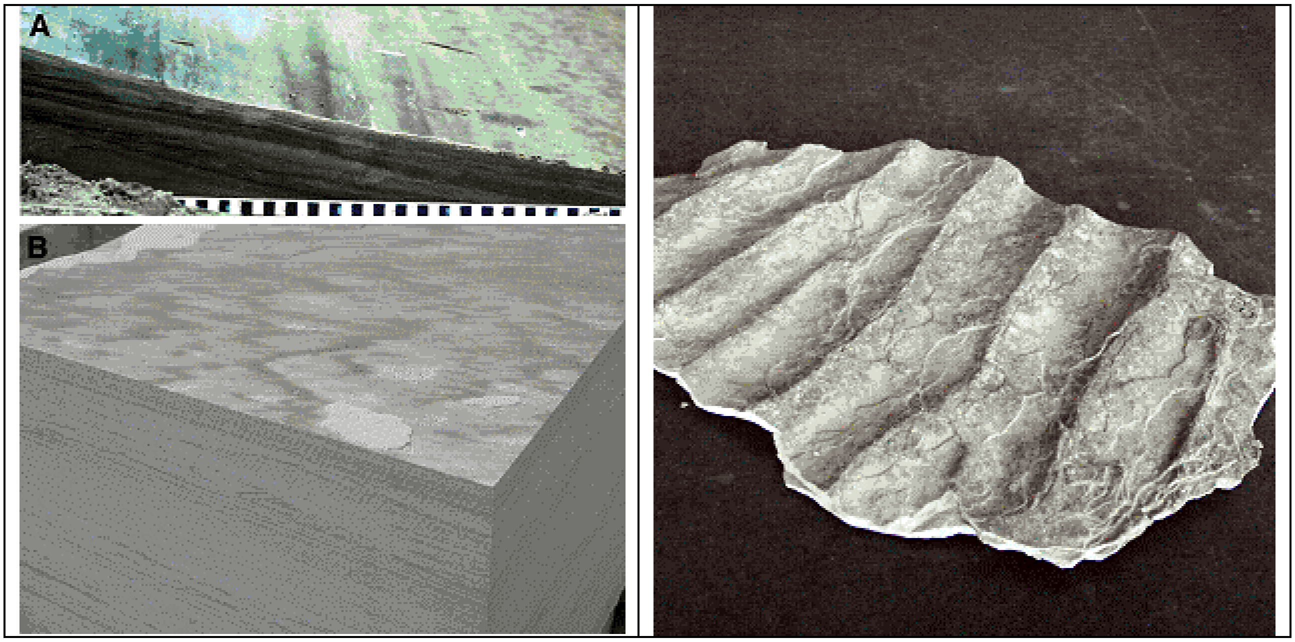

FIGURE 4 A) a trench through a modern beach, B) block of Berea Sandstone with planar beds reminiscent of modern beaches, both in cross section and along bedding surfaces, C) symmetrical ripples collected near Berlin Heights, Ohio, caused by waves approaching from open water to the west. The intimate association of these features with the delta sediments and planar beach beds infers coastal and nearshore environments for the lower sections of the Berea Sandstone.

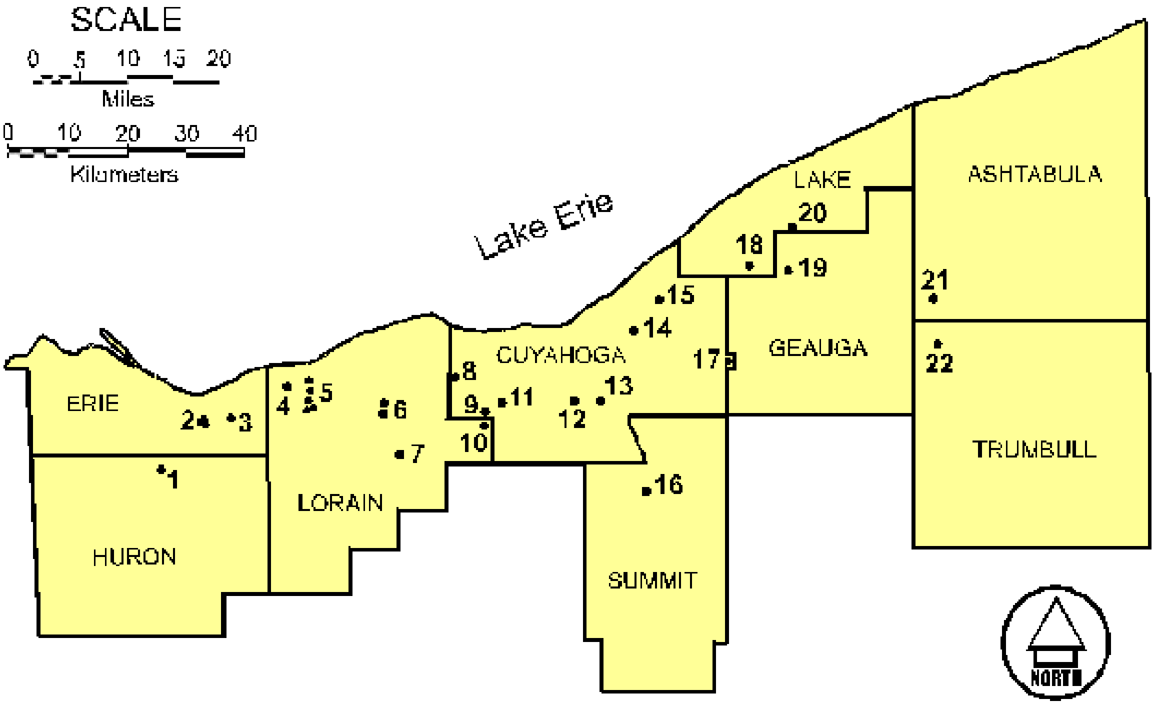

FIGURE 5 Map showing nine northeastern Ohio counties (colored yellow) and representative localities (black dots) where Berea Sandstone has been quarried. Many of these localities actually consist of a complex of individual quarries. The quarry localities are: 1) northeast of Norwalk, Huron County, 2) Berlin Heights, Erie County, 3) Birmingham, Erie County (the last remaining active Berea Sandstone quarry in the region), 4) the Brownhelm area, Lorain County, 5) Amherst area, Lorain County, extending from northern Amherst south to central South Amherst, and including the largest and deepest Berea Sandstone quarries, 6) Elyria, Lorain County, 7) Grafton, Lorain County, 8) Bradley Woods Metropark, Cuyahoga County, 9) Westview, Cuyahoga County, 10) Columbia Township, Lorain County, 11) Berea, Cuyahoga County (a large complex of former quarries, now partly filled in and party preserved as lakes in a Metropark), 12) Parma, Cuyahoga County, 13) Independence, a series of small quarries, Cuyahoga County, 14) Doan Brook, Cuyahoga County, 15) Euclid Creek, Cuyahoga County, 16) Peninsula, Summit County (several quarries, one of which, Deep Lock Quarry, is the most visited Berea Sandstone quarry due to its location along and above the Ohio & Erie Canal and in the Cuyahoga Valley National Park), 17) Chagrin Falls, Cuyahoga County, 18) Chapin Woods Metropark, Lake County (probable site of the stone used for the Kirtland Temple), 19) just west of Chardon, Geauga County, 20) Southern Concord Township, Lake County, 21) Windsor Mills, Ashtabula County, 22) Mesopotamia, Trumbull County.

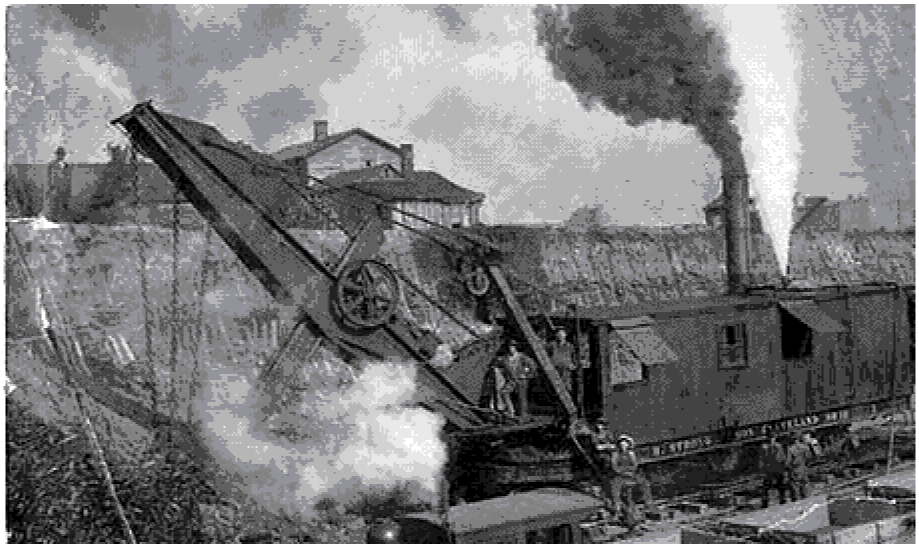

Figure 6 “Steam Shovel in use in one of Berea’s quarries.” Published by D.A. Beswick, Berea, Ohio. Dorothy M. McKelvey Collection, Berea Historical Society. Used with permission of the Berea Historical Society.

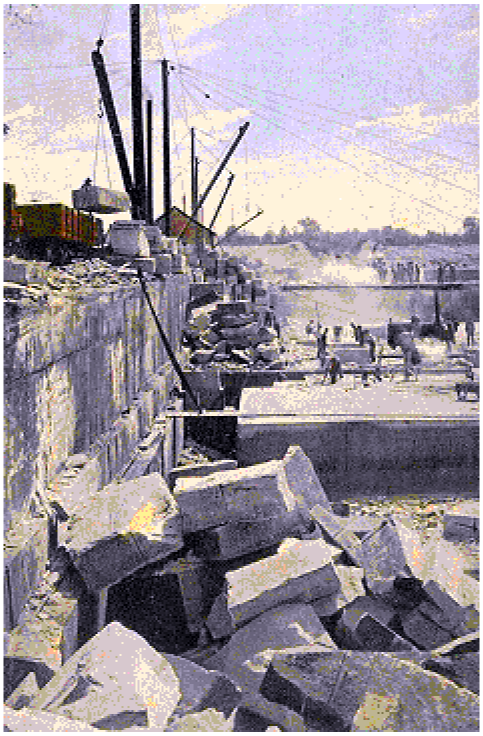

FIGURE 7 Colored postcard, “Grind stone factory, Berea, O.” Published by D.A. Beswick, Berea (made in Germany). Mildred Stevens Collection, Berea Historical Society. Used with permission of the Berea Historical Society.

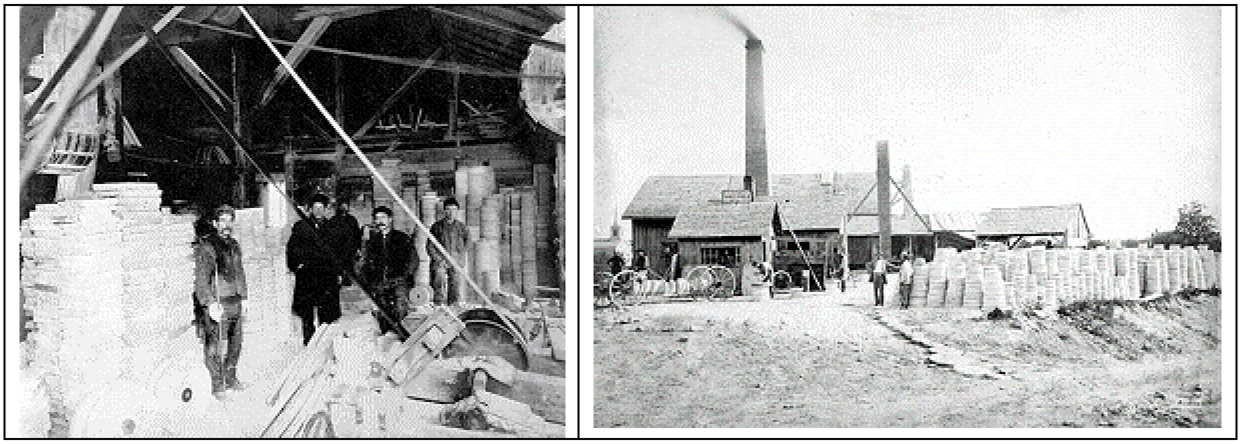

FIGURE 8 A) Grindstone factory, interior view, 1890s, showing rectangular sandstone blanks ready for grindstone production. A "Baldwin Blower" can be seen in the upper left corner of the photograph; Dorothy M. McKelvey Collection, Berea Historical Society. B) The McDermott Grindstone Factory, circa mid-1890s, with owner John McDermott leaning against stacks of finished grindstones in front. The factory was located on riverbank near present Baldwin Place Apartments on South Rocky River Drive. Photos used with permission of the Berea Historical Society.

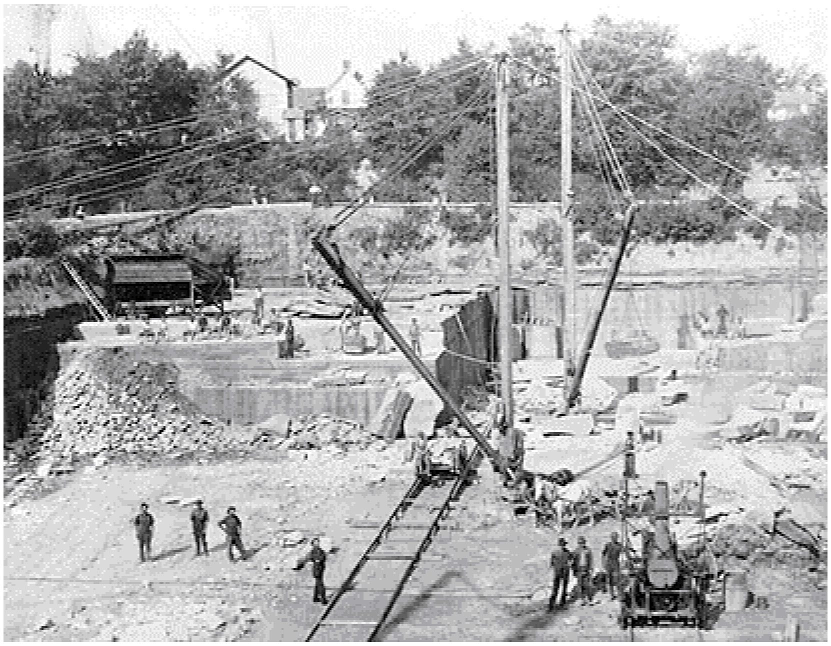

FIGURE 9 "Big Quarry – 1880 – Major Berea Industry." The residences in the background above quarry wall are on East Bridge St. Dorothy M. McKelvey Collection, used with permission of the Berea Historical Society.

Kipps' lime-magnesia: An unconventional agricultural lime and a 48-year perspective within the aglime industry

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ABSTRACT

Agricultural lime is an important soil supplement in pH control for optimal pasture and crop growth. Burnt lime has been the historic agricultural lime of choice, but between 1925 and 1973 Kipps' Lime-Magnesia won a share of the lime market in Shenandoah and Rockingham Counties, Virginia. A comparison of production methods for the lime from Meyers Lime Kiln with Kipps' Lime-Magnesia reveals an unconventional and economically competitive aglime.

The Kipps Quarry is situated on the eastern flank of Little North Mountain in southwestern Shenandoah County, Virginia. Advertised as lime-magnesia and as marl, the raw material is the fault breccia of the North Mountain Fault. The magnesium-rich lime product was marketed as an agricultural lime from 1925 – 1973. Initial processing consisted only of hand screening when this unburnt lime product was introduced at $3.00 a ton in a locality where burnt lime was marketed at $6.00 a ton. Sales records from 1925 to 1972 reflect the influences of mechanization, economy, climate, World War II, and market competition. In 1972 the Kipps Family sold the business and property to C.S. Mundy Quarries, Inc., who continued operations until the untimely death of their founder, Theodore Mundy.

Hubbard, David A., and Kipps, Elmer C., 2006, Kipps' lime-magnesia: An unconventional agricultural lime and a 48-year perspective within the aglime industry, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Agricultural lime is applied to soil to optimize pH for arable crop or pasture use. At near neutral pH, major plant nutrients are utilized more efficiently and some herbicides are more effective. Other benefits of liming include enhanced soil structure in clayey soils, which aids drainage, aeration, and root anchorage. Because calcium and magnesium are removed from soil by plant uptake and leaching, even soil developed on limestone (calcium carbonate) and dolostone (calcium-magnesium carbonate) bedrock may need liming.

The term *agricultural lime,* or *aglime*, refers to both lime (calcium oxide, also called *quick lime*, or in a hydrated state as calcium hydroxide, also called *slaked lime*) and limestone (or dolostone) materials. Lime is produced by calcining (burning) limestone (or dolostone). Historically, lime was produced in rock-constructed kilns. With the exception of marls (fine-grained, unconsolidated deposits of calcium carbonate) or limestone or dolostone fines that were the waste products of mining and milling other mineral commodities, limestone products could not economically compete with burnt lime until the development of relatively modern crushing and grinding technologies.

To contrast the uniqueness of Kipps' Lime-Magnesia (Figure 1), an annotated description of a nearby traditional lime operation is presented. Accounts of the actual operations of lime and other mineral producers are rare in the literature. Within most competitive industries, the release of detailed descriptions of methods and production figures can help competing producers in limited markets. Thus, the revelation of operation methods and production information for individual mineral producers provides an exceptional and important opportunity in our understanding of applied and economic geology. The Kipps operation is significant, because it spans a significant period of time and advances in technology.

MEYERS' LIME KILN

The Meyers lime kiln (Figure 2) was built of limestone from the New Market, Lincolnshire, and Row Park Formations by Christian Meyers in the early 1900s. It is located immediately east of the present town limits of Broadway, approximately 900 feet west of the intersection of State Highway 259 and State Highway 42, and south of State Highway 259 (Figure 3). This particular kiln was charged with a base course of wood and coke, followed by an alternate layer of high calcium limestone approximately 8 to 10 inches thick, overlain by a layer of coke approximately 4 to 5 inches thick, and so forth altering limestone and coke to the final limestone layer at the top of the oblong, brick-lined furnace chamber. The high calcium rock of the New Market Limestone was blasted from a small quarry, now covered with fill, a few hundred feet to the southwest and transported to the kiln by a railed cart. The charged kiln burned for a couple of days before the high-calcium limestone ($CaCO_3$) was completely oxidized to quick lime (CaO).

Harvesting the quick lime was an unenviable job. The men wore bandanas across their faces and shoveled as much of the still warm lime as they could before the lime dust and heat overwhelmed them. Quick lime is highly reactive with water in an exothermic reaction that can bring water to a boil. Exposed skin was seared as lime dust reacted with sweat. Some of the quick lime was hydrated by adding water to form slaked lime. Meyers' lime products included both quick and slaked lime.

Norvell Trumbo (personal communication, 2002) estimated that his grandfather Christian Meyers fired the Meyers Kiln three to four times a year from the early 1900s until 1928 or 1929. In addition to the use of this burnt lime for agriculture, customers used it for white-washing fences, tree bases, and roadside markers. Modern rotary kilns subsequently replaced the stone-constructed kilns for burnt lime production.

KIPPS' LIME-MAGNESIA

In marked contrast to the conventional quarrying and calcining of high-calcium limestone at the Meyers quarry and kiln site, the overlapping period production of Kipps' Lime-Magnesia brought about a significant change in the local lime market. The Kipps quarry is located on the eastern flank of Little North Mountain at a water gap, Kipps Gap, in southwestern Shenandoah County, Virginia (Figure 3) and sited on the North Mountain Fault. The mountain building forces that thrust older rock units over younger rock units, also crushed the rock along the zone of movement. The rock is a fault breccia and locally consists of ground matrix of dolomitic limestone (magnesium-rich calcium carbonate) and dolostone (calcium and magnesium carbonate) and coarser carbonate rock fragments of the Beekmantown Formation (foot-wall unit, or rock unit under thrust fault) and Elbrook Formation (hanging-wall unit, or rock unit displaced over foot-wall unit).

Beginning Operations

The initial idea for the quarry dates to the fall of 1914, after the rerouting of State Road 726 from streamside to a new hillside cut. A neighboring farmer from Hepner, located on the west side of Little North Mountain, stopped to examine the light olive gray colored soil exposed between tree roots in the new road bank. Satisfied by what he saw, John Runion, walked to the Kipps' house and asked if he could dig some "fertilizer." Somewhat surprised by the request, Elmer Allen Kipps told his neighbor to go right ahead and dig a load. Mr. Kipps subsequently sent a sample for identification and learned it was a carbonate of calcium and magnesium. Elmer Kipps knew that calcium and magnesium are important to plant growth.

In 1918, concern about his potential role in the World War prompted Elmer to sell his livestock and farm equipment and rent the farm before traveling to Washington, D.C. He was not drafted and although successful over the next few years in white-collar business in Washington, D.C., Elmer was intrigued about the commercial potential of his fertilizer. He learned that most agricultural limes were deficient in magnesium, which his lime product contained.

Elmer resumed management of his farm in 1922 by traveling back and forth between Washington and Getz, located 2000 feet southwest of present day Getz Corner, to supervise a full-time farmhand. In addition to replacing his farm equipment, he bought an end-gate spreader (Figure 4) with which to spread and test his magnesium-rich lime at the accepted rate of 2 tons per acre. The following year, he sent a sample of his magnesium-rich material for detailed analysis (Figure 5) and started promoting its use to friends and neighbors. He offered the lime-magnesia free for the taking and even loaned his spreader for its application. In 1924, Elmer married his sweetheart, Nenetah Kerlin, and moved back to Getz. Enthusiastic friends and neighbors, satisfied with the unusual magnesium-rich agricultural lime, were spreading word of Kipps' Lime-Magnesia. Locally, burnt lime was shipped into the Mt. Jackson area and sold for $6.00 per ton.

Elmer Kipps decided to price his lime-magnesia at $3.00 a ton to overcome any reluctance of farmers to switch to his new unburnt lime supplement. On the 22 August 1925, J.F. Lonas became the first customer of the new business by paying $6.00 for two tons of Kipps' Lime-Magnesia. By year-end, Elmer Kipps had sold 42.7 tons of agricultural lime (Table 1). The magnesium-rich ground limestone product of the Kipps' operation was registered as an Agricultural Lime starting in 1926.

At $3.00 a ton, Elmer Kipps was making a nice profit. Although he blasted to loosen the mixture of compacted fine-grained matrix and coarser rock fragments, no heavy equipment was needed to excavate and crush the rock nor was a kiln needed to burn (calcine) the magnesium-rich carbonate rock into a burnt lime - as was the case for his competitors. During the first ten years of the operation, mining and processing were accomplished by the use of hand tools, wheelbarrows, and a hand screen (Figure 6). During this phase of the operation, two men could screen 10 tons of agricultural lime during a 10-hour day. Mr. Kipps' promotion of his lime product reached a new level with the printing and distribution of a poster advertising Kipps' Lime-Magnesia (Figure 1).

Year	Farm Tonnage	Fertilizer Tonnage	Year	Farm Tonnage	Fertilizer Tonnage
1925	**42.7**		1949	**2846.6**	
1926	**90.25**		1950	**3179**	**724**
1927	**85.05**		1951	**2374**	**1048**
1928	**22**		1952	**1775**	**766**
1929	**189**		1953	**1398.6**	**825**
1930	**349**		1954	**731.7**	**748**
1931	**81.5**		1955	**665.9**	**737**
1932	**107.5**		1956	**841.2**	**353**
1933	**3**		1957	**593.4**	
1934	**41**		1958	**519.6**	
1935	**61.5**		1959	**1509.8**	
1936	**1965.6**		1960	**2595.2**	
1937	**1585.3**		1961	**2575.5**	
1938	**1840**		1962	**2909.4**	
1939	**2191.1**		1963	**3815**	
1940	**2452.3**		1964	**3109.8**	
1941	**2257.9**		1965	**2951.6**	
1942	**1611.5**		1966	**3735.3**	
1943	**1704.8**		1967	**2904.2**	
1944	**1568.6**		1968	**3731.1**	
1945	**3173.3**		1969	**3543**	
1946	**4219**		1970	**3552.6**	
1947	**3608.9**		1971	**3369**	
1948	**1650**		1972	**3095.3**	

TABLE 1 Tonnages sold by year, from 1925 through 1972, to farmers (column 1) and to Valley Fertilizer of Mt. Jackson (column 2 – limited to years 1950-56)

The economic effects of the stock market crash of 1929 are not reflected in Kipps' agricultural lime sales. During the Spring of 1929, sales were brisk enough for Mr. Kipps to purchase a new 1929 Chevrolet truck to replace a 1923 International 2-ton truck encumbered with solid rubber tires. The increased efficiency in hauling with the 1929 truck allowed enough additional sales that Mr. Kipps was able to buy a new car for his family in 1930. Although economic pressures of the ensuing depression were initially less in this farming community, a drought simultaneously affected the Shenandoah Valley. The combined effects are reflected as a decline in Kipps' lime product sales from 349 tons in 1930 to a low of 3 tons in 1933 (Table 1). During 1934, the drought eased. Modest sales increases occurred over the next few years. Additional interest in Kipps' agricultural lime was generated by Moore and others' 1931 Shenandoah County Geography Supplement. The report was published by the Shenandoah School Board and discussed in the county public school geography classes. Shenandoah County farmers learned about E.A. Kipps' unburnt lime product from other farmers as well as from their sons and daughters. As in the 1926 poster (Figure 1), the Supplement referred to the unburnt agricultural lime as marl. Marl is a naturally occurring unconsolidated fresh water calcium carbonate material that superficially resembles Kipps' lime-magnesia and deposits of marl actually occur along the stream on the Kipps' farm. Marl has been used as an agricultural lime elsewhere in the Shenandoah Valley (Hubbard and others, 1985; Giannini, 1990; Sweet and Hubbard, 1990). The lime-magnesia differs from marl chemically by having a significant percentage of magnesium and it originated as a fault zone crushed carbonate. The interest generated by the Geography Supplement was largely masked by diminished demand during the drought and production limits prior to the mechanization of 1936.

Mechanized Operations

In 1936, E.A. Kipps started advertising his new business address at the Moores Store Post Office, Social Security payments for workers were required of industrial and commercial operations, soil conservation aid allotments for lime started, and E. A. Kipps began the mechanization his agricultural lime operation. The closing of the nearby Getz Post Office in March of 1935, posed problems for Mr. Kipps' advertising and mail. The Getz Post Office literally had been located up the hill from the quarry, a mere 2100 feet to the southeast. The Moores Store Post Office was only two miles to the southwest, but the change required additional advertising to maintain business - even though the operation had not moved (Figure 7).

The 1936 taxation of industrial and commercial businesses for employee wages initiated a new era with respect to employee benefits and records. Elmer shifted his men from a 10-hour to an 8-hour workday and increased their pay from $1.25 to $1.40 a day. Employee records, over the years 1936 to 1950, reveal that no less than 86 local individuals worked for the Kipps' Lime-Magnesia operation.

The Soil Conservation and Domestic Allotment Act of 1936 was designed to support farm income by promoting soil-conservation and soil-building practices. Participating farmers could be reimbursed up to 50 percent of the cost of liming fields, but they had to layout funds prior to reimbursement. Kipps' new poster (Figure 7) alluded to the Government aid, in the form of "substantial refunds for lime," available to farmers complying with the "Soil Conserving" provisions.

The 1936 mechanization of the Kipps' Lime-Magnesia operation was of major significance. The J.B. Hammer Mill, used at Madden quarry in nearby New Market, was purchased and moved onsite to handle increasing amounts of rock found in the deposit. An old International Harvester Titan Tractor, formerly used by the Shenandoah County

Highway Department, was bought to power the mill. To handle the increase in production, a 50-ton storage bin was built by George Green and E.A. Kipps (Figure 8).

Production soared from 61.5 tons in 1935 to a total of 1965.6 tons for 1936 (Table 1, Figure 9). The increases in production were required to meet an increase in demand. The first order of 1936 was for 231 tons, more than the production of each of the previous years, except 1930. This large order was placed by C.C. Bowman who was particularly interested in the high-quality magnesium-rich agricultural lime for his fields as well as his orchards. Although mechanization was not completed until August of 1936, day and night operation resulted in an order of magnitude increase in production. The new levels of production prompted a separation of production and distribution. Marvin L. Lutz and his sons: Freeman, Alton “Bus” M., and Hirlye Ray Lutz, took over the business of delivering and spreading Kipps’ Lime-Magnesia.

As with most new systems, a few problems had to be worked out to tune the system for maximum efficiency. The elevator for the bin was linked to the hammer mill output, so that fine-grained lime product and rock passed through the mill. Sometimes the fines would cake and clog the mill. In 1937, Mr. Kipps had Bester and Long of Hagerstown, Maryland build a 10-foot by 3-foot cylinder screen to separate the fines from the feed to the hammer mill. A second bin with a capacity of 100 tons was built to house the screen (Figure 10). With the aid of a horse powered pond scoop to dig the unconsolidated lime product, the cylinder screen could process 40 to 50 tons of agricultural lime per day - even without the production of the hammer mill. The next problem addressed was the excessive wear of the J.B. Hammer Mill’s Babbit bearings. A new 3-hammer Stover Mill (Figure 11) provided a solution in 1938. Production soared to new highs in 1939 and 1940.

World War II affected production by reducing the available workforce, while product demand increased. As the country entered the War, the workforce continued to decline until only two to three additional workers could be found to assist Elmer A. Kipps and his son (coauthor E.C.K.). The nature of the quarry operations was shifted from scooping fines and deepening the quarry to bench shooting the quarry walls in 1942. The working face on the quarry walls was mostly rock. A jaw crusher had been bought to reduce the shot rock before it passed through the cylinder screen and on to the hammer mill. In 1943, a second-hand, Fortson shovel with a three-quarter swing (Figure 12) was purchased from Fred K. Betts III Quarry, Inc. of Harrisonburg to help offset personnel unavailability and the shift in quarrying methods. The domestic wartime petroleum-fuel shortages prompted a conversion to electric power (Figure 13). In 1944, the gasoline rationing, the suspension of domestic automobile production, and the scarcity of rubber for tires had prompted a 1.5 percent transportation tax that was applied to all sales that included hauling. During 1945, a few former workers returned from the war enabling production to reach a new high of 3173.3 tons (Table 1 and Figure 9).

With a renewed work force, even higher production and sales were achieved in 1946. But post-World War II unrest resulted in international economic woes. By 1948, escalating problems in a divided Berlin, Germany threatened to erupt into World War III and the U.S. economy plunged into a recession, which clearly shows up as a precipitous dip in tons sold (Figure 9). The reduction of the transportation tax, to a rate of 1.3 percent on sales that included hauling, was probably an economic stimulus initiative. A program that positively affected area farms during the 1948 economic recession was rooted in the Agricultural Adjustment Act (AAA) of 1938, which supplemented the Soil Conservation and Domestic Allotment Act of 1936. These programs were designed to support farm incomes through soil conservation and soil building practices. One such practice was soil testing to determine the amount of lime needed to optimize crop growth and soil conservation. By 1948, county agents could issue farmers purchase orders (POs), also called vouchers, for AAA aid allotments for the amount of agricultural liming needed on particular farm fields. Farmers presenting a voucher to E.A. Kipps paid only half the cost of their lime as opposed to paying the full bill and applying for reimbursment. Lime POs not only reduced farmers' cash outlays, but also provide an indication of the level of local participation in the AAA aid allotment program through Kipps' sales records. In 1948, thirty-four percent of Kipps' lime customers presented AAA vouchers. Increases in lime sales for 1949 (sixty percent of customers used lime vouchers) and 1950 (seventy-three percent of customers used lime vouchers; Table 1 and Figure 9) indicate a recovery from the recession. Increased participation in voucher use suggests increased acceptance of the government sponsored soil conservation initiatives. Subsequent U.S. involvement in the Korean War of 1950 to 1953 resulted in a slide in Kipps' Lime-Magnesia sales.

A number of economic changes occurred during the 1950s that affected operations. The transportation tax was reduced in 1950 to a rate of 1.24 percent on sales that included hauling. A set of scales was installed at the quarry in 1953, which eliminated trips to the Farm Bureau or to various other weighing stations to weight loads greater than the 5-ton capacity of a cattle scale. Additional recessions in 1953 and 1957 are reflected in the sales slump of the early to mid-1950s. Vouchers for AAA aid allotments for agricultural liming were suspended after 1953 when the Agricultural Conservation Program Service took over payments for the program. Farmers were still eligible for lime aid, but they had to pay the whole cost before they were reimbursed. The transportation tax ended with the change in the calendar from 1954 to 1955. The Lutz's sold back their interest in the hauling and spreading of Kipps' Lime-Magnesia in 1955. Henceforth, Kipps' Lime-Magnesia was spread with a Bulkman Spreader mounted on a 1946 Chevrolet truck. Agricultural lime sales were augmented from 1950 through 1956 by sales of lime product to Valley Fertilizer of Mt. Jackson (Table 1). Valley Fertilizer used Kipps' Lime-Magnesia as a filler/supplement for their fertilizer. A recovery in lime product sales to farmers began in 1956, but the death of Elmer A. Kipps (age 76) on 1 January 1957 stalled operations. Legal matters took a year to settle before Mrs. E.A. Kipps could assume control of Kipps' Lime Magnesia. Elmer C. Kipps, her son, had managed the quarry operations and distribution of the product during the transition year and was named General Manager in 1958. E.C. Kipps' well-schooled sister, Erma Kipps, took over the bookkeeping after the death of her father. Market competition added an additional complication when Tri-State Zinc, Inc. opened the Bowers-Campbell mine in nearby Rockingham County in 1957. Finely ground dolomitic host rock, from which the zinc concentrates were separated, was a waste product at the mine. Initially, this ground dolomitic-limestone was marketed as an agricultural lime by Fred K. Betts III Quarry, Inc. and later by the Timberville Lime Company. Despite the increased market competition, a recovery in sales began in 1959.

The old Fortson shovel was replaced in 1959 by a International TD9 front-end loader (Figure 14). In 1960, a 1955 GMC truck mounted with a Bulkman Speader (Figure 15) was purchased. The following year, the old 1946 Chevrolet mounted Bulkman Spreader was replaced by a 1957 Chevrolet mounted Bulkman Spreader. That same year, the 3-hammer Stover Mill was replaced with a 39-hammer Jeffrey Mill, obtained from Mr. Long of the Jamison Black Marble Company of Harrisonburg. The significantly greater power requirements of the 39-hammer mill prompted a shift from electric to diesel power for the milling operations. The worn cylinder screen was replaced by a shaker screen acquired from the old Page County Cooperative quarry, when it was taken over by Theodore W. Mundy of Elkton Lime and Stone Company.

Vouchers for aid allotments for agricultural liming were renewed in 1961 with the shift in authority for aid payments returning to the Agricultural Adjustment Administration (AAA). Mining, milling, and spreading operations continued with only a few changes for the next 10 years. AAA aid allotments for agricultural liming were replaced by ASCS allotments in 1967 and continued through the duration of Kipps' lime production. A 3.0 percent sales tax took effect at the onset of 1967 and increased to 4.0 percent from July 1968 through the duration of Kipps' Lime-Magnesia production. By 1970, a full-swing Unit shovel (Figure 16) was purchased to load shot rock for processing and the International front-end loader was switched to stockpiling and loading finished lime product.

The year 1972, was a year of significant change for Kipps' Lime-Magnesia. It was the last year the Kipps' Magnesium Limestone quarry was licensed to operate as a mine by the Kipps family. On 13 October 1972, Kipps' Lime-Magnesia was sold to Theodore Mundy of the C.S. Mundy Quarries, Inc. Mr. Mundy hired E.C. Kipps to manage operations. Quarry and agricultural lime operations were shut down at the old Kipps farm after the untimely death of Theodore Mundy, on 8 July 1973.

During the years the Kipps family operated Kipps' Lime-Magnesia (1925-1972), a total of 89,223 tons of agricultural lime were sold to farmers in Rockingham, Shenandoah, Page, and Highland counties in Virginia and Hardy County in West Virginia. Another 3,273 tons of agricultural lime were sold to Valley Fertilizer for use as a supplement/filler for their fertilizer. The total of Kipps' Lime-magnesia sold from 1925 through late 1972 was 92,496 tons. Tonnages sold during the Mundy operations are unavailable.

Mr. E.A. Kipps was fond of saying that his was the first unburnt lime operation in northern Virginia. Technically, Kipps' Lime-Magnesia was the second known unburnt lime operation in northern Virginia. Cornwall Lime Marl, of Winchester Virginia, sold 1,942 tons of marl as an agricultural lime in 1923 (Hubbard, and others, 1985, p. 7). No other records of production are known for Cornwall Lime Marl.

Mr. E.A. Kipps once told his son that he had found his pot-of-gold beneath the roots of the old mahogany tree and had pointed to their quarry, where the tree had once stood. Elmer A. Kipps was a man of vision and a man that not only knew an opportunity when he saw it, but a man that was willing and capable of developing his dream into reality. Few are those with vision, fortitude, and entrepreneurship. Fewer still are those who find the end-of-the-rainbow in their own yard.

EPILOGUE

The study of minerals and marls that enhance soil productivity was an interest of William Barton Rogers, who was appointed to undertake a reconnaissance of the geology of the Commonwealth of Virginia in 1835. A discussion of mineral fertilizers was a significant component of Rogers' subsequent report to the Virginia legislature in January 1836 (Rogers, 1884 and Adams, 1998). The economic prosperity of antebellum Old Dominion was linked to her soils and so to were the roots of the Virginia Geological Survey nurtured by the study of her mineral fertilizers.

The legacy of the history and development of Kipps' Lime-Magnesia is a rare treat for those of us that seek to learn more about the practical, applied, and economic geology around us. The rich details, in the form of photographs, records, experiences, and memories, of a significant segment of the Kipps' family history are a rare gift that the co-author has shared with us through this article. A word of thanks is due to Bob Minnick, who sent the senior author to meet and talk with the co-author, for otherwise the details of the Kipps' Lime-Magnesia operations might never have been put-to-print in such a well illustrated form that charts the development of a part of the aglime industry.

In May of 2001, the old Kipps' farm and quarry were sold to Valley Stone, LLC. The history of Kipps' Lime-Magnesia may have a chapter or two to yet develop.

ACKNOWLEDGEMENTS

Norvell Trumbo, of Broadway, graciously led the authors on a tour of the Meyers Lime Kiln and provided the history of grandfather Christian Meyers' mining and lime business. Mr. Trumbo also shared his own childhood memories of the mining and lime kiln operations.

Bill Keith, of the USDA's Natural Resources Conservation Service, provided information about the Soil Conservation and Domestic Allotment Act of 1936 and the Agricultural Adjustment Administration (AAA) programs for soil building practices such as lime applications. He also provided valuable information about the shift from the AAA to the Agricultural Conservation Program Service that accounted for the suspension of AAA lime vouchers from 1954-1960.

Jim Snyder, of the USDA's Natural Resources Conservation Service, indicated that, during 1954-1960, when lime vouchers were discontinued lime reimbursements remained in effect. Peter Warren, the Albemarle County Extension Agent, provided information about the beginning of Virginia's soil testing, for optimal soil pH and lime needs, circa 1938.

DMME/DMR personnel that contributed to this article include Karen Hostettler, who prepared the digital graphics version of Figure 3. Eugene Rader and Palmer Sweet enhanced the article by providing information and suggesting changes to improve the manuscript.

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LIME! LIME!

FOR CROP'S SAKE, LIME

Lime-Magnesia [marl] a quick acting, efficient, soil sweetener, conditions your soils for the BUMPER CROPS you have a right to expect - - - - -

EXCELLENT ALIKE FOR GARDENS OR FIELDS

CALL ON OR WRITE TO

E. A. KIPPS, - - - - Getz, Virginia.

FIGURE 1 Advertising poster, circa 1926, for Kipps' Lime-Magnesia.

FIGURE 2 Meyers lime kiln, built in the early 1900s in Rockingham County, Virginia.

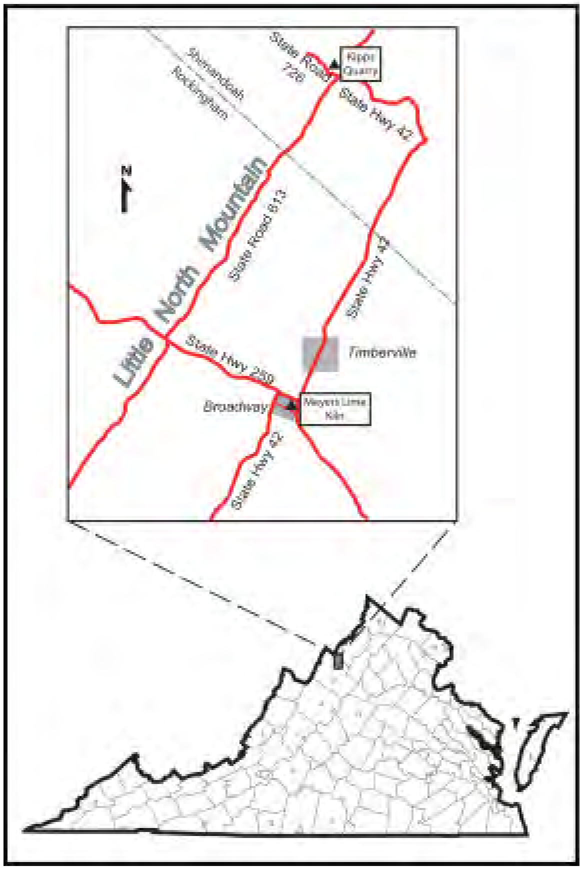
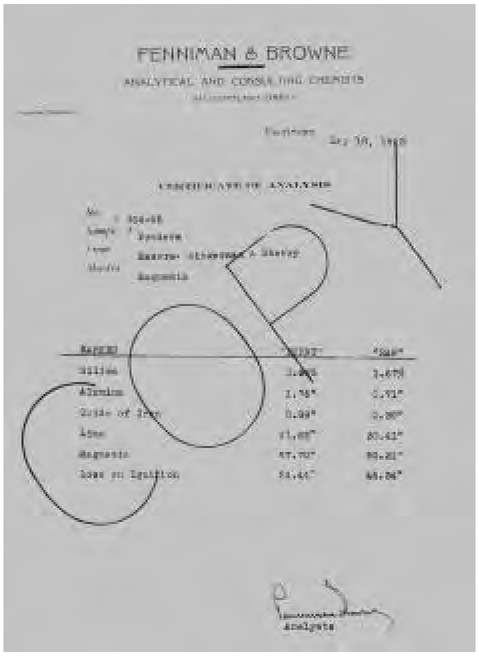


FIGURE 3 Location of Meyers lime kiln and Kipps quarry.

FIGURE 4 Illustration of an end-gate spreader in operation from old Stover Lime Pulverizer brochure. Note even distribution of lime, which obscures view of lower rear wheels. One person drove the team, while a second shoveled lime into the spreader unit, mounted on the wagon's end gate.



PENNIMAN & BROWNE

ANALYTICAL AND CONSULTING CHEMISTS

CERTIFICATE OF ANALYSIS

Silica

Alumina

Oxide of Iron

Lime

Magnesia

Loss on Ignition

Analysts

COPY

FIGURE 5 An analysis of the Kipps' "fertilizer."

FIGURE 6   View of Kipps quarry with hand-screen leaning against quarry wall at right edge of photograph.

LIME KIPPS' LIME

LIME-MAGNESIA

Immediately Soluble Quickly Available

General Analysis—58.60 Carbonate Lime——40.90 Carbonate Magnesium

This product is pulverized amply fine to insure quick and favorable action in the soil.

With Governmental aid as provided by Congressional act, farmers who comply with the "Soil Conserving" Rulings will receive substantial refunds for lime, etc., used on their farms. SEE YOUR COUNTY AGENT.

For 12 years this product has been used by many of our most substantial farmers, whose repeat orders yearly testify to the satisfactory results they receive.

Treat Your Soil With The Best

For Delivered Prices—Call to see or write to

E. A. KIPPS

Moore's Store, Va.

Call Through Mt. Clifton, Va.

LIME LIME

FIGURE 7 Advertising poster, circa 1936, for Kipps' Lime-Magnesia at Moores Store Post Office.

FIGURE 8 First storage bin (50-ton capacity) after completion, with Elmer A. Kipps in foreground and 11-year-old Elmer C. Kipps with shovel of milled lime from the J.B. Hammer Mill.

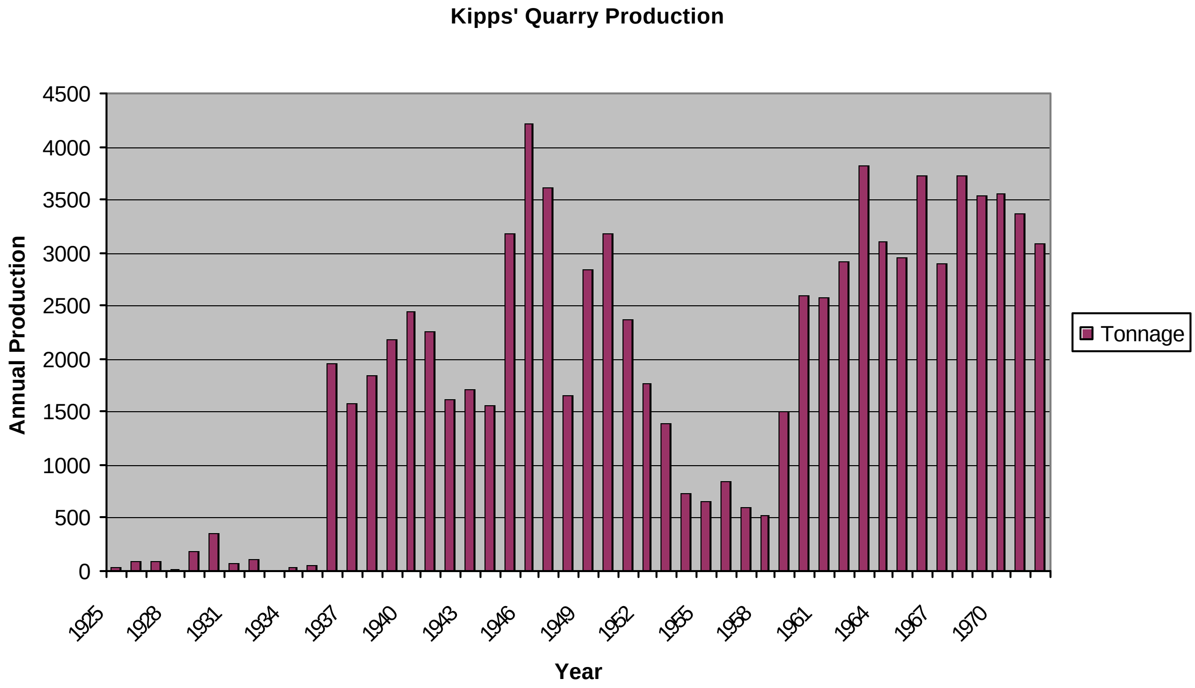


FIGURE 9 Graph of Kipps' Lime-Magnesia farmer sales in tons from 1925 through 1972.

FIGURE 10 View of twin storage bins with elevator feed to cylinder screen housed above 1st bin (100-ton capacity) and Stover Hammer Mill above second bin (50-ton capacity). The hammer mill was powered a by diesel Titan tractor, located behind bins.

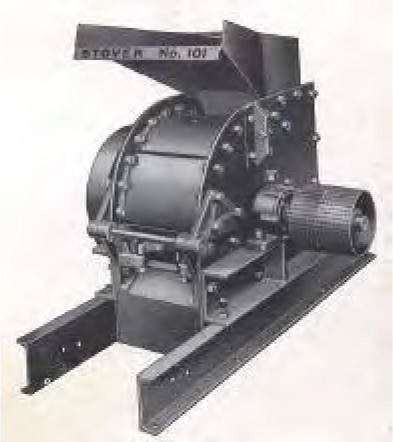


FIGURE 11 Illustration of Stover Hammer Mill from advertising brochure.

FIGURE 12 View of Kipps quarry with three-quarter swing Fortson shovel loading 1934 Ford dump-truck. Above quarry face a 1942 Oliver tractor powers an air compressor used to drill holes for bench shots.

FIGURE 13 Kipps' mill with new REA electrical power substation at right edge of photograph.

FIGURE 14 E.C. Kipps dumping International TD9 front-end loader into jaw-crusher in December 1959.

FIGURE 15 E.C. Kipps with the 1955 GMC mounted Bulkman Spreader on the scales.

FIGURE 16 A post operations photograph of E.C. Kipps on the old Unit shovel used in the early 1970s – the last years of operation of Kipps' Lime-Magnesia

The geologic and economic properties of East Anatolia (Mus District) barite deposits, Turkey

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ABSTRACT

The share of barite reserves in Turkey is about 2.1% of the world's total reserves. Being located near the most important users of barites, Turkey has a good opportunity to export its products. Known barites deposits in Turkey are located in Konya, Maras, Antalya, Kütahya, Mus and in many others provinces. Turkey has good quality barites whether ground, micronized or crude. Barite production has been growing rapidly. About 90% of barite production comes from the private sector. Grinding capacity has also increased rapidly.

Mus region Barites are located in Bilir, Kasor, Karakilise and Haskoy villages. Geologically, metamorphic schist, gray mica schist, dark green clorite-albite schist, marble and sandy clays are found and the barite has been formed as a filon around Bilir and Kasor villages. Basically, chemical properties of barite as follow.

% $BaSO_4$	% Fe_2O_3	SiO_2 %	Al_2O_3
90-99	0.48-1.53	0.80-3.62	0.20-0.80

Around the Kizilkilise occurrences hematite cemented quartzite breccia, sericite spolene and gray marble are found in the fields and also chemical properties of barite is % 90-98 $BaSO_4$, % 0.24-0.67 Fe_2O_3.

Mus Barites is commonly used in deep drilling for oil and gas by the rotary method to control reservoir pressure and prevent blowouts. This mineral is also used as a source of barium chemicals. Several industries use barites especially in paint, leather, cloth, ceramics glazes and enamels, glassmaking, electric furnace, metallurgy, detonators, signal flares and to recover sugar from molasses.

- **Note**: Paper not available at time of publication.

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Beypazari trona deposit, Turkey, and its expected effects on the global soda ash market

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ABSTRACT

This study outlines the trona deposit in Turkey and discusses about its expected effects on the world's soda ash market.

The field that contains the trona is located approximately in the middle of Turkey, exactly 15 km northwest of the small town called Beypazari. The deposits, that are Miocene aged, were discovered in 1979 when General Directorate of Mineral Research and Exploration of Turkey was drilling the area for lignite deposits. Trona exists mainly in 12 different zones which are associated with shale, clay stones and sand stones. Estimated trona reserve of the area is nearly 200 million tones which is the world's second biggest trona capacity after the deposits in Wyoming, U.S.A.

Eti Soda A.S. has the rights to mine the trona and export it. The expected time to start mining in the maximum production level is 2008 when the general plant is completed. The questions of the coming years are these: Will Eti Soda A.S. be able to take control of the soda ash market in Turkey? How will natural soda ash production of Eti Soda A.S. affect the global soda market? What kinds of difficulties are waiting the Eti Soda A.S.? What sort of new plans should Eti Holding A.S. do in order to be a strong member of the world's soda market?

First of all, it has been pointed out in the 2004 Company Report of Soda Sanayii A.S. – 30 years old soda ash producer of Turkey – that they will continue producing soda ash based on Solvay Process in the coming years also, then it seems hard to take control of the market in Turkey. Furthermore, it is another fact that Solvay Chemicals is the world's biggest soda ash producer and completely dominates the Europe's soda market, so this is also another problem for Eti Soda A.S. On the other hand; low production costs because of solution mining, low energy costs and better environmental conditions of natural soda ash production are the advantages of Eti Soda A.S. In addition, it also seems reasonable for Eti Soda A.S. to take part in other industrial areas, in which they can use the soda ash that will be produced by them, like some of other powerful soda ash producers.

In conclusion, although it seems hard to take part in the world soda market, increasing global soda ash demand seems to create suitable position for Eti Soda A.S. in the global soda ash market.

Demirkilic, Hakan, 2006, Beypazari trona deposit, Turkey, and its expected effects on the global soda ash market, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Trona $Na_2CO_3 . NaHCO_3 . 2H_2O$ is an evaporative crystalline or massive industrial mineral. The name trona is derived from the Arabic origin name of the native salt *tron* (Bates, 1988). It is also known as hydrated sodium bicarbonate carbonate or sesque carbonate. Trona is on of the most well known sodium compound in the industrial minerals science. In addition to this, gaylussite, natron, pirssonite, northupite, nahcolite and thermonatrite are other memorable sodium minerals concomitance with trona, on the other hand; they are not as familiar as trona (Paulson, 2005). This important mineral has a color of gray-white in the clear samples or yellowish-white in the impure samples so the color varies depending to pureness. Trona has a hardness of 2,5- 3 on Moh's Hardness Scale – easily could be marked by copper coin – and has 2,11g/cm^3 density value (Harben, 1995).

Trona is occasionally encountered as a saline lake deposit or evaporation product as efflorescence on arid soil (Bates, 1988). Trona minerals can be found under ground as example; Green River, Wyoming- USA, Inner Mongolia – China, Beypazari – Turkey or in dry lakes such as Searles Lake, California, USA, Magadi Lake– Kenya, Sua Pan – Botswana (Kostick, 2006). The most important and the biggest trona deposits were found in Green River Basin, Wyoming in 1938 during the drilling for oil on the plains of southwestern Wyoming. Wyoming's rich trona deposits are the residue of a huge lake – known as Lake Gosiute – that covered the southwestern part of the state 50 million years ago during Eocene epoch (Bates, 1969). Over millions of years, Lake Gosiute expanded and contracted in response to changes in the region's climate. During one lengthy period, when the lake was predominantly saline, it shrank to such an extent that large deposits of trona and occasionally halite $NaCl$ were left behind.

As similar as Wyoming Trona Deposit's occurrence, Beypazari Trona Deposits were also originated in Beypazari region during middle-late Miocene Epoch (nearly 15 million years ago) more or less 35 million years after the world's biggest deposit's forming in USA. The Beypazari region, which is a large area of volcano-sedimentary rocks of Miocene Epoch in the interior of the Central Anatolia, located nearly 100 km (62 miles) northwest of Ankara, the capital of Turkey. It is the greatest trona mineralization ever discovered in Turkey and Europe. A total of 33 trona beds have the thickness ranging from 0,4 to 5 m. in general (1,3 feet to 16 feet) (Akseki, 1999). Most of the scientists and engineers consider totally 12 main trona zones in the area with 6 at the lower part, 6 at the upper part because of having essentially thickness and continuity. The total reserve is roughly 237 million metric tones and the common grade is 85% trona therefore, Beypazari Trona Deposit is the world's second biggest trona deposit (Suner, 1989).

Trona is an ideal industrial mineral for producing the important industrial raw material commercially named as soda ash Na_2CO_3. In addition to this, soda ash is also called as sodium carbonate by the chemists. This important raw material always ranks among the top ten inorganic chemicals produced in USA. It may be manufactured synthetically according to Solvay Process (the major industrial process used in the synthetic production of soda ash, also referred to as the ammonia-soda process) or naturally from occurring industrial minerals such as trona (FMC, 2003). It is an important industrial compound used to manufacture glass, chemicals, pulp and paper, soaps and detergents, and many other familiar consumer products (Bateman, 1950). Production of natural soda ash from deposits of trona and brines rich in sodium carbonates is almost concentrated in the United States. It accounts for approximately 1/4 of global production from all sources. The balance is produced synthetically, particularly in China, Europe and Russia. In 2005, nearly the 71% of world's total soda ash production was manufactured synthetically and the rest was from natural sources mostly produced in USA. The United States is the world's second ranked soda ash producing country with the world's largest natural trona deposits and coming after the China's huge synthetic production. World's total soda ash production was 42 million tones in 2005 which was 4% higher according to the previous year (Kostick, 2004). This production value indicates that the industry has a slightly increasing mode.

Eti Soda A.S.(the abbreviation of *Anonim Sirket* in Turkish, joint-stock corporation in English) which is the joint venture company, is the holder of the rights of mining trona and fabricating soda ash in Beypazari. Turkey's the biggest private mining company Park Holding Company and the government corporation named Eti Holding Company are the associates of this joint venture. Although Eti Soda Company is a joint venture company, Park Holding dominates the commanding the project with 74% proportion on this joint venture, thus we can suppose Park Holding Company as the main character of this project. The probable time to start producing soda ash in the maximum level is 2008 when the general plant will be completed. Nonetheless, Eti Soda Company should overcome the expected difficulties waiting for them.

In spite of Soda Sanayii A.S, which is a sub company of the Turkey's biggest glass manufacturer Sisecam, it will be easy to dominate the market in Turkey for Eti Soda Company. It is a truth that Soda Sanayii is the first and only soda ash producer in Turkey at the moment but this company mostly consumes the soda ash that they produce in their own glass manufacturing factories. It is another fact that synthetic production's cost value more or less doubles the natural production's cost, so Eti Soda will have a very important advantage in the domestic market. On the other hand, the main aim of Eti Soda is exporting the soda ash, so Eti Soda and Soda Sanayii companies have 2 different cases. This is also a conspicuous factor in the domestic market.

The probable rival of Eti Soda Company look like will be the Solvay Chemicals S.A. (the abbreviation of Société Anonyme in French, joint-stock corporation in English) the world's biggest soda ash producer well-known Belgian based Company (Solvay, 2004). Today, Solvay operates 9 soda ash plants in the world; the biggest soda ash producing from the natural trona deposits in the Green River, Wyoming- USA and the 8 European plants operating the Solvay based process, consequently it seems truly hard to compete with this important company in the worldwide soda ash market, nevertheless low fabricating costs because of natural soda ash production, low energy costs, geographically well locating are the advantages of Eti Soda Company.

After a general over look on the topic, I would like to give the essential data about the geology of Beypazari District.

GEOLOGY OF THE REGION

Turkey is a well-known country with the several economically important Neogene Basins. One of the most well-known of these basins is Beypazari Neogene Basin. The Beypazari region is a big area of Miocene aged volcano-sedimentary rocks in the interior of the Central Anatolia, positioned more or less 100 km (62 miles) northwest of Ankara. It is also the closest neighboring town of the smaller town, which is famous with its lignite deposits, called Cayirhan. Trona is found in 1979 when the government foundation named General Directorate of Mineral Research and Exploration (MTA) was drilling the area to find out the continuance of Cayirhan lignite deposits. During the drilling, the water had suddenly foamed so the Beypazari Trona Deposits were discovered by luck like the Wyoming Trona Deposits.

Trona is found with lignite and bituminous shale in the lower part in addition to this, sodium sulfate and gypsum occur in the upper part of the sedimentary chain in the Miocene Beypazari Basin (Akseki, 1999). The rock units of the basin are divided in two main groups – Pre-Neogene basement rocks and Neogene rock units. The pre-Neogene basement rocks are Paleozoic to Eocene in age and consist of metamorphic, plutonic, volcanic and sedimentary rocks. The Neogene sedimentary units generally consist of clastic, clayey, calcerous, bituminous, evaporatic and silicified sediments. Neogene is represented by Miocene and Pliocene formations which are made up of volcanic and sedimentary units formed in lacustrine faces. Miocene series, named as Beypazari Group lies over all the older units discordantly. Average thickness is about 1000 m (3.280 feet) formations and their characteristics from bottom to top are as follows: Boyali, Hirka, Karadoruk, Sariagil, Cakiloba, Zaviye, Ucyatak Formations and Teke Volcanics.

The reason of trona's occurrence answer lies in volcanic action. Some sodium was contributed by volcanic ash that fell into the lake; more would have come via streams that drained the adjacent ash covered lands. After that there was hot mechanism, so the trona actually originated in volcanic processes from inside the earth.

Hirka Formation is the most important structure in the basin because trona is only found in this formation. Trona ore locates with the bituminous shale, clay stone and tuff of bottom parts related to Hirka Formation with clastic rocks within. Hirka Formation, which is buried into 250- 430 m. (820- 1410 feet), is the owner of the trona bed and includes 2 parts the upper and the lower. The trona bed is composed of 33 layers, of which 12 are main layers with 6 in the upper and 6 in the lower parts. The ore mainly composed of trona and the edge of the ore bed; there is a little amount of nahcolite, in addition little amount of mizzonite and thermonatrite also scatters in the ore (Akseki, 1999).

The trona layers exist at the bottom parts of Hirka Formation and the thickness of the section containing trona is 70- 100m. (230- 329 feet) The total thickness of the trona zone is 2,5m. (8 feet) at the corner and 34m. (112 feet) in the middle of the bed. Total reserve is more or less 237 million metric tones with average 85% pure trona and 2 million metric tones of nahcolite ore (Suner 1989). The upper trona zone, which covers 8 km^2 spaces (3 square miles), has the thickness containing trona approximately 40m. (131 feet), including 17 sub layers of which six are main ones numbered as U1- U6 and each has thickness varying 1,33 to 3,55 m. (4,36 to 11,65 feet) The most trona bed is located in the U4 section with an average of 3,55m. (11,65 feet). Between the main sub layers are clay rock, bituminous clay rock and oil shale. The distance between the two main parts is 20- 25m. (66- 82 feet) and clay rock and oil shale are occurs in this section. The lower zone has 5,5 km^2 areas (2 square miles), its thickness that contains the trona is 40- 60m. (131- 197 feet) including 16 sub layers, of which six are main ones numbered L1- L6 and each has 0,78 - 2,13m. (3- 7 feet) The thickest is L5 and L6. Between the main sub layers are clay rock, bituminous clay rock and oil shale (Akseki, 1999).

The surrounding rock of the bed mainly consists of oil shale, clay rock, tuff and dolomitic limestone of Hirka Strata. With medium degree of consolidation, the compressive strength of the rock is 1,39- 49,76 Mpa and the tensile strength is 0,3- 1,97, which shows large variation and can be explained by the different rock samples (Akseki, 1999). Generally, the intensity of the surrounding rock is lower than the intensity of the trona bed.

Before stepping into the soda ash market, I would like to summarize the world's biggest trona occurrence: The Wyoming Trona Deposits.

WYOMING TRONA DEPOSITS

The Wyoming trona deposits were also found by luck, during the drilling for the oil and gas on the plants of south-western Wyoming in 1938 (Bates, 1988). It was the biggest and the first trona deposit that had been found underground. The estimated reserve of the Wyoming trona deposit is almost 40 billion metric tones; this amount constitutes more or less the 96% of the world's founded trona deposits. The deposition of trona in Wyoming started about 50-60 million years ago during the Eocene Epoch in the Wilkins Peak Member of the Green River Formation. A large freshwater lake, Lake Gosiute, covered an estimated 38800 km^2 (15,000 square miles) in Green River Basin of the southwestern Wyoming. The lake was fairly shallow, and it evaporated rapidly and repeatedly. Therefore, the climate would change back and forth between arid and humid, trapping the once abundant life. All the minerals and mud settled in the bottom of the lake. Sodium, alkaline and bicarbonate were transported to the lake by runoff water. It is believed the sodium came from the volcanoes in northwestern Wyoming. The mixture of all these elements formed the trona deposits USA mines today.

For millions of years, the climate in southwestern would change from wet to dry. The wet periods would wash mud into the lake that would cover a trona bed. The dry periods would create trona beds. This is the reason the United States now have numerous beds of trona, marlstone, oil shale, and sandstone that can be found in areas as deep as 1066 m (3500 feet). In Wyoming, large deposits of trona are found in the Green River formation. There are 42 beds of Trona that cover about 3365 km^2 (1300 square miles). Approximately eleven of these seams are at least 2 m. (6 feet) in thickness, and 25 of them exceed 1 m. (3 feet) thick. The most common bed for trona mining, bed 17, is 488 m. (600 feet) deep; the bed 17 has 4 m. (12 feet) thickness and has a very high grade (Bates, 1969).

ETI SODA A.S.

After the Beypazari Trona Deposit had been founded in 1979, the government chose Eti Holding Company -Turkish Governmental Mining Foundation- as the owner of the area in 1983. After that moment, some of the world's biggest soda ash producing companies, such as FMC, Solvay S.A. and Rio Tinto started to give their attention on Beypazari Trona Deposits. Unfortunately, feasibility studies of the companies took very long time and finally these companies withdrawn from the project so Eti Holding Company wanted to return the area to private hands from Turkey. After the privatization offers, Park-Bayindir group presented the biggest offer and gained the rights to be the partner of Eti Holding Company in the district. After the privatization completed, the partners established the Eti Soda A.S. as the joint venture company, to mine trona, produce soda ash and export it. In progress, Bayindir Holding Company also withdrawn from the venture and sold their own shares - nearly 2% - to the biggest Turkish Government Bank; VakifBank. After some moment, Park Holding purchased the Vakif Bank's shares and became the one of the partners of the project with 74% proportion on it. Park Holding is almost the biggest private mining company in Turkey. This holding is also the owner of the Cayirhan Lignite deposits and the Turkey's first privatized thermic power plant in the region, so they are familiar to the district and mining business. These specialties also forced government to choose Park Holding, as the partner of Eti Soda for this project.

The expected time for mining trona and produce the soda ash in the maximum capacity would be 2007 but at the moment it seems hard to accomplish this project so there may be 1 year delay for the project to start in the maximum capacity. As a result of solution mining, the amount of the mine workers will be less but the company may also start under ground mining in order to upgrade the production capacity, so the number may increase. More or less 1,000 people will be ensured occupation directly and 3,000 people indirectly when the plant will work by full capacity.

As an undergraduate student, I experienced 36 days in Eti Soda A.S. for my university summer training duty in 2004. I had change to examine the district, company and workers during my training. I have also joined the Master Exploration Project (MEP) and experienced the way of drilling. Beypazari trona deposit area, of which the Eti Soda A.S. is the owner, was very huge so the MEP had started. The main reason of this project was limiting the trona deposit's border so the company would pay less hiring charge for the area to the government.

It is a fact that Park Holding is one of the best mining companies in Turkey and will do their best in mining business, but the most important part of this business is exporting the soda ash so they should develop some strategies for exporting the soda ash. We can classify the expected difficulties in two main categories; the first domestic, and the second is international difficulties. But before pointing out these expected difficulties, I would like to give some information about soda ash and soda ash market.

SODA ASH

Soda ash also chemically known as sodium carbonate has been used since the earliest times. We come across with the usage of soda ash in glass making approximately 3,000 BC. by the Egyptians. This civilization used soda ash recovered sodium carbonate from dried desert basin lakes. As different from Egyptians; Spanish, English and French used soda ash that was made from the ashes of seaweed or certain plants named as Salsola Vermiculata, Fucus Vesiculosus and Laminaria Digitata until the 19th Century (Kirchner, 1950). At the end of the 18th century, available production was far below the growing demand due to the glass and soap market so the French Academy of Science offered an award for the invention of a practical process to manufacture soda ash. One of the most well known French physician: Nicolas Leblanc proposed a process starting from common (Table 1) and obtained a patent in 1791.

TABLE 1 Leblanc Process

2 NaCl + H2SO4 ?   Na2SO4 + 2 HCl
Na2SO4 + CaCO3 + 2 C ?   Na2CO3 + CaS + 2 CO2

It was a big chance for France to organize this competition because after the year 1794 some factories based on Leblanc's Method were established in Marseille, Paris, Rouen and Chauny, so France could produce all the soda ash that the country needed by

1810 and cut off importing it from Spain. After France, England and Germany also continued that trend and set up the soda ash plants based on Leblanc Method (Kirchner, 1950). Although Leblanc's Method was a milestone in the industry, the Leblanc technique had serious drawbacks. Firstly, Leblanc process plants were decidedly not environmentally friendly. Furthermore it was complicated, wasteful of costly raw materials, fuel and labor-intensive. The process of generating salt cake from salt and sulfuric acid released hydrochloric acid gas, because this acid was industrially useless in the early 1800s; it was simply vented into the atmosphere. In addition, for every 8 tons of soda ash, the process produced 7 tons of calcium sulfide waste so this process should be enhanced. The Belgian brothers named Ernst and Alfred Solvay developed a more direct process for converting producing soda ash from salt and limestone through the use of ammonia in1861 (Table 2).

The only waste product of the Solvay process was calcium chloride, so it was both more economical and less polluting than the Leblanc method.

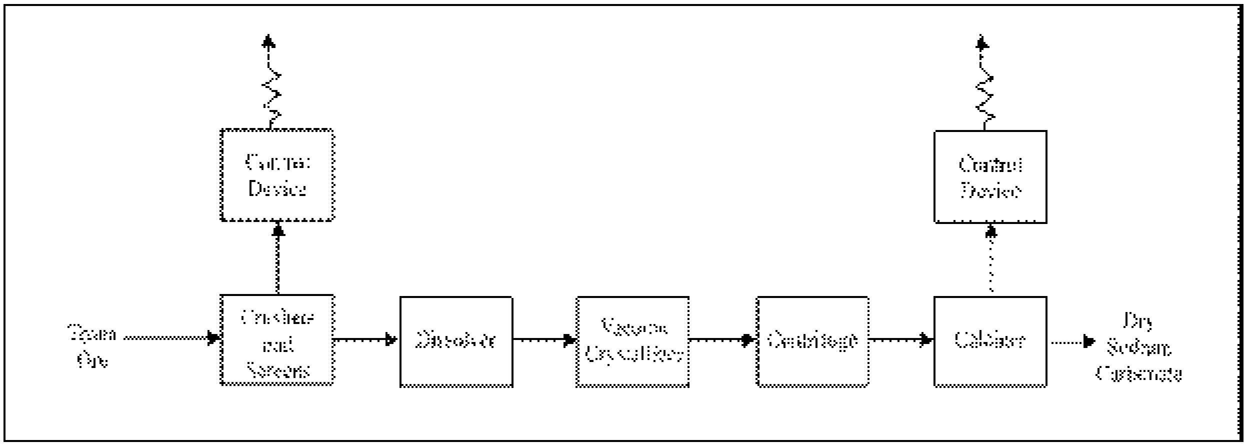
TABLE 2 Solvay Process

$$NaCl + NH_3 + CO_2 + H_2O \text{ ? } NaHCO_3 + NH_4Cl$$
$$2NaHCO_3 \text{ ? } Na_2CO_3 + CO_2 + H_2O$$
$$2NH_4Cl + Ca(OH)_2 \text{ ? } CaCl_2 + 2NH_3 + 2H_2O$$

From the late 1870s, Solvay-based soda works on the European continent provided stiff competition in their home markets to the Leblanc-based British soda industry. Additionally, the Brunner Mond Solvay plant which opened in 1874 at Winnington near Northwich provided fierce competition nationally (Kirchner, 1950). Finally, the last Leblanc-based soda ash plant closed in the early 1920s. By 1900, 90% of the world's soda production was through the Solvay method. On the other hand, the natural soda ash production in the Searles Lake, California, which was the first big challenger of the Solvay-plant factories, began in 1931 in USA. But after the trona deposits in the Wyoming had been discovered in 1938, the soda ash industry dramatically changed and Solvay-process factories came across with the biggest rival. In 1938, seventeen Solvay-process plants were producing soda ash in the United States, by 1969 the number dropped to ten; today there are none. The natural material has taken over. The product is even being exported to Europe, to the consternation of the long-established Solvay industry there (Bates, 1969). In 1947, a division of Food Machinery Corporation (FMC) developed a mine and a small plant to calcine the trona to a crude sodium carbonate. By 1953, FMC had improved the project (Table 3) via the sesquicarbonate crystal and built a new plant.

In the sesquicarbonate process; trona ore is first dissolved in water H_2O and then treated as brine. This liquid is filtered to remove insoluble impurities before the sodium sesquicarbonate $Na_2CO_3\ NaHCO_3\ 2H_2O$ is precipitated out using vacuum crystallizers. The result is centrifuged to remove remaining water, and can either be sold as a finished product or further calcined to yield soda ash of light to intermediate density.

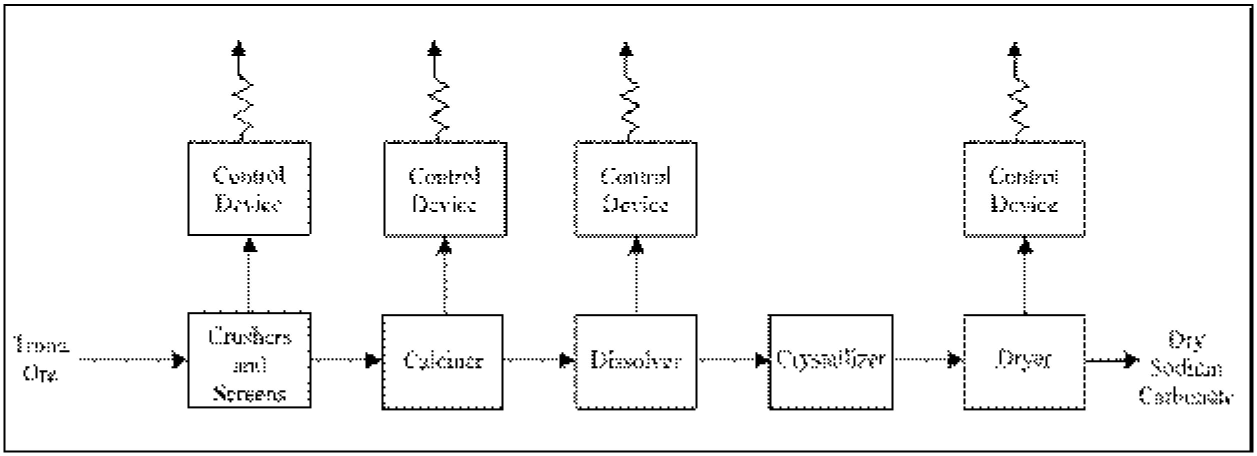
TABLE 3 Flow Diagram for Sesqui Carbonate Sodium Carbonate Process



(Saygili 1992)

FMC introduced the monohydrate process (Table 4) in 1962 and this remains the main process used today by the other natural soda ash producers. In the monohydrate process; crushed trona is calcined in a rotary kiln, yielding dense soda ash and carbon dioxide and water as by-products. The calcined material is combined with water to allow settling out or filtering of impurities such as shale, and is then concentrated by triple-effect evaporators and/or mechanical vapor recompression crystallizers to precipitate sodium carbonate monohydrate $Na_2CO_3\ H_2O$. Impurities such as sodium chloride $NaCl$ and sodium sulfate Na_2SO4 remain in solution.

TABLE 4 Flow Diagram for Monohydrate Sodium Carbonate Process.



(Saygili 1992)

The crystals and liquor are centrifuged, and the recovered crystals are calcined again to remove remaining water. The product must then be cooled, screened, and possibly bagged, before shipping.

USA-based soda ash producers have always exported soda ash mostly to Canada, Latin America and Asia. It is useful to indicate that the growth of exports accelerated after the formation of the American Natural Soda Ash Corporation (ANSAC) in 1982. Although ANSAC controls large fleets of rolling stock to transport a continuous stream of soda ash from Wyoming to shipping terminals on the West Coast and the Gulf Coast, all American producer also export soda ash individually (Andrews, 2004). Today, four companies; FMC Corporation, General Chemical, Solvay Chemicals Inc. and OCI Chemicals Corporation shares the Wyoming Trona Deposits and produce the world's biggest natural soda ash in the district.

After all of these details given above, it will be very useful to list the application areas of the soda ash before stepping into the domestic and international soda ash markets.

USES IN THE INDUSTRIAL SECTORS

Soda ash is a commodity chemical used in several branches of industry. Soda ash could be manufactured as two main products, the heavy and the light soda ash. The main difference of these main products are; the specific gravity and the application area differences.

The main application areas are quoted in the following paragraphs, in addition to this; the chemical specifications of soda ash produced in Beypazari at the pilot plant are also written below (Table 5) to give general information for the fabric of the natural soda ash.

TABLE 5 Chemical Specifications of Soda Ash Produced in Eti Soda A.S. Pilot Plant

Na_2CO_3	$NaHCO_3$	Density	Humidity	NaCl	SO_4^{-2}	Fe	Ca^{+2}	Mg^{+2}	SiO_2
(%)	(%)	(gr/cm^3)	(%)	(%)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)
99,63	0	1,337	0,05	0,126	344,97	0,86	0	0	0

A- Glass Industry
Soda ash is used in the manufacturing of flat and container glass. Acting as a network modifier or fluxing agent, it allows lowering the melting temperature of sand and therefore reduces the energy consumption.

B-Chemical Industry
Soda ash is used in a large number of chemical reactions to produce organic or inorganic compounds used in very different applications.

C- Detergent Industry
Soda ash is used in a large number of prepared domestic products: soaps, scouring powders, soaking and washing powders containing varying proportions of sodium carbonate, where the soda ash acts primarily as a builder or water softener.

D- Steel Industry
Soda ash is used as a flux, a desulfurizer, dephosphorizer and denitrider.

E- Non-ferrous Metallurgy Industry

- Treatment of uranium ores
- Oxidizing calcination of chrome ore
- Lead recycling from discarded batteries
- Recycling of zinc, aluminium

F- Other applications

- Production of various chemical fertilizers
- Production of artificial sodium bentonites or activated bentonites
- Manufacture of synthetic detergents
- Organic and inorganic coloring industry
- Annealing industry
- Petroleum industry
- Fats, glue and gelatin industry, etc.

After these data, importance of soda ash in the industry will be understood better so stepping into the soda ash market will be useful after this point.

DOMESTIC SODA ASH MARKET

The first and the only actor of the soda ash market in Turkey is Soda Sanayii A.S., 37 years old leader with its synthetic production (Soda Sanayii, 2004). The main reason of the establishment of this company was to cover the Turkey's biggest glass manufacturer's (Sisecam) essential raw material named soda ash. Sisecam, which is the leader of glass industry in Turkey, is one of the oldest and biggest companies established in Turkish Republic. Sisecam exports more then %25 of its production to more or less 140 countries so this big company consumes all the soda ash production of Soda Sanayii. It is detail that; in order to manufacture 1,000 kg flat glass, the factory must consume 219 kg soda ash, therefore soda ash is the most important raw material for glass manufacturing after the silica sand (Central Anatolian Exporter Unions, 2001). After this example the importance of soda ash in glass production will be recognized better. It is also valuable to add that; in association with the European Bank for Reconstruction and Development, Solvay Chemicals and the Turkish glassmaking and soda group Sisecam purchased the Bulgarian synthetic soda ash plant in 1997. Because of locating at Devnya, near the port of Varna on the Black Sea, Solvay Sodi and Soda Sanayii possess the world's largest synthetic soda production unit, with an annual capacity of 1.2 million tones (Solvay, 2000).

The main strategy of Eti Soda Company is to export the natural soda ash to Europe and Asia. When we examine the position of Soda Sanayii, we understand that they both have different plans on soda ash business. Eti Soda would like to export it; Soda Sanayii would like to consume it in the glass factories of their company group. Consequently, the real and the biggest difficult will be the international producers, especially American producers and Solvay S.A.

INTERNATIONAL SODA ASH MARKET

Today; soda ash, which is an essential raw material in the glass and chemical industries, consistently ranks among the top ten inorganic chemicals produced in the United States. ANSAC is one of the most important members of the soda ash market with the 1/3 production's exportation in the USA. We can suppose ANSAC as the leader exporter of soda ash in all over the world. ANSAC mostly exports to Canada, Latin America and Asia. Today the biggest problem that US producers come across is the high natural gas costs. The average price was 3,21$/MMBtu in 2002, but today the average price is 8,39$/MMBtu, so this difference impacts the manufacturers to increase the price 20$ per metric tones. The 2003 and 2004 yearend prices of the Wyoming soda ash is written below (Table 6). In addition to this, synthetic soda ash prices varies according to the country; the synthetic soda ash price is 170-180$ fob (abbreviation of free on board, an important international commerce term) per tone in China, 170-180$ fob per tone in India, 200-230$ fob per tone in Europe (Soda Ash Squeezed, 2005). The prices mostly vary according to long or short term contracts and exporting and importing country or company.

TABLE 6 Soda Ash Yearend Prices -Dollars Per Tone-

Year	2003	2004
Sodium carbonate (soda ash)		
Dense, 58% Na_2O 100-pound, paper bags, carlot, works, free on board	150.00-153.0	152.00-159.00
Bulk, carlot, same basis, tons	120.00-132.00	127.00-135.00
Light 58% 100-pound, paper bags, carlot same basis	186.00-210.00	188.00-215.00
Bulk, carlot, same basis, tons	174.00	176.00

Sources: Current prices of chemicals and related materials, Chemical Market Reporter, v. 265, no. 1, January 5, 2004, p. 19; v. 267, no. 1, January 3, 2005, p. 22.

Solvay S.A. is the biggest soda ash producing company in the world. As it was mentioned in the previous pages, this company has several plants in the Europe, USA and have interest on the operating a Solvay-based plant with the Chinese PetroChemical Corporotion, in China. Although it is fact that synthetic production cost is higher then natural manufacturing, Solvay uses the advantages of having an international network of plants and terminals all across the world (Solvay, 2002). Solvay also provides its customers with a global coverage and a long term reliability of supply. As a result of having lots of plants worldwide, Solvay is closing the deficiency.

If I have written this report ten years ago, I would not give information about China – the gigantic country – but today the year 2006 and this giant has become the world's biggest soda ash producing country. Although the high cost of raw materials and a shortfall in salt and the need to import from Australia (Flynn, 2005), this giant is the biggest producer until 2004 and never seems to lose this position.

After all these details, we can step into the Beypazari Trona Deposit's expected effects on the global soda ash market.

EXPECTED EFFECTS ON THE GLOBAL SODA ASH MARKET

Soda ash is one of the most important chemical compounds used in the industry. As I have pointed out before, it can be manufactured synthetically or naturally. Although the synthetic production has almost double production cost according to natural production, most of the countries keep on producing it because of the high transportation prices (Chegwidden, 1996). Although it seems useful to export the natural soda ash from the countries that naturally produce it from the trona ores or the brine lakes, this is not the same in reality. In 2005 only the USA, Botswana and Kenya produced the soda ash naturally and the estimated production was nearly 12 MT (abbreviation of million metric tone) which is the 28% of the world's total production, so the rest, almost 30 MT was produced synthetically

Soda ash demand rises every year because of the increasing in the glass and chemical products demanding. Because of the restriction of the natural sources, the balance year by year moving towards the synthetic production so the companies are ready to pay high values to produce this important industrial mineral. At this point, Eti Soda A.S. will be a strategic actor in the international soda ash. Even though, Eti Soda A.S. will be a new member of the global soda ash market in the coming years, this company will be a strong member with low production costs and well locating in the middle of the world.

First of all, as I have explained before; natural soda ash production has half production expense according to synthetic production. In order to produce 1 tone of synthetic soda ash, the factory must consume 1,4 tones limestone, 1,7 tones salt, 2,8 tones steam, 0,8 tone coke or gas so the manufacturing cost reaches almost 150$ per tone including labor and maintenance costs (European Soda Ash Producers, 2004).

This price will reach more or less 80-90$ per tone for natural production in Beypazari. In addition to this, Eti Soda will use the coal, which Park Holding also mines just 20 km (12 miles) away from the Beypazari Trona Deposits, for heating, therefore the production cost will be lower then the other natural producers.

Secondly, the location of the Beypazari Trona Deposit is the other main advantage of Eti Soda Company. The Wyoming Trona Deposits are located almost in the middle of the USA so that means almost 1,200 km (746 miles) distance to the nearest port and after natural soda ash's reaching to the port; the soda ash must reach to the other continents. When we have a look at the Beypazari Trona Deposits, they are just 200 km (125 miles) away from the Izmit Port. It is fact that USA producers are very well-known and experienced in the soda ash business. Instead of paying very high values for transportation fees, European and Asian costumers will choose exporting it from a closer location.

The synthetic soda ash users -especially in Europe- will also consider this situation and will change their route to Beypazari and export the natural soda ash from Turkey instead of purchasing it by very high prices from Solvay Based Plants in the Europe. When the general plant will be completed in Beypazari, mostly European customers will choose importing it from Eti Soda A.S.

OUTLOOK AND COMMENTS

Global soda ash demand increases almost 2% year by year. Although natural soda ash sources are limited, most companies would like to export it from the well known natural producers, mostly based in the United States. After the year 2004, USA producers have faced of with high natural gas prices and the natural soda ash prices have doubled in two years. Following the price doubling, synthetic producers also increased their prices because of raise in natural gas and raw material costs.

In this case; Eti Soda has many advantages because of low production costs and well locating. The only disadvantage of the company will be to being a new part in the global soda ash market. The only require of being an important member of this market will be to produce successful marketing strategies so Turkey and the Beypazari will gain very important benefits with this well done business.

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Session Five

Earth science education in the museum setting: Exhibits and a whole lot more

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ABSTRACT

The Colburn Earth Science Museum in Asheville, North Carolina has a mission to educate the public in the field of earth science, and to foster an appreciation of the Earth and its natural resources. To this end, the Colburn Museum offers educational programs and exhibits geared toward all segments of the public. These range from a variety of elementary and middle school classes to outdoor trips designed for the nature lover and life-long learner. Subjects covered by the Colburn Museum include geology, gemology, paleontology, meteorology, oceanography, and astronomy.

To meet the needs of public and private school children in grades 1 through 8, the Colburn offers classes specifically geared toward meeting the North Carolina educational competency goals for earth science. Classes incorporate a multitude of hands-on, inquiry-based activities for the kids, using materials that are not readily accessible by teachers. Many classes are also supplemented by related exhibits on the museum floor.

Summer camps and science clubs have been another successful medium for providing children with slightly less structured science educational activities. Three different week-long summer camp programs are offered, giving elementary school kids with an interest in science an alternative to more traditional summer camps.

Programs for adults and families are a key element in our mission. From astronauts to professional spelunkers, speakers in the Colburn's lecture series have brought many families to the museum. In the spring and fall, we also take advantage of Asheville's beautiful natural setting with outdoor programs such as geologic whitewater raft trips and mountain hikes combining area geology with other natural sciences.

Cooperative efforts with local businesses and organizations often help provide very valuable elements to our programs. A good example is our partnership with the Hedrick Industries at the nearby Grove Stone aggregate quarry. The quarry provides an excellent outdoor classroom for hands-on rock and mineral study, and the fascination of quarry operations thrills the kids that visit there.

Constant improvements to our museum displays and educational methods provide the return visitor with new educational experiences year after year.

Potter, Phillip M., 2006, Earth science education in the museum setting: Exhibits and a whole lot more, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

The Colburn Earth Science Museum began in 1960 as the Burnham Colburn Memorial Gem and Mineral Museum. It was named for Burnham S. Colburn, an avid Western North Carolina mineral collector and founder of Asheville's Southern Appalachian Mineral Society. The museum's original charter was to provide a setting where Mr. Colburn's significant collection of North Carolina and other minerals could be showcased to the public.

Through the years, the original mineral and gem collection grew larger thanks to donations from members of the Southern Appalachian Mineral Society and others. As the collection grew, the museum changed its name to the Colburn Gem and Mineral Museum, moved to a larger space, and broadened its scope to more fully encompass the subject of Earth Science and the Earth's resources. Mineral exhibits incorporated more educational themes, and other Earth Science exhibits were built to explain topics like volcanoes, earthquakes, and plate tectonics. The museum also hired an educator and began providing structured earth science classes to public and private elementary school students who ventured to downtown Asheville on field trips.

In 2002, the museum broadened its scope further to become the Colburn Earth Science Museum. We now include not only the subjects of geology, paleontology, and gemology, but cover other Earth systems such as meteorology and oceanography. Space exploration and astronomy are also now part of our focus, as reflected in our educational and public programming.

As the Colburn Museum has been growing and broadening its scope, the very nature of museums across the country and their role in public education has also been changing. One major change is in the educational methods employed in many exhibits. Increasingly, exhibits use hands-on or dynamic elements to demonstrate scientific principles to the visitor in an interactive way. A collection of static objects behind glass, while still a major part of most museums, is often complemented by an interactive component.

Many museums are also reaching out to patrons by offering programs such as a lecture series, outdoor field trips, or other special events outside of the traditional museum activities. A prime example of this sort of non-traditional museum activity is our outreach program conducted in partnership with the Grove Stone Quarry in nearby Swannanoa. The quarry serves as an excellent outdoor classroom for subjects ranging from geology and rocks and minerals to mountain ecosystems and stream ecology. This sort of cooperative effort within our community helps meet the educational needs of local and regional schools, while at the same time creating a platform for private industry to present itself in a very positive light. The quarry not only contributes to earth science education but also preserves the pristine forest that serves as buffer zone around active quarry operations. The quarry and the surrounding forest land make for an outdoor classroom that supports the teaching of diverse geologic and environmental topics. This is a model that could benefit both industry and educators in other communities across the country.

For science museums such as the Colburn, the need has been recognized to reach kids at an early age and instill in them an interest in science. As the rest of the world becomes increasingly competitive with a well-educated work force in the fields science and technology, museums within the United States are looking for ways to steer students toward science disciplines. Many science museums, including the Colburn, offer various science activities for elementary and middle school classes that make science fun.

The modern science museum must employ a multi-faceted approach to reach a broad cross-section of learners with science exhibits and programs that engage them. This is true for learners of any age, but is especially important for younger students and families with children.

THE ROLE OF EXHIBITS

Permanent and traveling exhibits displayed within the walls of the museum are still the educational components that give a museum its identity.

Upon entering the Colburn Earth Science Museum, visitors first encounter the "Hall of Minerals" where our permanent collection of worldwide minerals is displayed according to Dana's 1848 publication, S*ystems of Mineralogy*. Mineral cases are arranged by chemical classes of minerals, and each case has an introductory paragraph explaining the chemical property that defines that class of minerals. This portion of the museum also explains the scientific reasoning and historical basis for this classification scheme, so the visitor learns a bit about the scientific process that led to such a long-lasting method of grouping the thousands of minerals found in the Earth's crust.

A second, very simple element has been incorporated into these cases to further educate the public. Each specimen collected in North Carolina has a small but bold outline of the state in the corner of the label. Thus, at a glance, visitors can see which ones are local minerals. For North Carolina residents, seeing which minerals are found "in their own backyard" helps them identify with the exhibit, and makes it more personal for them. The theme of relating elements of an exhibit directly to the individuals viewing it is important, and is something that is repeated in other exhibits within the museum.

The Colburn's advance into interactive learning through hands-on exhibits began with the opening of the Grove Stone Earth Science Center in 2000. This portion of the museum utilizes models of various geologic features along with interactive elements to engage the visitor with a series of questions and explanations activated by the user. This interactive exhibit covers the Earth's interior, plate tectonics, earthquakes, volcanoes, and mountain-building. A panel explaining the Appalachian Orogeny, along with a large physiographic relief map of North Carolina provide a tie to our local geologic setting.

Interactive elements within an exhibit don't have to be high-tech or even electronic in nature to be effective. One exhibit that adds to an understanding of Earth history consists of a simple puzzle with sliding metal pieces on a magnetic board. Using painted outlines as guides, kids (and adults) can move the world's continents from their current locations to reconstruct the super-continent of Pangaea.

Most recently, we have added a new interactive exhibit. The History of Mining in Western North Carolina is presented with many historical photos and artifacts, but also includes an interactive way for visitors, especially school aged kids, to touch and learn about the beautiful minerals found here, as well as a mine replica complete with visuals and sound effects that allow those entering to experience what it might be like to actually go underground in search or gems.

Interactive exhibits, models, and even such things as replicating an underground mine provide an experiential component to learning Earth Science. Experiential learning has proven to be a very effective method for relating scientific principles to young learners, so while viewing static exhibits may be informative and aesthetically pleasing, participation in an activity or experiencing an environment first hand usually has more of an impact. Indoor exhibits are somewhat limited in their ability to immerse a student in the field of Earth Science. That's why exhibits alone, even interactive and entertaining exhibits, are not enough. Education in today's museum setting is greatly enhanced if programs can extend outside of the museum's walls with outdoor destinations that teach Earth Science where you can see it, in the field.

EXPERIENTIAL LEARNING: THE QUARRY EXPERIENCE

The Southern Appalachian Mountains offer a multitude of opportunities to experience natural science in a variety of locations and environments. As the Colburn Museum was looking for ways to offer Earth Science education in an outdoor setting, one local industry provided the opportunity. Hedrick Industries, owner of the Grove Stone aggregate quarry a few miles east of Asheville, has partnered with the Colburn Earth Science Museum by allowing their quarry as well as the surrounding forested mountain slopes to be used as an outdoor classroom for school groups and summer camp participants attending Colburn Museum programs.

Hedrick Industries participates in a program called WAIT (Wildlife and Industry Together). Through this program, quarry personnel have constructed nature trails, wildlife food plots of native plants, butterfly gardens, and a picnic area. Hedrick has won several environmental awards for implementing these measures at the Grove Stone Quarry.

Working with the Colburn Earth Science Museum, elementary and middle school classes from Western North Carolina and surrounding regions can sign up for a 2 to 3 hour field trip to the quarry, and 2nd through 6th graders attending the museum's summer camps will spend an entire day there. This unique destination provides great learning opportunities in many fields of natural science. Utilizing various vantage points and sites within the quarry property, scientific subjects covered include:

- Plate tectonics and geologic history of the Southern Appalachian Mountains
- Local geologic formations, rock types and mineralogy
- Uses of various industrial and metallic minerals
- Weathering and erosion
- Environmental geology and the importance of watersheds
- Macro-invertebrate stream sampling and stream ecology
- Native plants and wildlife

Visitors to the quarry learn from experiencing the various natural science settings and participating in activities related to that science. First, an overview of plate tectonics and the regional geologic history of the Southern Appalachians is presented as students stand at an overlook above the quarry viewing the Black Mountains, containing the highest peaks east of the Mississippi River. The Valley of the North Fork of the Swannanoa River lies below, creating a perfect opportunity to discuss the importance of watersheds. In fact, the reservoir for Asheville's source of drinking water is quite visible at the head of the valley. Much of the beautiful farm land occupying the valley floor happens to be reclaimed from former quarry operations, offering an excellent example of environmental geology and land reclamation.

Next, the group goes into the quarry itself for a close look at the rock types and the mineralogy of the rocks in the quarry. Features visible in the metamorphic rocks of the Ashe Metamorphic Suite include layering, folding, faulting, and pegmatite lenses and veins. Specific rock types are pointed out, along with the minerals found in the quarry, and collecting of as many rock and mineral samples as the kids can carry is strongly urged. With so much fresh rock material lying around, this is where the kids make their own discoveries. Their own curiosity drives their questions about what's in a particular rock, or how it formed (see Figure 1). And they get to keep the samples. This creates an impact that makes the experience memorable and the science memorable.

For the summer camp kids that stay all day, there's more to learn about the environment, wildlife, and stream ecology. Hiking the nature trail (see Figure 2) lets them experience local plant and animal life in the pristine forest surrounding the quarry. The highlight of the day is usually the macro-invertebrate stream sampling. In small groups, kids use the actual protocol for collecting insect larvae from the creek, identifying them, and using a chart to score the creek based on organisms found in the net. Again, the very memorable experience of participating in the sampling and identification is a powerful learning tool.

Some of the activities that the quarry environment provides are not strictly scientific in nature. The frequent close-up views of the heavy equipment used in an active quarry operation also make the trip memorable (see Figure 3).

In order to augment the information that visitors get from the Colburn Museum's educators, future plans include the posting of outdoor interpretive signage with text and graphics to provide visually appealing explanations of the scientific principles and examples being viewed in a given area of the quarry or surrounding forests.

But the signage will also cover other aspects of the quarry experience. Kids will learn about the product provided by the quarry and how it affects their community (see Figure 4). Other topics may touch on the jobs provided by the quarry and the role played by the quarry in the community's history and development.

The cooperative effort that resulted in the partnership between Colburn and Hedrick Industries has many benefits for both parties, and is a model that mineral or aggregate industries in other communities may wish to consider. As outlined above, the benefits to the museum and our educational programs are obvious. Benefits to industry in such a community partnership include:

- Involvement in a very real way in providing Earth science education to kids throughout the area
- Recognition from local schools that industry is participating as a good neighbor to the community
- Presenting industry to the community as a whole in a very positive light
- Recognition among industry peers of the proactive role being played in education and community relations

The Colburn Earth Science Museum is fortunate to be involved in this museum/industry partnership, and plans to continue to find ways to utilize this excellent teaching location to include as many learners as possible.

CAVES AND CLIFFS: OTHER OUTDOOR CLASSROOMS

Though the Grove Stone Quarry provides our most important and useful outdoor classroom, other periodic museum programs involve participants in experiential learning opportunities. Two examples are fieldtrips to Worley's Cave in Tennessee, and hikes to Looking Glass Rock in Western North Carolina.

For the past several years, the Colburn Museum has offered a program featuring Nancy Aulenbach, a well-known caver who starred in a National Geographic IMAX film on caving in the Southwest US. Along with the excellent program presented by Nancy about her caving experiences, the event includes a caving trip the day before for those interested in seeing the inside of a cave for themselves, guided by a real expert (see Figure 5). Besides the adventure of it all, a natural cave offers a great outdoor classroom for the geology of carbonate rocks. Again, the extension of the museum out into the natural environment creates a way to experience this type of geology through more than just text and graphics.

The same can be said about our trip to Looking Glass Rock. Participants in this program hike to the base of the rock face to learn about the history of the Precambrian metamorphic rocks of the Ashe Metamorphic Suite, and the Devonian igneous intrusions scattered through this part of the Southern Appalachians (see Figure 6). A unique feature about this trip is the presence of a Peregrine nesting area in the side of the mountain. The geology ties directly to the overhang containing the nesting area, so hikers can see the real influence that the rocks have on other aspects of the environment. Hearing the actual cry of a Peregrine as hikers approach the rock is an experience that can't be captured in the museum. The experience makes for more memorable learning of both the geology and the Peregrines.

CONCLUSIONS

Experiential learning in the field of Earth Science or any of the natural sciences makes the learning experience more enjoyable and more memorable. As the United States strives to maintain a competitive level of science education for our future workforce, informal education providers such as museums can play an important role in that education, both as a resource for schools and for families and individuals. The ability to provide learning opportunities outside the museum walls is critical, and cooperative partnerships with private industry can be beneficial to all parties involved.

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Geology and mineral resource education at Georgia Southern University: A seventeen year retrospective, and a bright outlook

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ABSTRACT

The Department of Geology and Geography at Georgia Southern University (GS) maintains a history of teacher preparation by providing opportunities for pre-service and in-service teachers to learn basic science concepts in classroom and field settings. In 1988, the authors began teacher education classes with federal funding through the Eisenhower Higher Education Act, now known as Improving Teacher Quality (ITQ). The ITQ-funded St. Catherines Island Sea Turtle Conservation Program provides fundamental science training as a field laboratory for coastal geology studies and serves critical conservation needs. The NSF-funded Partnership for Reform in Science and Math provides additional current funds to teach a growing population of teachers that must teach earth science in the 6th grade.

Industrial minerals have been a logical focal point for many classes. Teachers and students can appreciate the value of mineral components in a computer, CD player or car, making the subject matter fascinating, practical and relatively easy to teach. Field trips to kaolin pits, granite quarries, marble mines, glass sand deposits, kyanite deposits, various aggregate quarries, heavy mineral deposits and barite deposits allow teachers to build individual collections of samples and photographs upon which to construct lesson plans. Students at GS are introduced to industrial and metallic resources in the Environmental Geology Laboratory Course. An NSF grant (DUE 0311730) allowed the purchase of a Rigaku Mini-Flex XRD unit and JADE search-match software allowing students to identify mineral components in household products and construction materials. Another exercise examines potential mineral hazards such as asbestos and silicosis with a balanced view of risk management and regulation. The labs fulfill part of the core-curriculum lab-science requirements exposing a large, diverse cross-section of students to mineral science. Emphasizing mineral science in both undergraduate curriculum and graduate/enrichment courses for teachers is essential to improve public awareness of our industrial mineral requirements. The development of earth science learning communities promotes continuing earth science education programs and the dissemination of essential information and specimens to active teachers.

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INTRODUCTION

Interaction with the general public, coupled with many years of teaching introductory geology courses to college freshmen, as well as advanced courses for geology majors and teachers in graduate school, consistently demonstrates that there is very limited knowledge and appreciation for the ultimate source of raw materials required for basic construction and manufacturing needs. Unfortunately, this lack of appreciation for the essential role of industrial minerals also extends to the highest levels of government. In the winter of 2006 the U. S. Geological Survey is faced with the prospect of a $22 million cut in the Mineral Resources Program, the division that includes the national and international mineral commodity tracking program (see President's 2007 Budget Request). The lack of public knowledge of the sources of industrial minerals, and ignorance regarding industrial mineral applications may influence the direction of state or national regulatory trends, with negative consequences for mineral resource industries. At the local level, the lack of appreciation for industrial minerals can impact community decisions regarding land use planning and the general outlook toward the mining industry. For example, quarry operators near towns might well conform strictly to all environmental regulations and make substantial efforts to be "good neighbors" with landscaping being designed to conceal the operation in an attractive manner, reduce noise and suppress dust. Additional efforts could include scheduling blasting at times that minimize annoyance to local residents. In spite of these best efforts, however, the operators might still face an "uphill battle" for new permits or expanded operations if the public does not understand the application or essential need for the raw material.

The Department of Geology and Geography at GS has addressed this general lack of mineral resource knowledge by using the topic of industrial minerals as a logical and successful teacher education vehicle for exploring fundamental geologic principles, developing a working knowledge of the geologic framework of Georgia and building personalized teaching kits. Additionally, mineral resource education is a standard part of the introductory courses offered by the Department to satisfy the laboratory science and environmental science requirements of all GS undergraduates. Further to that, geology majors and science education majors can also take a one semester course in Economic Mineralogy as an upper level elective.

INDUSTRIAL MINERALS AND TEACHER EDUCATION ROGRAMS

Eisenhower Courses

Georgia Southern has a 100-year history of serving the education needs of southeast Georgia, beginning as the First District A & M School in 1906. The institution also has a strong record of teacher education and was known as South Georgia Teachers College from 1929 through 1938, and Georgia Teachers College from 1939 through 1958 (GS 2004/2005 Fact Book). Georgia Southern continues teacher education through the College of Education programs and the supporting courses and workshops offered by other Departments. Authors Bishop, Rich and Vance began teacher education efforts in 1989 when the federal Eisenhower Higher Education program provided a source of funds (Improvement of Mathematics and Science Instruction in Georgia) that supported summer programs for Georgia teachers. These programs were in great demand as delivery of the Earth Science curriculum shifted to the 8th grade, leaving many teachers unprepared. The Department of Geology and Geography offered concurrent summer courses such as “Geology of Georgia” and “Georgia’s Mineral Resources” to provide teachers with maximum graduate credit for degree programs or Staff Development Units (now known as Professional Learning Units, or PLU’s) for non-degree work. Courses and funding sources are summarized, with other program details, in Table 1. The courses can be month-long and are intensive (~ 130 contact hours) with a typical week consisting of 4 hours of lecture or laboratory instruction per day for two or three days, followed by field trips of two to three day duration.

Table 1 Mineral Resource Education at Georgia Southern University

Year	Courses/Program	Target Audience	Funding Source
1989 – 1995	Georgia’s Mineral Resources, Intro. To Industrial Minerals, Mineral Resources of S. Appalachians, Paired with: Field Geology of the Southeast U.S., Principles of Geology, Geology of Georgia	In-service and pre-service teachers (Mostly 6-8, but K-12 accepted)	Federal→state: Eisenhower Higher Education - Improving Secondary Math and Science Instruction in Georgia
1992 – present	Sea Turtle Natural History, Sea Turtle Conservation courses via the St. Catherines Island Sea Turtle Conservation Program	In-service and pre-service teachers (K-12)	Federal→State: Eisenhower Higher Education - Improving Secondary Math and Science Education in Georgia Southern University (now Improving Teacher Quality Professional Development Higher Education Program)
1991 – Present	Economic Mineralogy	Geology majors, science education majors	Faculty Course Development Grant for pilot course State (faculty salary – regular course)
1999-present	Environmental Geology (Intro. Level)	Undergraduates of all majors	State – regular course plus NSF CCLI Grant (DUE 0311730)
2005-Present	Geology Workshops	Pre-service and in-service teachers (K-12)	NSF PRISM (Partnership for Reform in Science and Math) MSP grant EHR 0314953

The Eisenhower-funded courses and field trips have been organized using the physiographic provinces of the southeastern U.S. as a framework. Field trips employed a uniformitarian approach, exploring fundamental geologic processes and depositional environments along the modern coast before working inland through older strata. Exploring the interaction of tides, waves and wind on the active beach and dune fields provides a chance to examine the active concentration of Heavy Mineral Sands (HMS) as beach placers. One group followed beach studies with a visit to E.I.DuPont de Nemours and Company's Trail Ridge mining and processing facility near Starke, Florida. Field excursions have typically worked into progressively older strata across Coastal Plain deposits, culminating in visits to active pits and quarries such as Martin Marietta's Berkeley limestone quarry in South Carolina. The Berkeley quarry provides historical geology lessons, with excellent Coastal Plain fossils, as well as presenting a great platform to introduce limestone as one of the premier industrial resources on the planet. Open pit kaolinite mines along the western edge of the Coastal Plain provide unparalleled vertical exposures of older strata as well as allowing for an introduction to Georgia's most important industrial mineral. Visits to Thiele Kaolin Company's Avant Mine, processing plant and research labs and to ECC's (now IMERYS) Buffalo China Mine at Sandersville and the J. M. Huber mines and processing facilities (Figure 1) near Wrens supplied important Georgia teaching samples and images for the teachers for instruction in the laboratory and classroom.

Excursions to the deeply weathered igneous and metamorphic rock of the Piedmont province have provided excellent uniformitarian exercises, allowing teachers the opportunity to explore the present exposures of eroding saprolite to understand the ancient chemical weathering and erosion that played a critical role in formation of Georgia's Cretaceous and Tertiary kaolinite deposits. Piedmont excursions have also included visits to outcrops of serpentine, talc and vermiculite with sample collection and discussions of the origins of, and the present and past applications of these materials. Graves Mountain, Georgia, is best known for world class specimens of rutile; however, the "mountain" was mined for kyanite. This deposit of kyanite-quartz granofels was an important regional refractory resource until mining ceased in 1984. Unfortunately, the high pyrite content made the mine an acid drainage liability. The efforts to contain, neutralize and monitor the site provide lessons in environmental responsibility. South Carolina became a significant gold producer following the rise in gold prices in the 1980's; consequently, the active mines at Barite Hill and Ridgeway, and some historic deposits such as the Dorn Mine were part of the field trip menu. Georgia has long been a leading producer of granite monuments; therefore, a visit to Elberton was required, with stops at the Granite Museum, several granite quarries and one of the Keystone Memorials finishing plants. Some of the Piedmont trips also included visits to the saprolitic pegmatitic granites that host economic muscovite deposits near Hartwell, Georgia. Tours of the muscovite mines enhanced understanding of igneous resources, the weathering process and the many applications of fine, pulverized muscovite.

Blue Ridge excursions included trips to explore the feldspar, mica, and quartz production from the Spruce Pine pegmatite district in North Carolina. Georgia stops included tours of the underground marble operations of Georgia Marble at Marble Hill. Visits to the Dahlonega Gold District added an important historical perspective relative to the great eastern gold rush of the early Nineteenth Century and allowed for another chance to explore metallic resources. Talc deposits in the fault zone at the base of Fort Mountain have provided a chance to examine that industrial mineral and the impact of asbestos legislation on a local mineral industry.

The final part of the physiographic province transect (Valley and Ridge and Appalachian Plateau) included visits to high purity quartz sand deposits (Short Mountain

Silica) and the Idol zinc mine in eastern Tennessee. The Idol Mine produced zinc ore, but kept the operation viable while zinc prices were low, by selling limestone and dolostone "waste rock" for agricultural "lime" and aggregate. Additional stops in eastern Tennessee added new samples to the industrial minerals list with visits to the inactive Ballard barite mine, where teachers collected samples of barite, fluorite, and pyrite in a coarse dolomitic host typical of Mississippi Valley Type Deposits. The concept of residual ore deposits has been developed with visits to the New Riverside Ochre Company barite pits and Fe-oxide pigment operations at Cartersville, Georgia (Figure 2).

St. Catherines Island Sea Turtle Conservation Program

The St. Catherines Island Sea Turtle Conservation Program was developed through conservation work during 1990 and 1991 and was implemented in 1992 as a long term Loggerhead Sea Turtle research and conservation program that also trains teacher interns in scientific data collection and interpretation as they perform conservation duties (Marsh and Bishop, 1994). The extended hours working on the beach (Figure 3) provide time to examine the role of the tides, waves, and wind that shape the beach. Accumulation of HMS in several areas provide another "Present is the Key to the Past" teaching opportunity that is relevant to recent HMS mining operations and concentrations in older Coastal Plain strata in Florida, Georgia, and Virginia. HMS samples collected on the beach provide class and lab opportunities to explore the properties of placer minerals and to explore the provenance of the HMS suite. Distinctive beach environmental markers such as ghost shrimp burrows can be examined and applied to facies recognition and the exploration of HMS deposits in ancient strata (Bishop and Brannen, 1993). Initial funding for the long-running St. Catherines program came through the Eisenhower Higher Education program and is continued today through funding from the Improving Teacher Quality program (ITQ).

PRISM

The NSF Partnership for Reform in Science and Math (PRISM) grant provides additional opportunities for teacher education through workshops and partnerships with ITQ programs. The delivery of earth science in the Georgia K-12 curriculum has shifted once again (now being at the 6th grade) with the new Georgia Performance Standards; PRISM is helping teachers meet the challenge. A typical geology workshop during the summer of 2005 included a fossil collecting trip, basic mineral and rock identification training with assembly of teaching collections, plus an X-Ray Diffraction (XRD) exercise to investigate industrial mineral components in floor tiles and other common building materials. The XRD approach led the teachers to consider numerous new ways to use industrial mineral applications to introduce rocks and minerals to their students. The PRISM grant has also fostered the development of earth science learning communities that promote continuing earth science educational programs with both the formal and informal dissemination of information and teaching materials.

INDUSTRIAL MINERALS IN UNDERGRADUATE EDUCATION

Although mineral and rock identification have always been part of physical geology laboratory exercises, instructing students as to the applications of these materials is usually a minor footnote. An in-depth course in economic geology is necessary to fill this void in the education of geology majors. After a successful pilot course in1991, Economic Mineralogy was added to the curriculum at GS to serve geology majors and science education majors. Traditional Economic Geology courses focus on the study of metallic resources; this course devotes equal time to industrial minerals (Figure 4). In 1999, the Department of Geology and Geography began using an in-house laboratory manual (Reichard, 1999) for all Environmental Geology laboratory classes. Industrial and metallic mineral resources are the primary focus of the first chapter in this manual, serving as the delivery vehicle for general mineral and rock information. In 2003, XRD exercises were added to the lab manual as part of a project-based learning approach (Asher, Vance, and Jenkins, 2004 and 2005; Vance, Asher, and Jenkins, 2004) to the study of industrial minerals by exploring both household products and construction materials. Students also explore mineral hazards such as silicosis and asbestosis with a balanced presentation on realistic versus perceived health risks and the history of product use and legislation. This development was made possible through an NSF CCLI grant (DUE 0311730) to purchase the XRD unit and support equipment, and summer salaries to develop the exercises and supplies. Students and teams of students investigate household materials such as make-up and cleansers as well as common construction materials to determine the mineral content and evaluate the role of the mineral in the product. The students prepare and scan their samples, and use the JADE search/match software program to identify the diffraction patterns (Figure 5). The use of this technology at the introductory level has dramatically raised enthusiasm for learning about industrial minerals.

CONCLUSIONS

Although economic growth demands a continuous supply of industrial minerals for construction materials and fabrication of countless everyday items, few people make the connection between the limestone quarry and the Portland cement in their home foundation, garage or driveway, or between the mica and the joint compound used in their home, or between the kaolinite and titanium dioxide and the coating on their high gloss paper. It is essential that industrial minerals operations staff, geology departments, and teachers of all grades maintain a concerted effort to educate the public regarding the essential nature and everyday application of these materials. Courses for teachers are a superb “force magnifier” in this effort as the number of students that “get the message” grows continuously, and exponentially, through time. Accommodating teachers and other educational groups with tours of mines and processing facilities is a solid public relations investment. The teachers receive a good overview of modern mining practice with tours of active mines, reclaimed land (Figure 6), discussions of community and state economic impact and a valuable first-hand look at the science and applications of industrial minerals. The tours of the processing plants and research labs reveal many applications of chemistry and physics that stimulate new ideas for delivering science to the students. Teachers deliver this information to their students with more energy and enthusiasm because they possess first hand experience exploring the geology, collecting samples, and taking pictures! This process repeats in class after class, year after year with each teacher impacting hundreds or thousands of students. Consequently, whether it is a few hours or a full day that a mining company donates to educating a few teachers, that effort may be the best public relations investment of all.

The best mine visits include constructive interaction among mine staff, teachers, and professors. Teachers relay common student misperceptions (Obtained from parents?) or general lack of knowledge about the mineral or product to the mine geologists, engineers, or supervisors. Mine staff have an opportunity to relay correct information through the teachers to the students to the parents, and to exchange ideas with the teachers for delivering mineral science to the students and public. Professors learn much from the mine staff, updating their economic geology knowledge and their understanding of the local geology. Geologists, engineers, and professors get a chance to exchange non-privileged information on deposit genesis, characteristics, prospecting or delineation. Each group should play an active role in minerals resource education.

The Department of Geology and Geography at Georgia Southern has aggressively promoted industrial minerals education through teacher programs that have evolved to fit the changing educational mandates in the nation and Georgia. The Department provides advanced industrial minerals education for geology majors but also uses industrial minerals as a vehicle to deliver mineral science to undergraduates of all majors in introductory level Environmental Geology laboratories. Targeting both teachers and students greatly expands the audience and maximizes the impact of this effort.

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Short Mountain Silica, TN and Darrell Trigg
The St. Catherines Island Foundation and Royce Hayes
Thiele Kaolin Company (Sandersville) and Ed Riley and Michael Smith

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FIGURE 1 Fred Rich (left) and Eisenhower program teachers touring the JM Huber kaolinite processing facilities between Wrens and Thomson, Georgia.

FIGURE 2 Stan Bearden (New Riverside Ochre Company, Inc.) uses a barite-rich Cartersville road cut to explain the development of a residual ore deposit to one of the Eisenhower program teachers.

FIGURE 3 Nancy Marsh (with shovel) and Gale Bishop (black pants) train a group of teacher interns at the site of a Loggerhead Sea Turtle crawlway and nest on a St. Catherines Island beach.

FIGURE 4 Thiele Kaolin Company geologists Ed Riley (with shovel) and Michael Smith (red shirt) teach a group of Georgia Southern Economic Mineralogy students at the Avant Mine near Sandersville.

FIGURE 5 **Undergraduates taking the Environmental Geology Laboratory course at Georgia Southern use JADE search/match software and a Rigaku Miniflex XRD unit to identify the mineral components in household products and construction materials.**

FIGURE 6 Fred Rich (green shirt) and Eisenhower program teachers view reclaimed mine land at an overlook near ECC's (IMERYS) Buffalo China Mine Six.

The Spruce Pine Mining District – A brief review of the history, geology, and modern uses of the minerals mined in the Spruce Pine Mining District, Mitchell, Avery and Yancey Counties, North Carolina

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ABSTRACT

The story of prospecting and mineral production of the Spruce Pine Mining District began before recorded time when Native Americans mined for glittering muscovite mica during the Woodland Age 2000 years ago. From Native American grave decoration to semi-conductor computer chips and tiles for the Space Shuttle, the Spruce Pine Mining District has been providing vital minerals for mankind. These minerals, including Feldspar, Quartz, and Mica are used in many applications of our daily life.

It took colliding continents, plutonic heat, and millions of years of cooling to place this rare geologic source in the once mighty and lofty Appalachian Mountains. These mountains, now worn and distinctly beautiful lie in western North Carolina within sight of the small town of Spruce Pine, North Carolina – nicknamed 'The Mineral City'.

Glover, Alex, 2006, The Spruce Pine Mining District – A brief review of the history, geology, and modern uses of the minerals mined in the Spruce Pine Mining District, Mitchell, Avery and Yancey Counties, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

HISTORY

The story of prospecting and mineral production of the Spruce Pine Mining District began before recorded time when the "Ancients" mined for glittering mica during the Woodland age 2000 years ago. The Ancients, an early name given to the Native Americans by settlers of the area, mined mica for grave decoration and wampum, which they traded as money. The mica is known to have been traded as far away as the Ohio valley and is believed to have originated from Native American mines in the Spruce Pine area now known as the Clarissa, Ray, and Sinkhole mines. Legend is that this mining of mica led Hernando Desoto to the Spruce Pine area around 1540 in search of mineral wealth that he thought to be gold and silver. He found only silver mica better know as muscovite mica.

Later, around 1744, legend is that Cherokee Indians mined semi-weathered feldspar and kaolin from the Spruce Pine pegmatites and used oxen drawn sleds to transport it to the coast where it was loaded on ships bound for England. In England it was used as an ingredient for patented English ceramic wares.

From 1767 to 1911, mining of feldspar and mica occurred sporadically. Mica was mined to fuel the demand for the newly developed Edison electric motor in 1878. The motor required the electrical insulting properties of sheet mica.

Around 1910, gem prospector William E. Dibbell of Baltimore became interested in the large waste piles of feldspar discarded by early mica miners. He sorted material from the Flat Rock Mica mine near Penland and hand scrubbed it with steel brushes to enhance purity for trial shipment to the Golding Sons Ceramic Plant in East Liverpool, Ohio. Management of the Golding Sons Plant liked the ceramic grade feldspar so much that they contracted Dibbell to supply more. This led to Dibbell receiving bank backing to organize the Carolina Minerals Company of Penland. The first production load of feldspar was shipped from the Deer Park mine in 1911 and eventually supplied Golding Sons Ceramic Plants in Trenton, Wilmington, and East Liverpool, Ohio.

Three years later, in 1914, feldspar-grinding plants were built in Erwin, Tennessee by the Clinchfield Mineral and Milling Company. This plant was organized by Charles Ingram and financed by Blair and Company of New York. This same company financed building of the Clinchfield railroad, which was completed in 1908.

In 1917 North Carolina became the primary feldspar producer in the US and has continued to maintain that status ever since. Feldspar grinding continued in Erwin, TN along with new feldspar plants constructed in 1921 at Beaver Creek, NC and in 1923 at Micaville, NC. As the feldspar industry became more active and prosperous, many investors and producers were starting new companies and buying others. Feldspar and mica were being hand mined at hundreds of holes, pits, and mines throughout Mitchell, Avery, and Yancey counties, which make up the Spruce Pine Mining District.

Until 1949 most work, especially ore separation of minerals, was done by hand with crude machinery and hand tools. In 1949, the process of chemical separation of minerals was jointly developed by the Feldspar Mining Company, The North Carolina Feldspar Corp., The Tennessee Valley Authority, and The North Carolina State Mineral Research Laboratory of Asheville. This process led to the current large volume, high capacity process of separating the minerals of feldspar, mica, quartz, and garnet from the rock (ore).

GEOLOGY

The geologic history of Spruce Pine Mining District is as fascinating as its mining history. About 380 million years ago the African Continent was being forced toward the Ancestral Eastern North American Continent by plate tectonic force. The subduction, or forcing down of the Oceanic Crust underneath the North American Continent produced tremendous friction-generated heat from the two colliding continents.

This friction-generated heat in excess of 2000(F melted the surrounding rock 9-15 miles below the surface. This igneous molten rock was generated under intense pressure that forced the molten rock into cracks and fissures of pre-existing rock. This molten rock under pressure is similar to hot hydraulic fluid being forced into a chamber. Due to the pressure exerted on the molten fluid, it hydraulically pushed its way through the cracks of the host rock. This opened the rock up, along with melting contact areas of the host rock and sucking up rich mineral forming fluids. As these cooled, they crystallized and became a mineral rich buried treasure.

It then took an estimated 100 million years for this deeply buried (and insulated) mass to cool and crystallize. The slowly cooling mineral crystals grew within the Spruce Pine District to some of the largest feldspar and mica crystals in the world. After molten emplacement and cooling, it took millions of more years of Appalachian Mountain building and subsequent erosion to expose the deposits we see today.

TODAY'S USES

Modern day mining methods, research, plant production, and product development have enabled the use of these high purity natural resources from the earth to enhance our quality of life.

Feldspar

Feldspar is a major ingredient in the manufacture of many types of glass, from automobile windshields and computer screens to baby food bottles and electric light bulbs. Feldspar comprises about 65% of the rock from the Spruce Pine pegmatite and is a major source of aluminum, sodium, and potassium for glass manufacturing. Feldspar provides aluminum, which improves glass workability during forming, retards glass blooming, improves glass strength, and imparts resistance to thermal shock. About 110 pounds of feldspar is used to make a ton of container glass (bottles and jars) and about 100 pounds is used to make a ton of flat glass (auto windshields and window glass).

Feldspar is also a major ingredient in the manufacture of ceramic products. It acts as a flux to fuse (melt) other ingredients at lower temperatures; it cements the crystalline phases of other ingredients together; and it imparts strength, durability, and toughness to ceramic bodies. Feldspar's special qualities and glazing properties allow ceramic product manufacture of pottery, plumbing fixtures (sinks and toilets), electrical porcelain, ceramic tile, dinnerware, structural ceramics, art pottery, planters, and much more. The use of feldspar in the manufacture of ceramics has come a long way since its development during the Tang Dynasta of China around AD-621 to 945.

Mica

Mica, another ingredient from the rock of the Spruce Pine Mining District comprises about 10% of the rock mass. Once highly valued for wood and coal burning stove windows (often called isinglass) and for radio tube insulators during both world wars, it is now used as an industrial products special additive.

Muscovite, which is silver to white mica variety, is mostly ground to a fine particle size. It is valued for its flat particle shape. It is used mostly as a major ingredient of dry-wall joint compound or sheetrock joint cement. Muscovite's flat particle shape and light color allow it to serve as an anti-shrinking agent for the cement after it is applied to sheet rock joints. It applies as smooth damp putty, but because of muscovite mica's flat particle shape, it interlocks the mud as it dries, therefore reinforcing the mud as it dries-without shrinkage. It also acts as a fire retardant within the sheet rock joint.

Mica is also produced from the Spruce Pine Mining District for use as special electrical insulators, automobile metallic flake paint, women's make-up, and as a reinforcing additive in special plastics, and paints. It is used in oil well drilling fluids to seal and lubricate the borehole during drilling.

Quartz

Another major ingredient of the Spruce Pine rock is quartz. Through the years, quartz was always discarded as waste. Now it is recovered through froth flotation and is used as industrial sand in concrete and concrete mortar. It is also a highly valued white golf course trap sand and is sold across the country to the finest golf courses including, the Augusta National, the host for the Masters.

Comprising about 25% of the rock, the quartz has now become one of the most strategic minerals of the entire world. Because of its extreme purity, it is used in several critical process steps during the manufacture of computer semi-conductors (chips). At present, no other quartz in the world can match the processed quartz purity from the Spruce Pine District. As a matter of fact, every computer chip in the world uses Spruce Pine quartz in its' manufacturing process.

Also of high value to the lighting industry, the Spruce Pine quartz meets stringent purity requirements to serve as extreme high temperature light tubing required for light bulbs installed in automobiles, streetlights, and film projectors.

SUMMARY

It is amazing that this small 25 mile long by 10 mile wide pegmatite of the Spruce Pine Mining District (lying in Mitchell, Avery, and Yancey counties of North Carolina) is so important an ingredient for making products we use everyday. We often take for granted its role in the quality of life that we enjoy today.

The Spruce Pine District's importance has increased as mankind's need for minerals has progressed from early Native American burial decoration to space-age computer parts of today. Even more amazing is the fact that it took colliding continents to place this valuable resource in such a beautiful area as the Western North Carolina Mountains.

Feldspar: Ceramic application review

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ABSTRACT

Feldspar is the most common mineral comprising perhaps as much as 60% of the earth's crust. There is a range of uses from fillers to abrasive to fluxing of ceramic bodies (including glass sanitaryware and ceramic tile). The focus of this discussion is on what it does for the ceramic body with specific review of the its sue in sanitaryware and modern ceramic tile production.

Feldspar from the Spruce Pine, locate in Mitchell County, North Carolina area is a mixture of Albite ($NaAlSi_3O_8$), Orthoclase ($KAlSi_3O_8$) and Anorthite ($CaAl_2Si_2O_8$). This mineral series provides significant fluxing (lowering of glass forming temperature) contribution to the ceramic body.

The presentation will review touch briefly on the phase diagram of the body as well as general ranges of feldspar use in the bodies and some of the economic contribution of feldspar.

Click here for the presentation (~628 kb MB) – MS PowerPoint format only

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Leach, Billie E., 2006, Feldspar: Ceramic application review, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Geology of the Day Book Dunite, Yancey County, North Carolina

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ABSTRACT

The Day Book Dunite is one of several Alpine-type ultramafic bodies in the southern Appalachians. Evaluation of the tectonic history of the region and the petrogenesis of the ultramafic rocks indicate that these bodies represent oceanic crust obducted onto the Laurentian margin during the Ordovician Taconic orogeny. Regionally, these ultramafic rocks are associated with metapelitic rocks (metamorphosed ocean floor sediments), amphibolite (metamorphosed ocean basalt), and eclogite (subduction-related metamorphic rocks). This lithotectonic suite of rocks is interpreted to represent an accretionary complex associated with the closure of an ocean basin (Iapetus?) during early stages of the Taconic orogeny. All of the rocks in the region show evidence of deformation and metamorphism resulting from the multiple Paleozoic orogenic events in the southern Appalachians. While the Day Book body is predominantly a dunite, virtually all of the ultramafic bodies in this area show some evidence of alteration with the dominant hydrous phases including serpentine, talc, and anthophyllite.

Unimin Corporation currently mines olivine from the Day Book Dunite in the Green Mountain area of Yancey County, North Carolina. The primary applications for the olivine are in the foundry and refractory industry. The annual average production for the olivine mine is approximately 30,000 tons.

Adams, Mark, 2006, Geology of the Day Book Dunite, Yancey County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Ultramafic rock is a general name given to a plutonic rock composed of at least 90% ferromagnesian minerals (Streckeisen, 1976). This rock classification includes, among others, dunite, peridotite, and pyroxenite. Alpine-type ultramafic rock bodies are found as masses occurring in the folded rocks of orogenic belts. Numerous Alpine-type ultramafic bodies occur along the Appalachian orogen from Alabama to Newfoundland. Generally these bodies are relatively small, isolated blocks (<1 m to > 1 km across) that tend to be associated with, or are close to, terrane boundaries or other major structural features. All of the ultramafic rocks in the Blue Ridge belt have been metamorphosed to some degree and, as such, are no longer considered plutonic rocks, *sensu stricto* (Scotford and Williams, 1983). Although the occurrence of these rocks have long been known (Keith, 1905; Pratt and Lewis, 1905; Hunter, 1941; Hess, 1955; Larrabee, 1966), more recent understanding of the petrogenesis of these rocks and the lithotectonic associations of adjacent rocks and structures have lead to the recognition that these rocks mark sutures of plate boundaries within the orogen (Hatcher, 1978; Abbott and Raymond, 1984; Horton et al., 1989; Raymond et al., 1989; Willard and Adams, 1994; Adams et al., 1995; Adams and Trupe, 1997). While the economic significance of these ultramafic rocks have been realized for over 100 years, complex geologic relationships resulting from the overprinting effects of multiple metamorphic and deformation events, combined with ignorance of modern concepts of structural geology and tectonics, have inhibited many earlier workers from recognizing the petrogenesis and the tectonic importance of the occurrence of the rocks.

The Day Book Dunite (or more appropriately “Meta-dunite”) is one of more than 200 ultramafic bodies that occur in the Blue Ridge belt of the southern Appalachians (Hunter, 1941). The mineralogy of some of these bodies reflects the original protolith, while others are totally overprinted by subsequent metamorphic phases. Several of these small bodies have historically been utilized for their economic minerals, such as corundum, olivine, chromite, vermiculite, and asbestiform minerals (Hunter, 1941; Hunter et al., 1942; Murdock and Hunter, 1946; Conrad et al., 1963). This paper provides a brief overview of the regional geology, the petrogenesis and economic geology of the Day Book Dunite.

REGIONAL GEOLOGY

The Day Book Dunite lies within the Blue Ridge thrust complex of northwestern North Carolina (Figure 1). The Blue Ridge thrust complex in the vicinity of the Grandfather Mountain window consists of a series of crystalline thrust sheets bounded by shear zones up to a kilometer thick (Goldberg et al., 1986, 1989; Butler et al., 1987). The complex forms the hanging wall of the Linville Falls fault and is bounded on the west by the Stone Mountain-Iron Mountain-Hol Mountain fault system and on the west by the Brevard fault zone. The individual thrust sheets show evidence for distinct tectonic and metamorphic histories.

The structurally highest thrust sheet in the Blue Ridge thrust complex is the Fries sheet. The Fries sheet is composed of two major lithotectonic units: the Ashe Metamorphic Suite and the Pumpkin Patch Metamorphic Suite. The Ashe Metamorphic Suite consists predominantly of high-grade metavolcanic rocks (amphibolite) and metasedimentary rocks (pelitic schist and gneiss). The Ashe Metamorphic Suite also contains isolated blocks of ultramafic rocks, rare eclogite, rare marble, and Paleozoic granitic intrusive rocks of the Spruce Pine Plutonic Suite. The majority of the ultramafic rocks in northwestern North Carolina occur within the Ashe Metamorphic Suite. The Ashe Metamorphic Suite is juxtaposed with the Pumpkin Patch Metamorphic Suite along the Burnsville fault. The Pumpkin Patch Metamorphic Suite is composed predominantly of Mesoproterozoic gneisses with subordinate Neoproterozoic mafic and granitic intrusive rocks. The rocks of the Pumpkin Patch Metamorphic Suite are undisputedly associated with the Laurentian continent, while the rocks of the Ashe Metamorphic Suite are of less certain affinities.

The remaining thrust sheets of the Blue Ridge thrust complex lie structurally below the Fries thrust sheet and are separated by thick, Paleozoic shear zones. Immediately below the Fries sheet is the Stone Mountain thrust sheet. Like the Pumpkin Patch Metamorphic Suite, Mesoproterozoic gneisses with Neoproterozoic mafic and granitic intrusive rocks dominate the rocks of the Stone Mountain thrust sheet. However, the Paleozoic metamorphic history of the Stone Mountain thrust sheet differs from the Pumpkin Patch Metamorphic Suite in that the pervasive metamorphic grade in the Stone Mountain sheet is greenschist facies as opposed to upper amphibolite facies (or higher) for the Pumpkin Patch Metamorphic Suite (Adams and Trupe, 1997). Other thrust sheets below the Stone Mountain sheet are dominated by Paleozoic sedimentary rocks of the Laurentian margin and show progressively lower grades of metamorphism.

All of the rocks in the Ashe Metamorphic Suite show evidence of metamorphism, some exhibiting evidence for multiple metamorphic events. Butler (1973) describes evidence for at least three metamorphic events affecting the rocks of the AMS, corresponding to the Taconic, Acadian, and Alleghanian orogenies. Abbott and Raymond (1984) recognize two additional metamorphic events evidenced only in the ultramafic rocks. Isotopic data from various rocks in the AMS are consistent with at least three Paleozoic thermal events in this part of the Appalachian belt (Goldberg and Dallmeyer, 1997; Miller et al., 2000).

Most interpretations for the origin of the Ashe Metamorphic Suite include opening of an ocean basin (Iapetus ?), or rift basin, east of (present-day reference) Laurentia during the Late Precambrian. Opening of this basin necessitated generation of oceanic crust, including ultramafic rocks and ocean basalts. Clastic material shed from adjacent continental crust was deposited into the basin. These processes resulted in the generation of the protoliths of the rocks of the Ashe Metamorphic Suite, i.e., ultramafic rocks, basalt, and ocean-floor sedimentary rocks (shale, siltstone, sandstone). Closure of the ocean basin in the Ordovician initiated subduction of the rocks in the basin. Metamorphism associated with subduction and subsequent crustal thickening during collisional tectonics culminated in the assemblage of rocks now found in the Ashe Metamorphic Suite, i.e., metaultramafites, eclogite, amphibolite, pelitic schist and gneiss. Deformation associated with these Paleozoic orogenic events resulted in faulting and folding so intense that any postulation of original stratigraphic sequences is speculative, at best. These lithologic associations, combined with structural relationships, have lead recent workers to interpret the Ashe Metamorphic Suite as an accretionary complex associated with continent-continent or continent-arc collision in the early stages of the Appalachian orogenic events (e.g., Odom and Fullagar, 1973; Abbott and Raymond, 1984; Adams et al., 1995).

Previous workers have interpreted the ultramafic rocks in the Ashe Metamorphic Suite to be intrusive into the surrounding amphibolite and pelitic rocks (e.g., Keith, 1905;

Pratt and Lewis, 1905; Hunter, 1941). More recent workers have applied more modern analytical techniques and structural concepts to understanding the petrochemistry, mineral chemistry, microstructures, petrography, and field relationships of these rocks (Misra and Keller, 1978; Swanson, 1981, 1999, 2001; Swanson et al, 1999; Raymond and Swanson, 1981; Raymond et al., 1989, 2003; Raymond and Abbott, 1997; Abbott and Raymond, 1984; McSween and Hatcher, 1985; Willard and Adams, 1994). Some of these more recent studies have recognized the ultramafic bodies as phacoids tectonically incorporated into the surrounding matrix.

The lithotectonic association of metamorphosed equivalents of ultramafic rocks, eclogite, ocean basalt, and ocean floor sediments in the Ashe Metamorphic Suite, juxtaposed with Laurentian continental crust is recognized as marking the Ordovician (Taconian) suture zone in the southern Appalachians. However, overprinting effects of the subsequent Paleozoic orogenic events have modified the suture such that the original trace is obscured. In the area south of the Grandfather Mountain window, the Ashe Metamorphic Suite is juxtaposed with Laurentian continental crust along the Burnsville fault. The Burnsville fault is a dextral strike-slip fault that was most likely active in during a Devonian (Acadian ?) orogenic event involving transpressional tectonics (Adams et al., 1995; Trupe et al, 2003). The Burnsville fault either represents a reactivation of the original Taconian suture, or it cut through the lower parts of the Ashe Metamorphic Suite and the original suture is obliterated. Similarly, north of the Grandfather Mountain window, the fault juxtaposing the Ashe Metamorphic Suite and Laurentian continental crust is the Gossan Lead fault. While this fault locally shows evidence of strike-slip movement, the pervasive shear sense indicators suggest top to the northwest thrust movement (Adams et al., 1995; Adams 2000). This suggests that either the original Taconic suture (or the Burnsville fault) was reactivated as a thrust fault in this area, or later faulting overthrusts the suture such that it is no longer exposed.

DAY BOOK DUNITE

Mineralogy

The Day Book Dunite is one of the largest ultramafic bodies in northwestern North Carolina. The deposit is somewhat lens-shaped and extends approximately 1500 feet long by 500 feet wide and greater than 200 deep. The deposit is located approximately 4 miles north of Burnsville, North Carolina along NC Highway 197, which cut across the southwestern one-third of the deposit. The primary mineralogy is dominated by olivine with minor chromite and lesser amounts of orthopyroxene. As with all of the ultramafic rocks in the Blue Ridge, the primary phases in the Day Book Dunite have been variably altered to hydrous minerals. The secondary phases include talc, anthophyllite, tremolite, phlogopite, vermiculite, magnestite, serpentine, magnetite, and chlorite. The least altered rock in the deposit is metadunite, composed of greater than 90 per cent yellowish-green to green, equigranular, medium-grained, olivine with an average forsterite component of 92 %. The average grain size is approximately 0.2mm (Table 1). Overall, the rock is fairly massive, but is locally weathered, resulting in very friable material. Chromite occurs as disseminated grains, as well as in pods and locally in well-defined bands ranging in thickness from a few millimeters to greater than one centimeter.

Along the western boundary and close to the center of the deposit, a pegmatite, related to the Spruce Pine Intrusive Suite, intrudes the dunite and surrounding country rock.

Alteration of the olivine is most conspicuous along the contact with the pegmatite and along fracture zones within the body. Talc veins with and without significant accessory anthophyllite locally exceed 5 meters across. Massive serpentinite veins, generally less than 2 cm, are locally common and all three common polymorphs of serpentine (antigorite, lizardite, and crysotile) occur in the deposit.

TABLE 1. Size distribution for olivine grains in Day Book Dunite

Sieve	+20	+30	+40	+50	+70	+100	+140	+200	+240
opening in mm	0.850	0.600	0.425	0.300	0.212	0.150	0.106	0.075	0.061
Size distribution (in wt.%)	0.08	5.71	12.48	17.35	22.04	17.61	11.96	8.95	3.17

Sieve numbers are for U.S. Standard sieves.

Economic Geology

Olivine is virtually the only mineral that occurs as a significant economic mineral in the Day Book deposit. Historically, there have been some prospects for chromite in the Day Book deposit. Hunter et al. (1942) reported chromite prospects in the Day Book deposit around 1901 and again during 1917-1918. Very minor tonnages were produced during this period. The occurrence of chromite is too limited to be considered as a viable economic mineral in this deposit. Vermiculite and anthophyllite asbestos have been economically mined from other ultramafic bodies in the Blue Ridge belt in the past; but, again, the occurrence of these minerals in the Day Book deposit is not of economic importance.

Mining of the ultramafic bodies in the Blue Ridge began as early as Pre-Columbian time. Turner and Swanson (1998) discussed evidence of Native American mining of soapstone from ultramafic bodies. Corundum, vermiculite, chromite, and talc have historically been minerals of economic interest from ultramafic bodies in western North Carolina. Olivine was mined from the Day Book dunite as early as 1937. The Day Book Dunite is, and has been for many years, the largest domestic producer of olivine. The deposit is estimated to contain greater than 2 million tons of olivine ore. Unimin Corporation currently mines approximately 50,000 tones of ore per year. The mine is an open-pit quarry where the rock is drilled and blasted by benches, then ore is mined with excavator and hauled to the plant with trucks.

Because of the high melting point for olivine and its relative durability, by far, the most important application is for foundry and refractory industrial applications. Another minor application for olivine is as an abrasive, which is attractive due to the fact that there is a low risk of health hazards related to the presence of free silica dust during use of the product. Minor past applications for olivine include use as a raw material for producing magnesium sulfate. No gem quality peridot has been reported from the Day Book Dunite.

Recent studied have evaluated the ultramafic rocks in the Blue Ridge for potential future applications for the rocks. Goff et al, (2000) prepared an evaluation of ultramafic rocks as sources of magnesium for carbon dioxide sequestration. Forsterite, as well as serpentine minerals, are relatively soluble in HCl, which can easily dissolve large quantities of Mg for further chemical use. The conclusions of this study state, “The best ultramafic rocks for CO_2 sequestration are the relatively pure dunite deposits such as …Day Book.” With an increase in CO_2 emissions as an environmental concern in urban areas, use of ultramafic rocks as sources for magnesium for sequestration of CO_2 could become an important application for olivine in the future.

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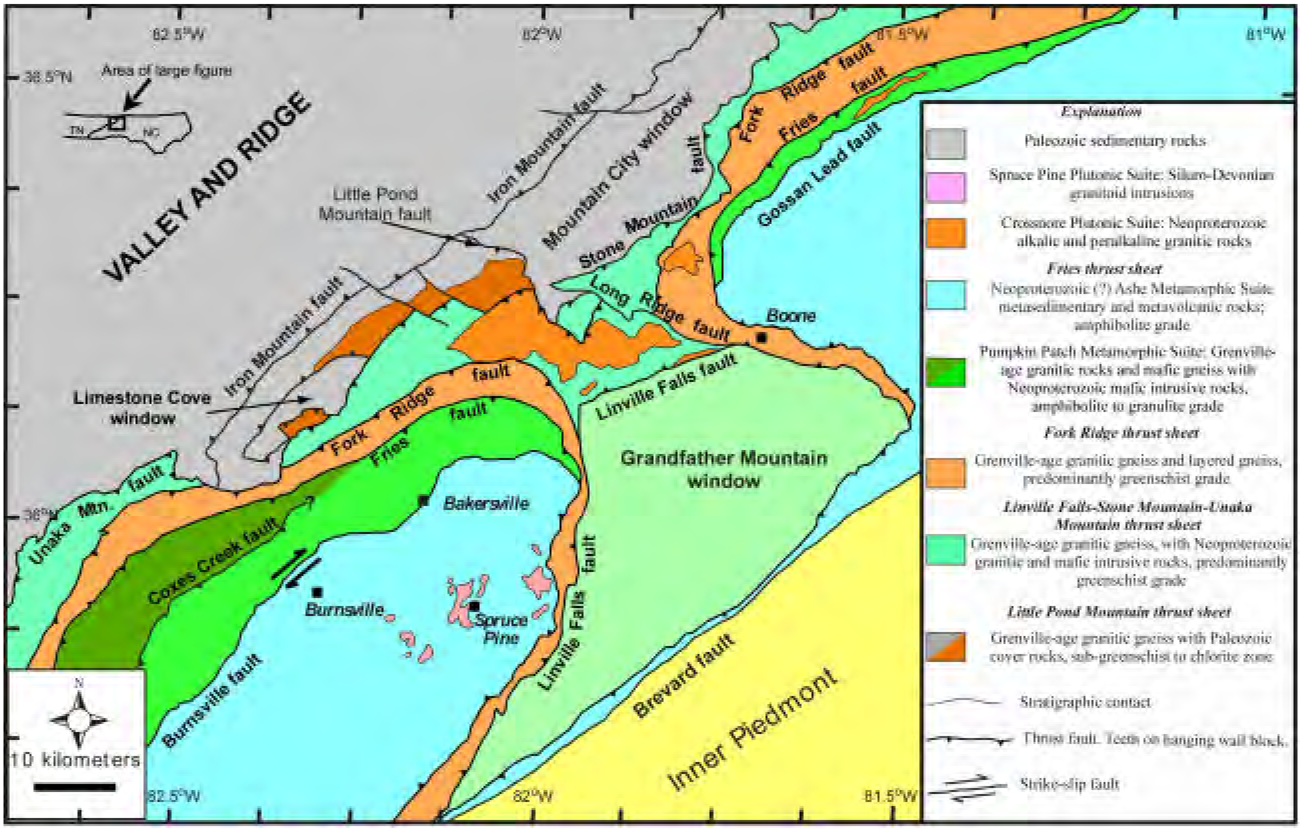

FIGURE 1 Generalized lithotectonic map of the Blue Ridge thrust complex, northwestern North Carolina and eastern Tennessee. Modified from Trupe et al. (2003).

The Sink Hole at Bandana: A Blue Ridge mica mine reveals Its prehistoric past

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ABSTRACT

Aboriginal mining activity in the Blue Ridge Mountains during the Woodland period is a neglected aspect of North Carolina prehistory. Abundant evidence of such activity was still visible in the nineteenth and early twentieth centuries, before modern mining obliterated it. From published reports of this evidence, it appears that Woodland mining activity in the Blue Ridge was devoted largely, if not exclusively, to the extraction of a single mineral, mica, and its transport to centers of Adena and Hopewell culture in the Ohio Valley. Evidence for future study consists of tools and artifacts in museum collections. A cursory inspection of one such collection shows that much material is available, only awaiting renewed interest in the subject. A review of the literature and visits to a prehistoric mining site, the Sink Hole mica mine in Bandana, North Carolina, suggest future lines of inquiry, chief among these being the identity of the prehistoric miners.

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INTRODUCTION

Intermittently, for a period of over two millennia, large clear sheets of mica—the isinglass of previous generations—have been extracted from deposits in North Carolina's mountains. The prehistoric inhabitants of North America used sheet mica in ways very different from modern civilization. Whereas modern uses have been strictly utilitarian, ancestral Native Americans found ritual and ornamental uses for mica. Nevertheless, the aboriginal mining industry corresponded to its modern counterpart in two significant respects: (1) both prehistoric and modern miners invested large amounts of time and energy extracting sheet mica from the same deposits, excavating many tons of rock in the process; and (2) both transported their product hundreds of miles from mine to user.

In 1913, when the Smithsonian Institution's William Henry Holmes came to Spruce Pine to investigate ancient mica mining in Mitchell County, evidence could still be seen where countless generations of prehistoric miners had extracted huge quantities of mica from the area's many deposits. Although his discussion of this prehistoric industry betrays no awareness that Woodland period inhabitants of the region might have used mica themselves (Holmes 1919), later archaeological work at places such as the Warren Wilson site in Buncombe County and the Garden Creek site in Haywood County has resulted in the discovery of mica funerary objects (e.g., Dickens 1976; Wilson 1986), but in quantities that pale in comparison with those found in Ohio Valley mounds. Mica is soft but the large sheets that the miners prized, up to three feet in diameter, occur in the form of thick, heavy crystals. Thus, preparing the mineral and transporting it hundreds of miles away required a great expenditure of time and effort.

This article was written in hopes of directing renewed interest in this neglected aspect of North Carolina prehistory. Toward that end, it: (1) records early speculations on the origins of ancient workers at a mica mine in Mitchell County; (2) describes two Ohio Valley burial mounds in which large quantities of mica from western North Carolina were discovered and the circumstances of its discovery; and (3) describes how the Woodland people of the Ohio Valley used this mica. A secondary aim is to present, in broad outline, the 2,000-year history of what may well be the oldest mine in the southern Appalachians.

Mica mining has a venerable history in the New World. Among the many mineral deposits exploited by prehistoric Native Americans, few were worked over a longer period than the mica veins of North Carolina. The State's many historic mica mines, now abandoned, were first opened 2,000 years ago. By contrast, historic records of mica mining extend back barely two centuries, to 1803 when the mineral was first mined in New Hampshire.

Much of North Carolina's prehistoric mining activity was centered in an area known in historic times as the Spruce Pine mining district. Until the 1950s, mica mining was an important industry in the district, supplying much of the domestic mica used in electrical and electronic applications. At the beginning of the twenty-first century, some 2,000 years after work began there, none of these mines offers better documentation of this vast span of history than the Sink Hole, located in the Mitchell County community of Bandana. Taking the period of prehistoric activity into account (and bearing in mind the distinction between mining minerals and quarrying rock), this may be among the oldest mines in North America. Its location is noted by an historical marker four miles northeast of the site on U.S. 226, between Spruce Pine and Bakersville. The latter, the county seat, is six miles northwest of the mine.

EARLIEST DESCRIPTIONS

In 1868, rumors of Spanish silver mines gave General Thomas Lanier Clingman the idea to sink a shaft on the site of some ancient excavations in Bandana, located 15 mi upstream from where North Carolina's Toe River flows into Tennessee and becomes the Nolichucky River. He hoped to find silver ore there; instead, he found sheets of mica as large as any he had ever seen (Clingman 1877).

Clingman first visited Bandana in 1867 to investigate reports of ancient silver mines, according to William H. Holmes. Holmes was Chief of the Bureau of American Ethnology at the Smithsonian Institution from 1902 to 1909. His description of Clingman's work at Bandana was included in the earliest and possibly only comprehensive study of prehistoric Native American mining ever attempted (Holmes 1919) (Figure 1).

When General Clingman visited Bandana, evidence of mining there consisted of a series of overgrown pits dug into hillsides opposite what is now known as Sink Hole Creek. The diggings coincided with a band of outcrops of pegmatitic rock stretching a total distance of about 1,600 ft in a northeast-southwest direction and averaging 8–12 ft in width. (Pegmatite is an igneous rock, similar to granite in composition, consisting of uncommonly large crystalline masses of three minerals: feldspar, quartz, and mica.) Clingman thus became one of the first to record how the Bandana workings looked centuries after they had been abandoned, and before their disruption by nineteenth- and twentieth-century mining. On the north side of the creek, on land belonging to a farmer named William Silvers, Clingman observed a line of excavations that extended some 400 yards uphill onto a ridge crest. A similar but shorter line was visible on the south side, over the hilltop and about 1,000 feet away. As Clingman described the excavations, it appeared as though a large number of miners had been at work there for many years (Clingman, 1877). Although Clingman gave no estimate of the depth of the workings, Holmes, who saw them in 1913, described the diggings as having reached depths of 30 to 40 ft (Figure 2).

Clingman's first inclination, believing the stories that had brought him there, was to credit the men of De Soto's expedition with the mining. The conquistadors had trekked through the Carolinas looking for precious metals in 1540. Having studied mineralogy with Professor Elisha Mitchell at Chapel Hill 35 years previously, Clingman regarded the waste material lying in piles around the pits at Bandana as resembling "Mexican silver ore." Thus, in 1868, he decided to sink a shaft there and had two tunnels dug beneath the old excavations (Figure 3). Instead of silver, though, Clingman found an abundance of "large mica of good quality."

As Clingman observed, the size of the trees then growing on waste material heaped up around the pits suggested that the work had been done hundreds of years earlier. In a letter from Asheville, North Carolina, dated April 8, 1873, he speculated: "It does not seem improbable that a former race of Indians – possibly the 'Mound-Builder,' who used copper tools, made these excavations for the purpose of procuring the mica." Clingman was not alone in venturing a guess as to the origin of the prehistoric miners at the Sink Hole. In 1880, W. C. Kerr, State Geologist of North Carolina, wrote as follows concerning North Carolina's ancient mica mines: "I have stated elsewhere, several years ago, that these veins were wrought on a large scale and for many ages by some ancient peoples, most probably the so-called Mound Builders" (Kerr 1880:457).

Kerr summarized his observations of aboriginal work at a number of mica mines in western North Carolina as follows:

> They opened and worked a great many veins down to or near water level. . .as far as the action of atmospheric chemistry had softened the rock so that it was workable without metal tools. . . . Many of the largest and most profitable mines of the present day are simply the ancient Mound Builders' mines reopened and pushed into the hard undecomposed granite by powder and steel. Blocks of mica have often been found half imbedded in the face of the vein, with the tool-marks about it, showing the exact limit of the efficiency of those prehistoric mechanical appliances [Kerr 1880:457].

Examples of the "appliances" Kerr referred to were illustrated by drawings that appeared in Holmes' 1919 report (Figure 4). Kerr had also heard the stories of old Spanish silver mines. He visited the prehistoric diggings at Bandana in the same year that Clingman sank his shaft; however, his *Report of the Geological Survey for 1875* made no mention of Clingman's presence or activities there. The geologist described "a dozen or more open pits 40 to 50 feet wide, by 75 to 100 long, filled up to 15 or 20 feet of depth" (Kerr 1875:300). He went on to relate that two years after his visit to Bandana (by 1870), he had learned that "mica was of common occurrence in the tumuli of the Mound Builders" and that "cut forms similar to those found in the mounds were occasionally discovered among the rubbish heaps about and in the old pits" (Kerr 1875:300). This latter piece of information Kerr (1875:300) took as revealing "unmistakably the purpose and date of these works [the pits at Bandana]." If it could be verified, it would have a direct bearing on the question of where the ancient miners originated. Among Kerr's general comments on North Carolina mica mines in 1875 were the following observations regarding prehistoric work:

> Since the development of mica mining on a large scale in Mitchell and adjoining counties, it has been ascertained that there are hundreds of old pits and connecting tunnels among the spurs and knobs and ridges of this rugged region; and there is no doubt that mining was carried on here for ages, and in a very systematic, skillful way. . . . The pits are always open "diggings," never regular shafts, and the earth and debris often amounts to enormous heaps. . . . The tunnels are much smaller than such workings in modern mining, generally only three to three and a half feet in height and considerably less in width. Some have been followed for fifty and a hundred feet and upwards [Kerr 1875:300].

A year after Kerr's visit and Clingman's departure, two stove merchants from Tennessee, J. G. Heap and E. B. Clapp, began mining mica at what by then was known as the Sink Hole Mine. They established in Bandana the headquarters of what grew to be a large, profitable enterprise, producing mica from many properties within the district. The economic value of their product was based on its transparency, its resistance to fire and heat, and the ease with which it could be split into thin flexible sheets that could be trimmed to any size or shape. These qualities made mica eminently suited for stove and furnace windows, lanterns, and lampshades.

Within a few decades, by the turn of the century, it became apparent that mica would play an even more important role in industry. This new role depended upon an additional quality, mica's dielectric properties, which made it a peerless electrical insulator. "Until a few years ago, almost the only commercial use of mica was in the doors or windows of stoves and furnaces. To a less extent it was used in lanterns and the portholes of naval vessels, where vibrations would demolish the less elastic glass. . . . Since the introduction of the present system of generating electricity, there has risen a considerable demand for it in the construction of dynamos and electric motors" (Merrill 1901:290).

THE HISTORICAL PERIOD OF MICA MINING

The workings at Bandana eventually grew to include over 30 shafts and 2,000–3,000 ft of drifts and stopes. The deepest shafts were connected below by a 900-ft tunnel which drained water that otherwise would have filled the underground workings. The tunnel extended under the paved road that is now N.C. Highway 80 (Figures 5 and 6). In the latter decades of the nineteenth century, the Sink Hole was known as a source of the highest grade of flat stove mica. In the twentieth century, when electrical and electronic applications overshadowed older uses, the Sink Hole became renowned as the source for a variety of reddish brown muscovite mica, known as "ruby" in the trade, that was regarded as possessing the highest dielectric properties and therefore preferred by industry.

Activity at the mine fluctuated over a 90-year period. When sheet mica was in demand, the selling price rose and fell depending on the amount imported from abroad (chiefly India) and the needs of the defense industry. After a 20-year interruption following the First World War, new shafts were sunk in 1941 a short distance southwest of Clingman's original shaft (see Olson 1944:Plate 5), as America prepared once more to go to war. In 1942, the U.S. Government established the Colonial Mica Corporation, headquartered in Asheville with an office in Spruce Pine, in order to encourage local miners by offering to buy all the mica they could produce and to help finance the purchase of mining equipment.

With peace, work came to a halt in 1945, only to be revived again by the Korean War. The buying program was reestablished in 1952, when the government began stockpiling mica to ensure against interruptions in overseas supplies. During the 10-year period from 1952 to 1962, the mine produced over 200,000 pounds of sheet mica (Lesure, 1968:68). When the federal buying program ended in 1962, so did activity at the Sinkhole Mine.

ANCIENT MINERS

When Clingman and Kerr visited Bandana, signs of prehistoric activity there consisted of deep pits and trenches with stone tools left lying in the bottom. The actual identity of Bandana's prehistoric miners is a matter of conjecture; however, questions about why the mica was mined, how it was used, and where it was used was solved by the excavation of burial mounds hundreds of miles away in the Ohio River Valley of Ohio, Kentucky, and West Virginia.

In 1913, some four decades after Clingman searched for silver there, W. H. Holmes visited Bandana to investigate reports of aboriginal tools found in mica mines of the Spruce Pine district. He arrived at a time when modern work had not quite obliterated the ancient diggings. Holmes appears to have been the second archaeologist to investigate the diggings. In the report he published in 1919, Holmes mentioned a reconnaissance in 1893 by De Lancey Gill, also of the Smithsonian Institution's Bureau of American Ethnology, made under his direction. According to Holmes, the results of that work were never published. However, Gill may have collected some aboriginal mining tools in 1893, because Holmes mentions that by the time of his 1913 visit, the U.S. National Museum already had a dozen artifacts from the Spruce Pine area in its possession (Figures 7 and 8).

While Holmes did not do any digging in 1913, he did visit two mines in the vicinity of Spruce Pine (the Deake and an unnamed mine), one near Bakersville (the Clarissa mine), and the Sink Hole at Bandana. Judging from the information he published in 1919, Holmes devoted most of his time and attention to the workings at Bandana. Supplementing his description of the Sink Hole was a topographic map sketched in the field (see Figure 3). In addition to showing the locations of the various pits and trenches, the map indicates the sites of what he described as mica workshops. One, a wooded hummock situated on a ridge top immediately south of Sink Hole Creek, can still be seen. A review of the literature suggests that these are the only features in North Carolina that have ever been identified as such.

When Holmes reported the results of these and other investigations in 1919, he credited Clingman with having been the first to "bring to light. . .the sources of supply" of the mica found in Ohio Valley burial mounds. To Holmes, there was no question that mica unearthed in the graves of the Mound Builders came from deposits in North Carolina. This conclusion appears incontestable, for although they are hundreds of miles apart, North Carolina deposits are nearer to the mounds than any others available to the prehistoric miners. The identity of the miners themselves, however, remains open to conjecture.

NORTH CAROLINA MICA IN OHIO VALLEY BURIAL MOUNDS

The earliest Ohio Valley burial mounds are over 2,000 years old, firmly within the context of the Woodland period. Radiocarbon dating of organic remains found in the mounds indicates that they were constructed over a period of hundreds of years, beginning around 200 B.C., by a people in the early stages of adapting to a settled, agricultural existence. By the early nineteenth century, when the Ohio Valley was first being settled by people of European descent, the Native Americans whom the settlers found living there could shed no light on the identity of the people who had raised the mounds, people who had preceded them by more than a thousand years. The earthworks of these vanished people were excavated by amateurs as early as the 1840s (Squier and Davis 1848). In the decades that followed, professional archaeologists, faced with the necessity of attaching labels, assigned the names Adena and Hopewell to the Woodland people who built the mounds.

Archaeologists who excavated Adena and Hopewell burial mounds discovered an unusually rich array of artifacts, including images cut from tortoise shell, copper, and large smooth sheets of mica. The latter included stylized human torsos, hands, claws and talons, and geometric figures.

Other mica artifacts found in the mounds included large numbers of perforated disks as well as elliptical forms that may have served as mirrors. Several hundred mica disks were found in one of a group of two dozen mounds called Mound City, near Chillicothe, Ohio, in what is now Hopewell Culture National Historic Park (see Holmes

1919). Holmes and others have speculated that the disks and others like them were strung together to form part of the costume of a medicine man or shaman. Adena and Hopewell mica artifacts such as these now reside in the collections of the Museum of the Ohio Historical Society in Columbus, Ohio, and in the Smithsonian Institution.

The author visited the Smithsonian Institution's Museum Support Center (a storage and curatorial facility in Suitland, Maryland) in order to examine the stone tools and mica that Holmes and presumably Gill had collected from the Sink Hole and other mines in Mitchell County. This visit also served as an opportunity to examine some of the Smithsonian's collection of Hopewell and Adena artifacts made of mica, copper, and stone that came from various mounds in the Ohio Valley.

Holmes and Gill collected more than just stone mining tools at the Sink Hole. The Smithsonian collection of artifacts from Mitchell County also includes large elliptical sheets of mica, possibly retrieved from a cache left behind by the ancient miners. Discoveries by C. D. Smith at prehistoric mica mines in Macon County established that the miners commonly stored their mica in pits, especially dug for this purpose, until it was time to transport it westward (Smith 1877).

One of the conical mounds at Hopewell Culture National Historic Park was named the Mica Grave because of the great quantity of the mineral found when the mound was excavated in 1846 by amateur archaeologists Ephraim G. Squier and Edwin H. Davis (1848) (Figure 9). During a later, more systematic excavation by William C. Mills and Henry C. Shetrone in 1920 and 1921, workers uncovered 13 graves at a depth of 20 ft. One was decked with thick sheets of mica. Mills (1922) described the sheets as having been cut into rectangular shapes of up to 10 inches by 14 inches and completely covering an area 8 ft by 4 ft. Until 1997, when it was closed at the request of contemporary Native Americans, perhaps descendants of the Hopewell, the Mica Grave was on public display with a short tunnel providing entrance into the dimly lit interior.

At Seip Mound, located 20 mi west of Mound City, archaeologists unearthed the foundations of two workshops, the floors of which were littered with mica trimmings and blades used in the cutting process (Baby and Langlois 1979:18) (Figure 10). Here, presumably, Hopewell artisans cut mica sheets into designs of ritual significance, the sheets having been split from heavy books at mine sites such as the Sink Hole.

The oblong Seip Mound, originally 30 ft high and the focal point of a complex of mounds enclosed by a 10-ft high earthen embankment, was found to contain 122 burials when thoroughly excavated between 1926 and 1928 (Shetrone and Greenman 1931). In addition to mica from North Carolina and copper from Michigan, the graves contained thousands of freshwater pearls, estimated in 1960 to have been worth as much as $2 million when new and in good condition (Woodward and McDonald 1986:93–95). Burial mounds such as Seip are characteristic of the Middle Woodland culture of the Ohio Valley which also produced large earthwork enclosures laid out in geometric designs, including squares, circles, and octagons.

What distinguishes the Woodland people of the Ohio Valley as much as monumental earthworks is the richness of their grave goods. These consist of artifacts crafted from a wide variety of materials, including not only mica but also copper, gold, silver, galena, flint, obsidian, pipestone, and saltwater shells. Such variety is remarkable considering that only flint is native to the valley region. The other materials were brought from sources hundreds of miles distant, without the aid of wheeled conveyances or beasts of burden. Copper, for example, came from aboriginal mines on the shores of Lake Superior, over 600 mi north of the Hopewell heartland. Were the Hopewell and Adena exclusively traders, bringing flint and ceramics to North Carolina's mountains to exchange for mica, or could they have done some of the mining themselves?

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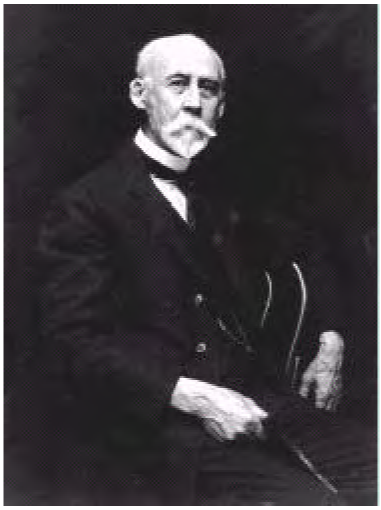

FIGURE 1 William H. Holmes, taken during the period when he was Chief of the Smithsonian Institution's Bureau of American Ethnology. Courtesy of the Smithsonian Institution.

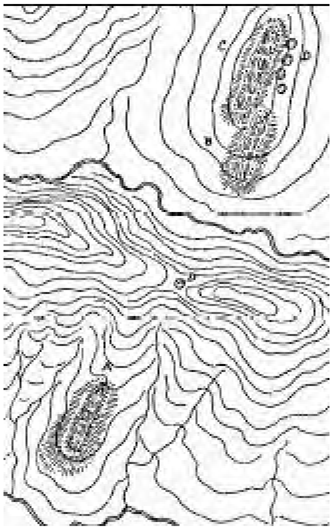

FIGURE 2 Sketch map of the Sink Hole Mine in 1913 (from Holmes 1919:Figure 116): B and C – Sink Hole; A – Robinson; and D – aboriginal mica workshops. Sink Hole Creek meanders from east to west across the middle of the map area. (north to top)

<u>Figure 3 – not available</u>

FIGURE 3 Plan of openings at the Sink Hole Mine in 1940, including the location of Clingman's shaft (from Olsen 1944:Plate 5). [not available – oversize see Olsen, 1944)]

FIGURE 4 Drawings of prehistoric mining implements (one-fourth actual size) recovered from a deep pit near upper end of the Sink Hole Mine (from Holmes 1919:Figure 115).

FIGURE 5 The vicinity of the Sink Hole Mine in 1936 (view to south). The mine is to the right (not in picture). Photograph by Joffre L. Coe. Courtesy of the Research Laboratories of Archaeology.

FIGURE 6 View in 1936 of "ancient" workings at the Sink Hole Mine. Photograph by Joffre L. Coe. Courtesy of the Research Laboratories of Archaeology.

FIGURE 7 Stone mining implements recovered from the Sink Hole Mine and curated by the Smithsonian Institution.

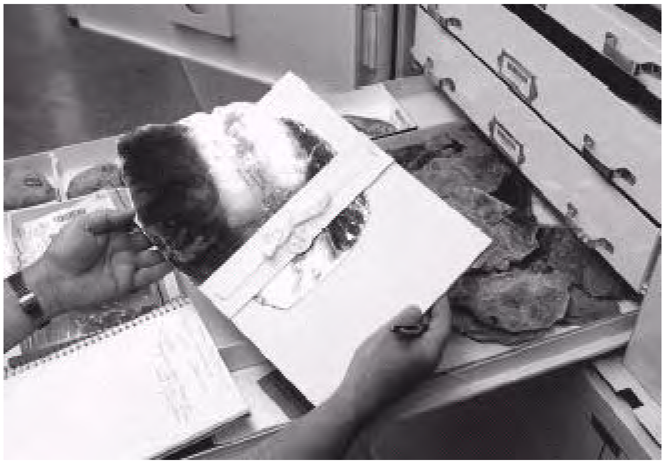

FIGURE 8 Green sheet mica mined by prehistoric Native Americans and collected by I. G. Heap from one of his mica mines in the Bakersville area of Mitchell County. Curated by the Smithsonian Institution.

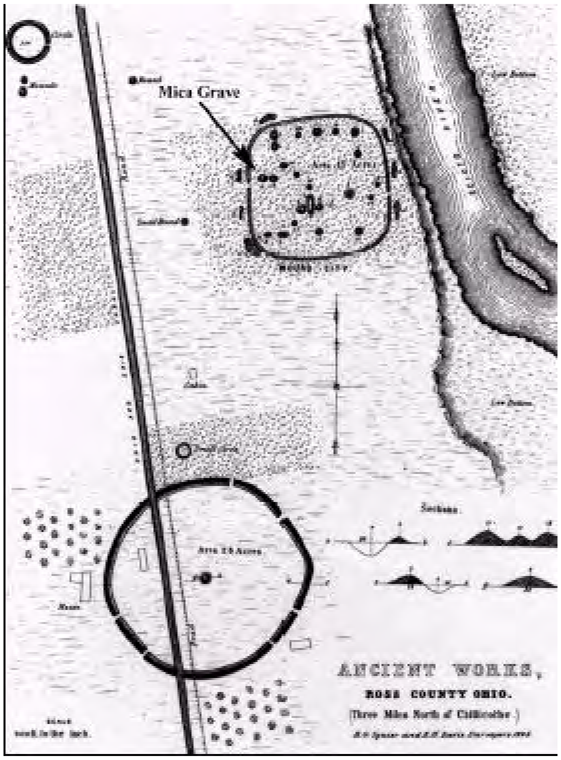

FIGURE 9 Map of the earthworks at Mound City, Chillicothe, Ohio, showing the location of the Mica Grave (from Squire and Davis 1848:Plate 19, label added).

FIGURE 10 View of the Seip Mound, Ross County, Ohio.

Session Seven

Ultramafic-hosted talc-magnesite deposits

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Important talc deposits occurring in the areas of Proctorville and Windham, Vermont are localized within a north-south trending band of scattered serpentine and ultramafic rock bodies of probable ophiolitic affiliation that transect the New England states. Talc-rich portions of these ultramafic-hosted talc-magnesite deposits are generally located along the periphery of the serpentine bodies where they are in contact with schist and siliceous granofels lithologies and along regional faults that cut the serpentine bodies. The largest talc-magnesite lenses are localized along the north and south margins of individual serpentine bodies, elongated parallel to the trend of regional foliation and faults.

The serpentine bodies that host the talc deposits are chemically and mineralogically zoned, with silicate-carbonate mineral assemblages in the serpentine cores of antigorite+forsterite+/-magnesite, surrounded by antigorite+magnesite+/-talc assemblages that transition, often abruptly, into talc+magnesite(breunnerite)+/-dolomite(ankerite) assemblages near the periphery of the serpentine bodies and along shear and fault zones. The metamorphic alteration minerals talc and magnesite are formed by metasomatic (mass transfer) additions of carbonate and silica to the serpentine coupled with loss of water and magnesia. The carbonation reactions progressively destroy magnetite-spinel in the altered serpentine forming breunnerite. The high-grade massive talc-magnesite assemblages typically exhibit patchy textures and discontinuous zones of intersecting carbonate veins. These textures are interpreted to result from volume increase and associated fracture permeability caused by mass gain during metasomatism. The metasomatic alteration processes tend to concentrate talc in the outer part of the alteration zone. Enrichments in arsenic, nickel, and sulfur also occur in the outer parts of the talc-magnesite alteration zones in the form of trace pyrite, nickel arsenide minerals, and nickel arsenate films on weathered fracture surfaces. Arsenic concentrations in talc and process waters need to be monitored during mineral processing and waste disposal.

The regional geologic setting of the serpentine bodies and the pressure-temperature-time evolution of regional metamorphic conditions are important controls on the formation of large high-grade talc deposits associated with ultramafic rocks. These metamorphic constraints can be used as guides for talc exploration. Peak metamorphic conditions need to occur in the stability zone of forsterite+antigorite and antigorite+talc assemblages ranging from about 450 to 550 C at 5 to 10 kilobars pressure. The carbonation reactions responsible for much of the talc and magnesite mineralization are controlled by the activity of CO_2 in the metamorphic fluid. The mineral buffers controlling, and relative timing of changes in, carbonate activity in the fluid phase during the metamorphic cycle influence the texture and abundance of talc in the alteration assemblage. High-grade talc deposits tend to occur in serpentine bodies enclosed in reduced (graphite-bearing) siliciclastic metamorphic host rocks that lack carbonate minerals. In these settings, the activity of CO_2 is controlled by graphite-water equilibria.

(continued)

Serpentine bodies localized in siliclastic metamorphic rocks containing carbonate minerals tend to have higher activities of CO_2 in metamorphic fluids, with the result that serpentine reacts early in the metamorphic cycle to form fine-grained soapstone and listwanite. These rock types generally do not contain recoverable talc resources. The optimal metamorphic pressure-temperature-time path for the generation of high-grade talc deposits occurs where the early phase of prograde metamorphism occurs at high pressure and temperature conditions where the activity of CO_2 is very low, fostering silica metasomatism during the early phase of serpentine alteration. This metamorphic phase is followed by a high temperature decompression trend that fosters gradual carbonation of the alteration assemblage in response to the increasing activity of CO_2 in fluids buffered by the graphite-water system as pressure is reduced.

Robinson, Gilpin R., Van Gosen, Bradley S., and Foley, Nora K., 2006, Ultramafic-hosted talc-magnesite deposits, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Talc is a soft inert industrial mineral commodity commonly used as a component or filler in ceramic, paint, paper, plastic, roofing, and electrical applications (Lindsey, 2003; Piniazkiewicz and others, 1994). Ultramafic-hosted talc-magnesite deposits are important sources of talc (Simandl and Ogden, 1999; Harben and Kuzvart, 1997). The geologic setting, mineralogy, and geochemistry of related talc deposits in Vermont have been described by Chidester (1962). The geological, mineralogical, and geochemical features of talc deposits in the Proctorville, Vermont area will be used to illustrate the important characteristics of ultramafic-hosted talc-magnesite deposits and provide data that constrain the physical conditions and processes that form talc deposits hosted by ultramafic rocks.

GEOLOGICAL CHARACTERISTCS OF TALC-MAGNESITE DEPOSITS

Tectonic Setting

The ultramafic rocks that host talc-magnesite deposits, typically serpentine or serpentinized peridotite, occur in metamorphic belts in lithotectonic settings commonly associated with seafloor subduction (Simandl and Ogden, 1999). Individual ultramafic rock bodies occur as fault-bounded rocks that were tectonically-transported bodies or as olistolith blocks of serpentinized seafloor deposited in an accretionary subduction complex. The talc deposits at Proctorville, Vermont, are localized within part of a north trending band of scattered ultramafic rock bodies, primarily serpentine, that transect the New England states (Larrabee, 1971). The talc deposits in the Proctorville area are associated with one of the most extensive belts of ultramafic rock found in western New England and large to small masses of ultramafic rock lie scattered along a 30 kilometer zone from Proctorsville to Townshend reservoir, Vermont (Ratcliffe, 1996; Ratcliffe, Walsh, and Aleinikoff, 1997). In this area, the ultramafic rocks are interspersed in the Moretown Formation (Ratcliffe, 1996; Ratcliffe, Walsh, and Aleinikoff, 1997) at or near the contact between dark gray carbonaceous sulfidic biotite schist (Omb unit, Figure 1) and laminated siliceous biotite granofels (Oml unit, Figure 1). The Moretown Formation was interpreted as a lithotectonic unit formed as an allochthonous accretionary complex produced on the upper plate of an Ordovician oceanic subduction zone (Stanley and Ratcliffe, 1985; Ratcliffe, Walsh, and Aleinikoff, 1997).

Geologic Setting

Ultramafic-hosted talc-carbonate deposits occur near the contacts between ultramafic rocks and siliceous country rocks and along regional faults cutting ultramafic rocks (Piniazkiewicz and others, 1994; Simandl and Ogden, 1999). The talc and magnesite minerals formed during metamorphism of the ultramafic protolith.

In Vermont, talc-rich parts of the ultramafic rock bodies are generally located along the periphery of the serpentine bodies where they are in contact with schist and siliceous granofels and along regional faults that have cut the serpentine bodies. The largest talc-magnesite lenses in the Proctorville, Vermont area are localized along the north and south margins of individual serpentine bodies, elongated parallel to the trend of regional foliation and faults (shown as talc-carbonate rock in Figure 1). These large talc-carbonate rock bodies are structurally located in areas of least compressive stress around the larger ultramafic rock bodies.

ROCK GEOCHEMISTRY, MINERAL ASSEMBLAGES AND REACTIONS

Vermont Talc Deposit Study

Field mapping and geochemical and mineralogical studies of rock and core samples from ultramafic-hosted talc-carbonate deposits in the Proctorville, Vermont area were used in this study to define the geologic setting, geochemical controls, and mineral reactions involved in the formation of the talc deposits. Access to company property and continuous rock core drilled from the Frostbite, Black Bear, and Kelly talc deposits were made available from Luzenac America for this study. Major and trace element chemistry of whole rock samples was determined using X-ray Fluorescence (XRF) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) methods at Activation Laboratories, Ancaster, Ontario, Canada and Xral Laboratories, Don Mills, Ontario, Canada. Semi-quantitative mineralogy of whole rock samples was determined, using Rietveld methods with x-ray powder-diffraction data (Raudsepp and Pani, 2003).

Mineralogy and Mineral Assemblages

Rock sample transects from the interiors of the serpentine host-rock bodies crossing talc-carbonate zones into country rock indicate that the ultramafic rock bodies that host the talc deposits, and adjacent country rock, are mineralogically and chemically zoned. Four mineral and chemical zones in the ultramafic rock bodies were defined, and their characteristic mineral assemblages and modal abundances are shown in Figure 2. Mineral names, abbreviations, and formulas are given in Table 1. The interior serpentine core zone consists of silicate-carbonate mineral assemblages of antigorite+forsterite/-magnesite. Samples FB-32-71-S-109 and 122 shown in Figure 2A illustrate the mineralogy of the interior serpentine core zone (Ant-Fo Serpentine Zone). Serpentine that surrounds the core zone contains antigorite+magnesite±talc assemblages (Ant-Mgs Serpentine Zone, the eight samples on the left-hand side of Figure 2A) that transition, commonly abruptly, into 3) talc+magnesite assemblages (Talc-Carbonate Zone B, Figure 2B) and 4) talc±magnesite±dolomite assemblages (Talc-Carbonate Zone A, Figure 2C) near the periphery of the serpentine bodies and along shear and fault zones. The serpentine generally contain magnetite-spinel minerals, whereas the talc-carbonate rocks generally lack magnetite and the magnesite and dolomite minerals incorporate the iron formerly hosted by magnetite. The rocks in Talc-Carbonate Zone B contain talc and magnesite in roughly equal proportions by weight (Figure 2B). The rocks in Talc-Carbonate Zone A have a higher weight proportion of talc to magnesite and frequently contain dolomite and minor amounts of chlorite (Figure 2C). The Talc-Carbonate Zone A rocks are usually localized near lithologic contacts with siliceous metamorphic rocks and the calcium and aluminum components required to form dolomite and chlorite, respectively, are likely derived from these surrounding country rocks.

Rock Geochemistry

Geochemical relations between the ultramafic rock groups are illustrated by Figure 3, which portrays the relative concentrations of magnesia, iron, silica, and carbonate, in terms of molar ratios, in the rock groups. Using molar ratios of Si/(Mg + Fe), shown as Si/MF, and C/(Mg + Fe), shown as C/MF, as graph variables allows both rock and mineral compositions to be shown in a way that illustrates the dominant mineralogy of the rock groups and the relative differences in silica, magnesia + iron, and carbonate compositions between the rock groups.

The least altered serpentine rock in the cores of larger ultramafic rock bodies are the Ant-Fo (antigorite-forsterite) Serpentine group rocks shown in Figure 3. These rocks have a Si/MF value near 0.5, which is the composition expected from a dunite (olivine-rich) ultramafic rock protolith. Serpentinization by hydration of the precursor dunite oxidizes iron in the olivine forming antigorite-magnetite assemblages. Carbonation of the ultramafic rock protolith (increasing C/MF) form rocks in the Ant-Mgs serpentine group, however two clusters of Ant-Mgs serpentine rocks can be seen in Figure 3. The cluster with Si/MF values near 0.5 can be formed dominantly by carbonate addition, but the cluster with Si/MF values near 0.6 require carbonation accompanied by a relative gain in silica and/or relative loss in magnesia.

The ultramafic rocks in Talc-Carbonate Zone B indicate increased carbonation relative to the serpentine rocks (increasing C/MF) accompanied by small gains in silica relative to magnesia from the ultramafic rock protolith. Talc-carbonate rocks in zone A lie along the talc-magnesite join and exhibit moderate to large gains in silica relative to magnesia to form from the ultramafic rock protolith.

Geochemical Zonation Across the Ultramafic Rock Zones

The mineralogy and bulk composition of the ultramafic rock groups tend to lie along binary silicate-carbonate mineral joins (Figures 2 , 3, and 4). The small number of minerals present in these rock zones, the scale of the talc occurrences, and the significant and consistent mineral and chemical zoning developed between the ultramafic rock bodies and their enclosing metamorphic host rocks suggest that a fluid flow system driving metasomatic (mass transfer) alteration led to the formation of the talc deposits (Korzhinskii, 1970). The metasomatic reaction paths experienced by the ultramafic rocks and their enclosing siliciclastic metamorphic rocks are shown as blue lines in Figure 4. The metasedimentary rocks, shown as the “pelite” composition lose silica and gain magnesia during metasomatism to form biotite and chlorite-rich alteration zones bordering the ultramafic rocks.

Chemical zonation patterns in the metamorphic rocks surrounding the ultramafic rock bodies indicate that silica, magnesium, potassium, carbon, sulfur, arsenic, and water were all mobile components, to varying degrees, during metasomatism (Sanford, 1982). The metapelitic rocks were altered to chlorite-biotite rocks, termed blackwall by mine geologists, at their contacts with ultramafic rock (Figure 4). Figure 5 shows the relative distribution of ultramafic rock alteration zones and inferred mass transfer changes because of metasomatism along generalized transects from the contact of ultramafic rock with country rock (blackwall alteration zone in metapelitic rocks) to the interior of the serpentine bodies, crossing talc-carbonate alteration zones. Talc and magnesite in the ultramafic rocks were formed by metasomatic additions of carbonate and silica to the serpentine coupled with loss of water and magnesia (Figure 5).

TABLE 1 Mineral names, abbreviations, and formulas

Mineral name	Abbreviation	Formula
silicates		
Antigorite	Atg	$Mg_{48}Si_{34}O_{85}(OH)_{62}$
Fayalite	Fa	Fe_2SiO_4
Forsterite	Fo	Mg_2SiO_4
Talc	Tlc	$Mg_3Si_4O_{10}(OH)_2$
Tremolite	Tr	$Ca_2Mg_5Si_8O_{22}(OH)_2$
carbonates		
Dolomite	Do	$CaMg(CO_3)_2$
Magnesite	Mgs	$MgCO_3$
Siderite	Sid	$FeCO_3$
oxides		
Magnetite	Mgt	Fe_3O_4

TABLE 2 Characteristic reactions by ultramafic rock zone (zones numbered from blackwall contact)

3) Serpentine Zone	
$72\ Fo + 30\ Fa + 113\ H_2O = 3\ Atg + 20\ Mgt + 20\ H_2$	
$34\ Fo + 31\ H_2O + 20\ CO_2 = Atg + 20\ Mgs$	
$24\ Fo + 10\ SiO_{2(aq)} + 31\ H_2O = Atg$	(3B zone)
2) Talc-carbonate Zone B	
$2\ Atg + 45\ CO_2 = 45\ Mgs + 17\ Tlc + 45\ H_2O$	
$4\ Mgt + 11\ CO_2 + CH_4 = 12\ Sid + 2\ H_2O$	
$Atg + 30\ SiO_{2(aq)} = 16\ Tlc + 15\ H_2O$	(2B zone)
1) Talc-carbonate Zone A	
$2\ Atg + 45\ CO_2 = 45\ Mgs + 17\ Tlc + 45\ H_2O$	
$Atg + 30\ SiO_{2(aq)} = 16\ Tlc + 15\ H_2O$	
$2\ Mgs + CaO_{(aq)} = Do + MgO_{(aq)}$	

Mineral-Fluid Reactions

The characteristic mineral-fluid reactions occurring in the ultramafic rock zones portrayed in Figure 5 are given in Table 2. Mineral assemblage relationships as a function of fluid composition in the MgO-CaO-SiO_2-H_2O-CO_2 system at 5 kilobars pressure are shown in Figure 6, calculated using the thermodynamic data and TWQ program of Berman (1988; 1991), provide a framework to interpret the relative temperature and fluid composition relationships of the reactions listed in Table 2.

In addition to providing the silica needed to form talc from antigorite, the carbonation reactions in the talc-carbonate zones progressively destroy magnetite in the altering serpentine, forming ferroan magnesite. The high-grade massive talc-magnesite assemblages typically exhibit patchy textures and discontinuous zones of intersecting carbonate veins. The mineral reaction and mass balance relationships in the talc-carbonate alteration zones imply a negligible to small volume increase should develop in the Talc-Carbonate Zone B rocks and a larger volume increase should occur in the Talc-Carbonate Zone A rocks. The preferential development of the largest talc-carbonate alteration zones in areas of least compressive stress around ultramafic bodies is consistent with the structural setting expected to result from rock volume increase and associated fracture permeability caused by mass gain during metasomatism. The metasomatic alteration processes tend to concentrate talc in the outer part of the alteration zone where silica is likely to be more available from siliceous country rocks. Enrichments in arsenic, nickel, and sulfur also occur in the outer parts of the talc-magnesite alteration zones in the form of trace pyrite, nickel arsenide minerals, and nickel arsenate films on weathered fracture surfaces. Arsenic concentrations in talc and process waters need to be monitored during mineral processing and waste disposal.

DISCUSSION

The regional geologic setting of the serpentine bodies and the pressure-temperature-time evolution of regional metamorphic conditions are important controls on the formation of large high-grade talc deposits associated with ultramafic rocks. These metamorphic constraints can be used as guides for talc exploration. Peak metamorphic conditions need to occur in the stability zone of forsterite+antigorite and antigorite+talc assemblages, and the stability field for these mineral assemblages in the MgO-SiO_2-H_2O system (Bucher and Frey, 1994) are shown in Figure 7 in relation to metamorphic conditions estimated for rocks in the nearby Chester-Athens Domes area of Vermont (Vance and Holland, 1993; Armstrong and Tracy, 2000). Metamorphic rocks in the Proctorville area equilibrated at slightly lower temperature and pressure conditions than the Chester-Athens Domes areas (Ratcliffe, Armstrong, and Aleinikoff, 1997, Figure 9), but are within the stability zone for antigorite+talc assemblages ranging from about 450 to 550 C at 5 to 10 kilobars pressure (Figure 7). The metamorphic pressure-temperature-time conditions modeled for the Chester-Athens Domes area (Armstrong and Tracy, 2000), adjusted to the slightly lower pressure-temperature conditions most likely in the Proctorville area, indicate that metamorphic fluids related to dehydration reactions (Bucher and Frey, 1994) in the metapelitic rocks surrounding the ultramafic rock bodies are likely to be present during the metamorphic temperature-pressure-time path under conditions exceeding about 450 C and 5 kilobars.

At 5 kilobars (and higher pressures), antigorite is stable only with metamorphic fluids with very low concentrations of CO_2 and antigorite-magnesite assemblages coexist with talc-dolomite assemblages only at temperatures below about 490 C with fluid compositions between 0.5 and 1.5 mole percent CO_2 (Figure 6). At temperatures below 490 C, antigorite-forsterite-magnesite assemblages are stable at very low concentrations of CO_2 (less than 0.4 mole percent).

The mineral buffers controlling, and relative timing of changes in, carbonate activity in the fluid phase during the metamorphic cycle influence the texture and abundance of talc in the alteration assemblage. In Vermont, the talc deposits occur in serpentine bodies bordering or enclosed in reduced (graphite-bearing) siliciclastic metamorphic host rocks that lack carbonate minerals. In these settings, the activity of CO_2 in metamorphic fluids is controlled by graphite-water equilibria. Figure 8 shows the CO_2 concentration in fluids buffered by graphite-water equilibria (Connolly and Cesare, 1993) as a function of pressure and temperature. CO_2 concentrations increase with increasing temperature and decreasing pressure. The area where talc forming reactions are likely during the metamorphic temperature-pressure-time path of the Vermont rocks is shown in green.

Serpentine bodies localized in siliclastic metamorphic rocks containing carbonate minerals tend to have higher activities of CO_2 in metamorphic fluids, with the result that serpentine reacts early in the metamorphic cycle to form listwanite (magnesite-quartz-talc rocks) or a fine-grained soapstone containing less than 50% of talc by weight. These rock types generally do not contain recoverable talc resources. The optimal metamorphic pressure-temperature-time path for the generation of high-grade talc deposits occurs where the early phase of prograde metamorphism occurs at high pressure and temperature conditions where the activity of CO_2 is very low, fostering silica metasomatism during the early phase of serpentine alteration. This metamorphic phase is followed by a high temperature decompression trend that fosters gradual carbonation of the alteration assemblage in response to the increasing activity of CO_2 in fluids buffered by the graphite-water system as pressure is reduced.

ACKNOWLEDGMENTS

Luzenac America provided access to company property in the Proctorville, Vermont area and also provided site maps, drill core logs, and continuous core samples drilled in the Frostbite, Black Bear, and Kelly talc deposits in the study area. The authors particularly thank Mr. David Marek, Senior Mine Engineer at Luzenac America for arranging our access to the mine sites, company property, and rock core storage sites that made this study possible. We appreciate the assistance of Emily Laity, who drafted many of the maps and figures.

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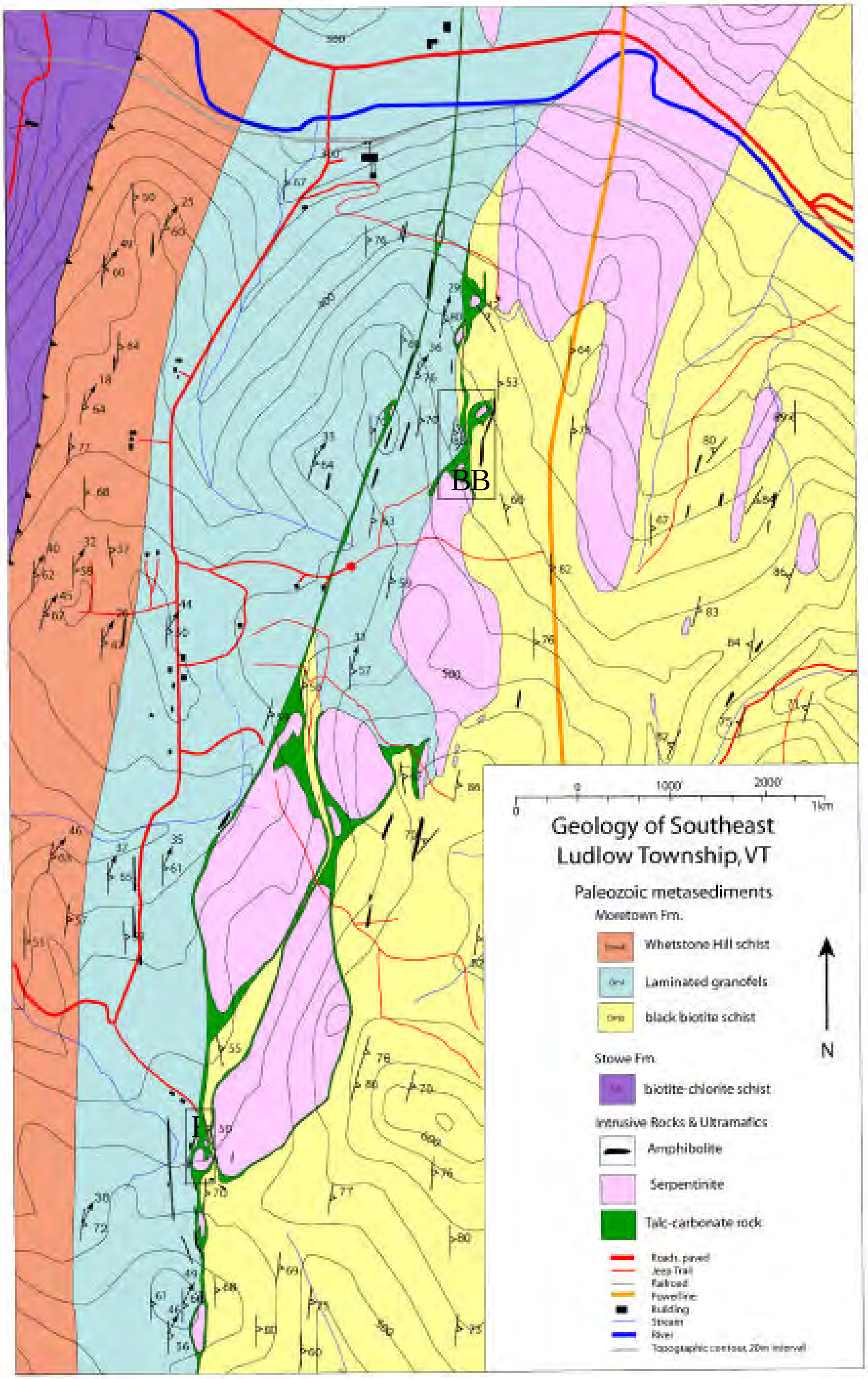


FIGURE 1 **Geology of southeast Ludlow Township, Vermont. Geology modified from Ratcliffe (1996), Walsh and others (1994), and mine site maps provided by Luzenac America. The locations of the Frostbite (F) and Black Bear (BB) mine areas identified in text are outlined by rectangle boxes on the map.**

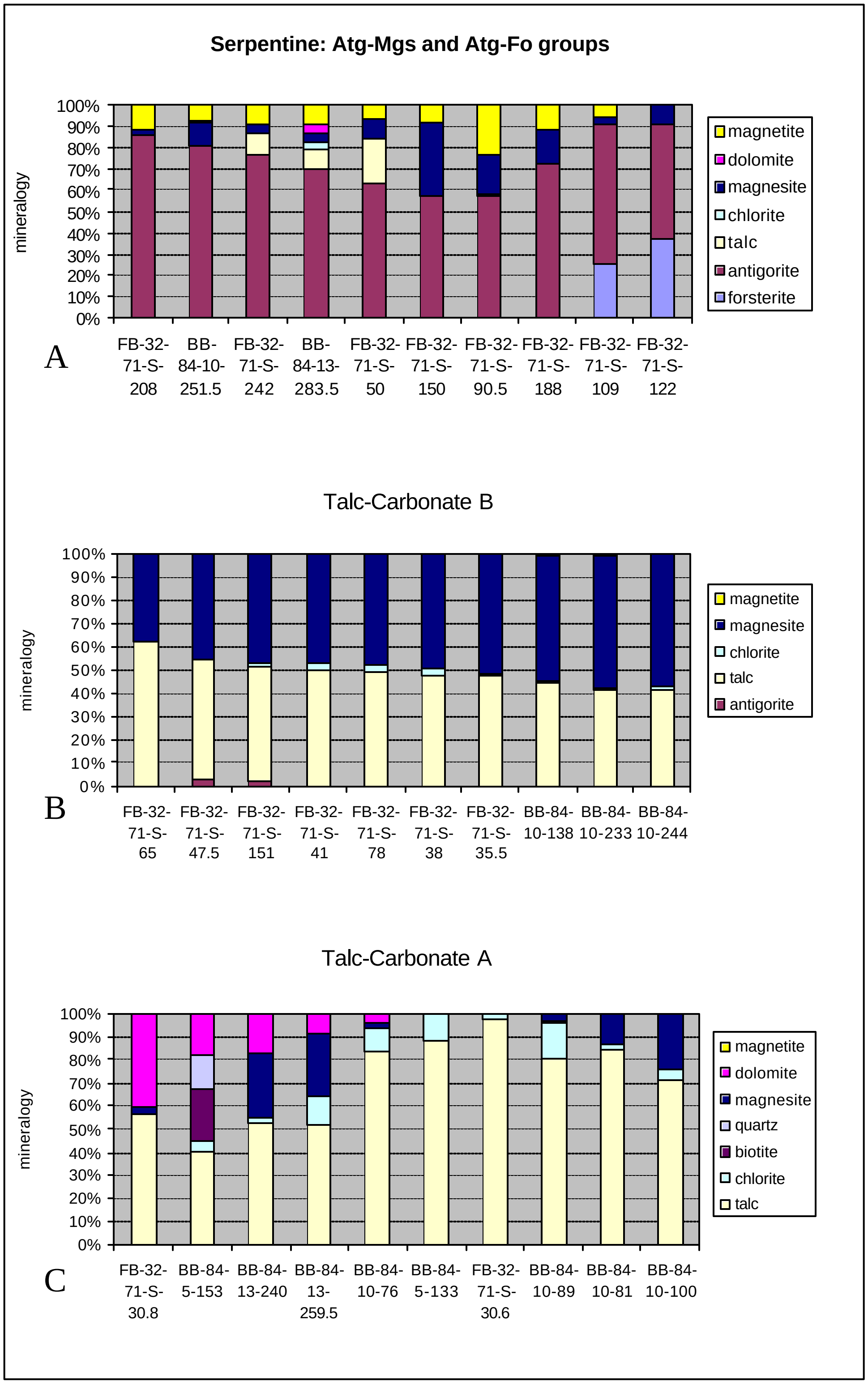


FIGURE 2 Mineralogy of ultramafic rock groups. The mineralogy of representative rock samples from core are shown in stacked bar format by weight percent; mineralogy colors follow legend stacking order. The samples are labeled by drill hole and depth. FB identifies Frostbite mine samples; BB identifies Black Bear mine samples.

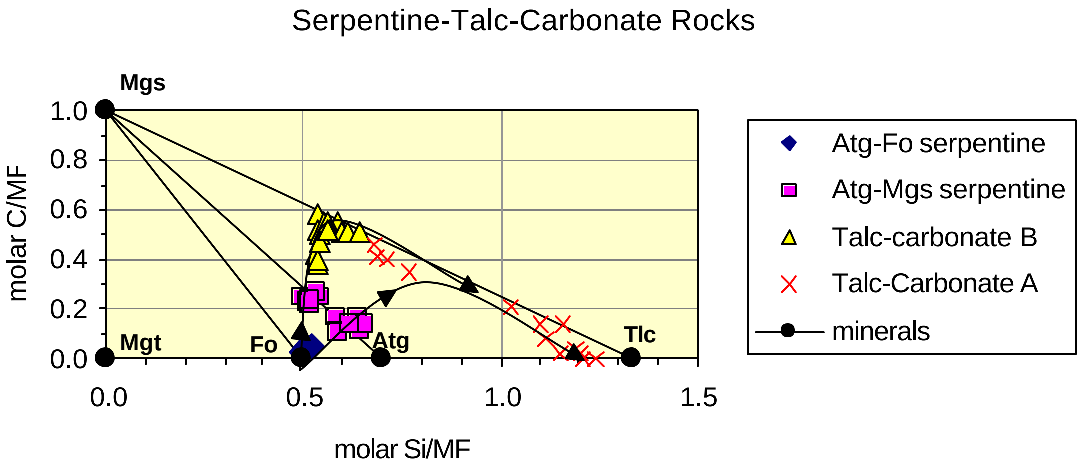


FIGURE 3 Geochemistry of serpentine-talc-carbonate rocks. The x axis is the molar ratio of Si/(Mg + Fe), labeled as Si/MF. The y axis is the molar ratio of C/(Mg + Fe), labeled as C/MF. The locations of end-member mineral compositions are shown by black dots, labeled according to the abbreviations listed in Table 1. Characteristic mineral assemblages of the ultramafic rock groups are shown by black tielines between the mineral compositions.

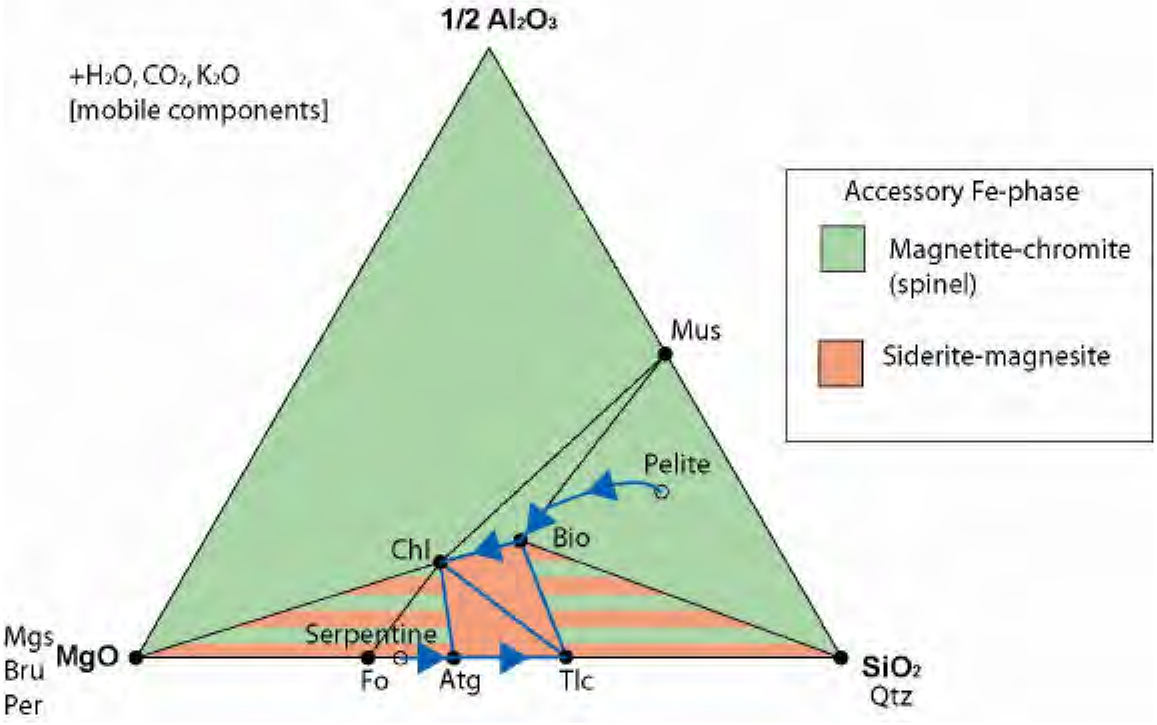
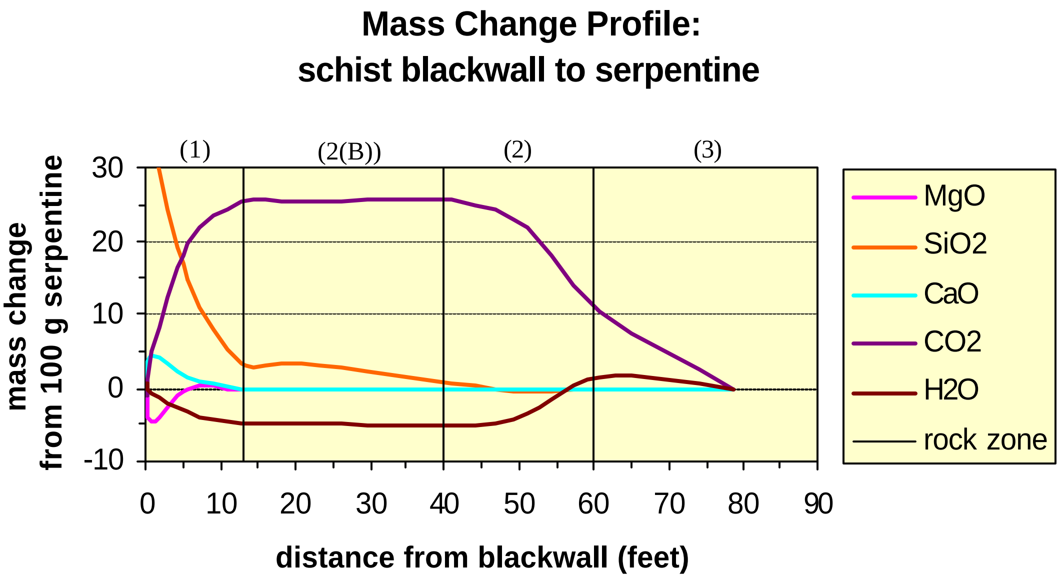


FIGURE 4 **Metasomatic reaction paths portraying the development of reaction zones between serpentine and siliclastic metamorphic rocks. The blue lines with arrows show the alteration paths in the serpentine and siliclastic in response to metasomatic changes in silica, magnesia, and carbonate composition. Field in which magnetite is stable are shown in green and where ferroan magnesite (siderite-magnesite) is stable is shown in orange. Areas where either magnetite or ferroan magnesite is stable is shown by the striped pattern.**



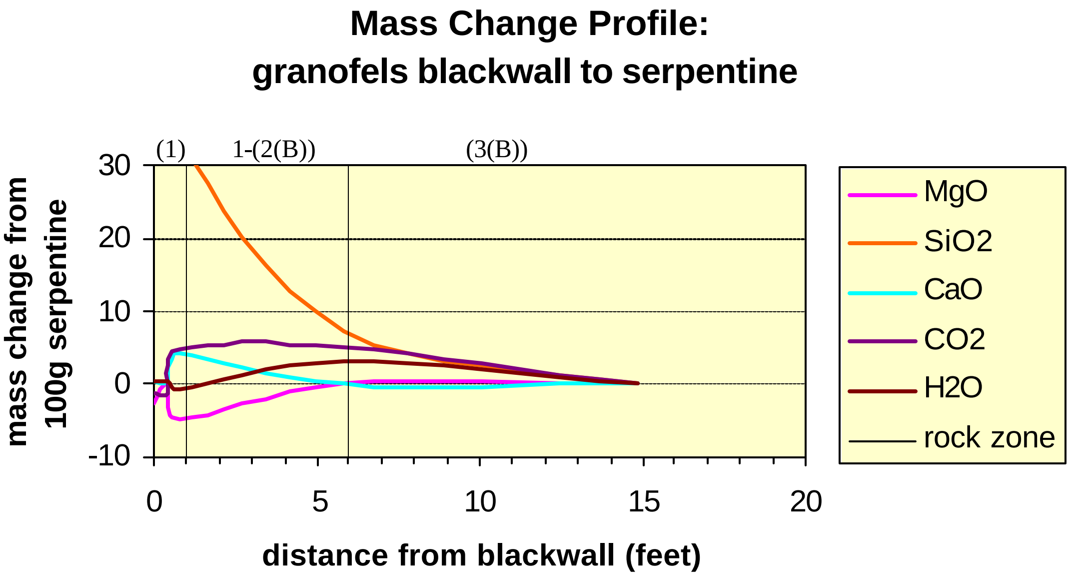


FIGURE 5 Mass change profiles from country rock to serpentine, relative to 100 g of serpentine, calculated for rock core sequences through the Frostbite and Black Bear mines. Positive numbers indicate mass gain by the serpentine protolith to form the rock zone composition. The numbers and letter codes above the graph refer to the rock zone and characteristic mineral reactions listed in Table 2.

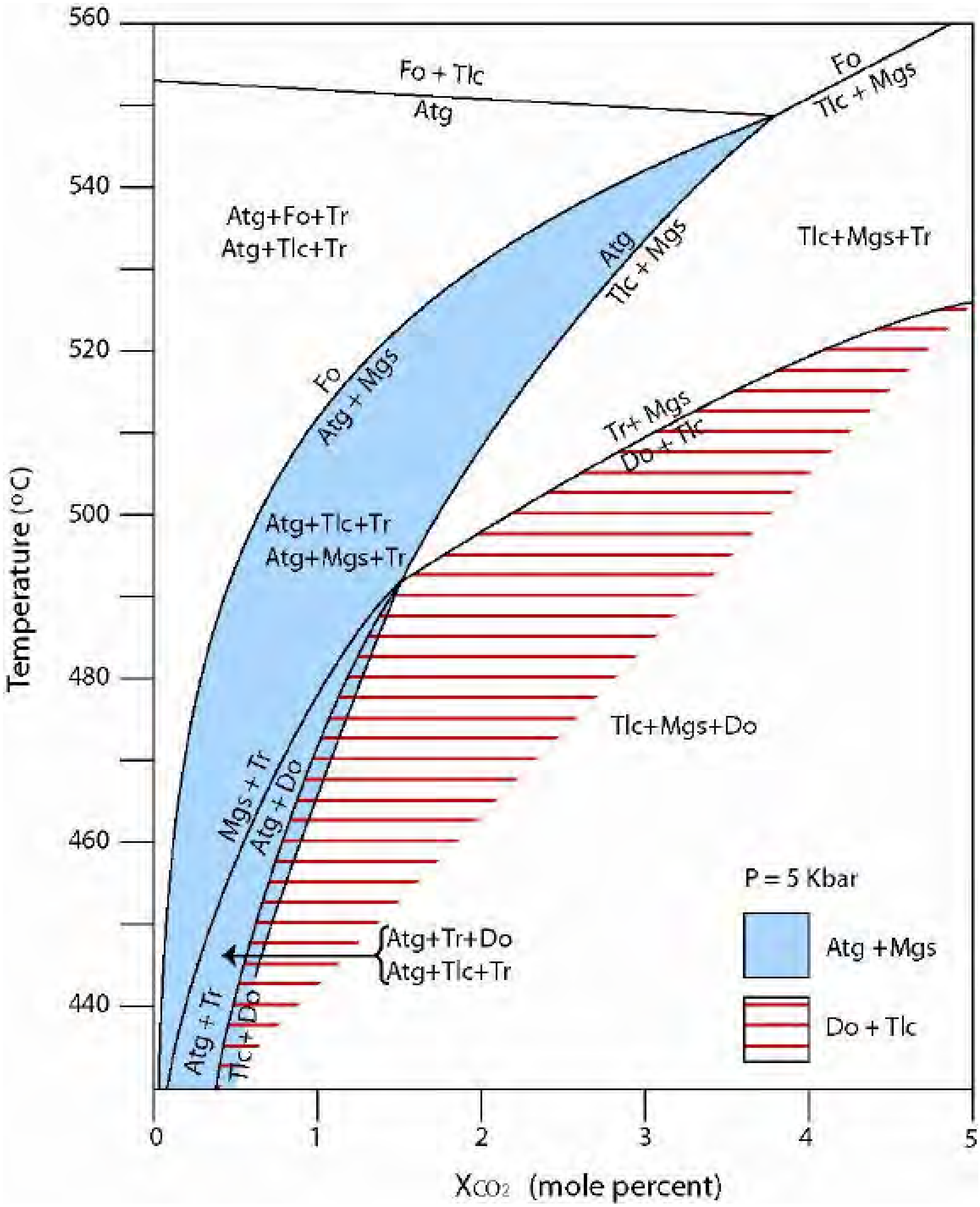


FIGURE 6 Mineral stability relations as a function of temperature and XCO_2 calculated at 5 kilobars pressure using the TWQ software program (Berman, 1991). Mineral abbreviations are from Table 1. The stability fields of dolomite + talc and antigorite + magnesite are shown by pattern. These assemblages coexist only at temperatures less than 490 C at 5 kilobars pressure in water-rich metamorphic fluids containing less than 2 mole percent CO_2.

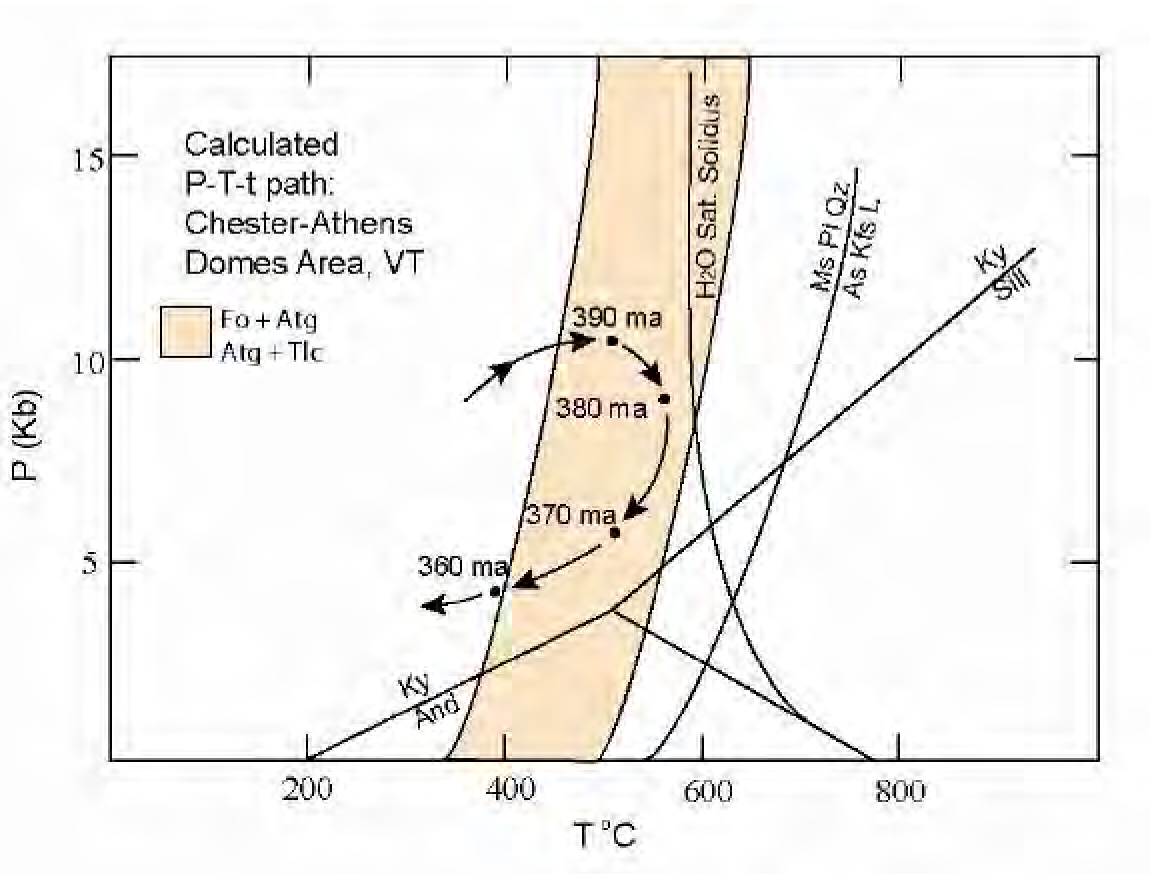


FIGURE 7 metamorphic conditions and timing in relation to mineral stability fields, Chester-Athens Domes area, Vermont. Temperature-pressure conditions and timing are from Vance and Holland (1993) and Armstrong and Tracy (2000). The stability field of antigorite serpentine in the $MgO-SiO_2-H_2O$ system (Bucher and Frey, 1994) is shown in relation to other mineral phase equilibria.

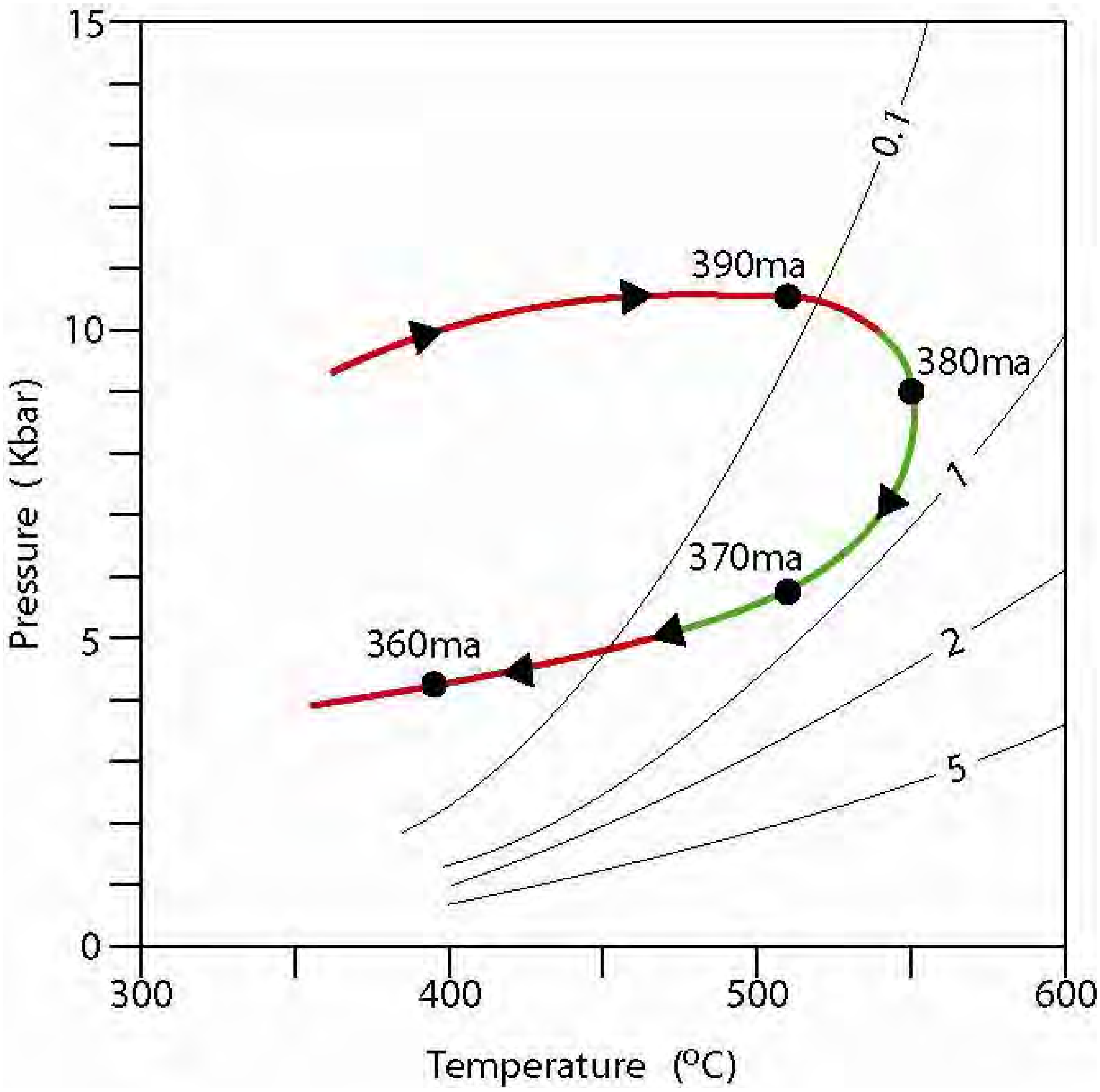


FIGURE 8 Metamorphic conditions and timing in relation to X_{CO_2} composition of fluids buffered by graphite-water equilibria. The colored line shows the pressure-temperature-time (PTt) conditions from Figure 7. Black contours show X_{CO_2} composition in mole percent, calculated using methods of Connolly and Cesare (1993). The PTt conditions where talc-magnesite assemblages are likely to form in the metamorphosed ultramafic rocks is shown in green.

The geology of and product applications for the Argonaut Talc Mine, Ludlow, Vermont

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ABSTRACT

The eastern ore body of the Argonaut Mine near Ludlow, Vermont is the largest talc mining operation in the eastern United States. This open pit deposit is the sixth ore body that has been exploited over the past 30 years in the serpentinite-hosted Ludlow talc carbonate trend. The annual production from this mine is currently at 140,000 short tons of talc magnesite ore.

The origin of this type of serpentinite-hosted ore body is rooted in the emplacement of ultramafic magmas within the lower Paleozoic Iapetus oceanic crust within a spreading center or island arc prior to the Taconic Orogeny. Magmatic segregation produced layered dunite and peridotite lithologies, which were later hydrated and serpentinized during or after cooling. Crystalline chromite was generated within the ultramafic section during cumulate segregation, and magnetite then formed and crystallized during the serpentinization process.

Prior to orogenic emplacement within the Taconic belt, carbonatization associated with carbon dioxide metasomatism altered the serpentinite host to a talc and magnesite body. Aluminous zones were altered to chlorite, and schistose and gneissic country rock folded within the altered serpentinite became chloritized to mafic "cinders". Additional hydrothermal alteration along the body margin between the talc carbonate and the mica-quartz-feldspar country rock produced an enriched "steatite" zone and an alteration front of chlorite called the "blackwall".

For many years these deposits in Vermont were processed by flotation to produce a nearly pure talc concentrate that was utilized for body powders, cosmetics, paint and other high purity applications. In 2003, the West Windsor flotation plant was closed and now all processing is done utilizing roller mills at the Ludlow dry grinding plant, which processes whole ore for a number of commodity and niche applications. The mineralogy and platiness of the Vermont Argonaut ore provides our customers in the eastern United States with a unique and cost-effective mineral solution for numerous industrial mineral applications.

Ronald, Erik, O'Brien Erroll, and Crouse, David, 2006, The geology of and product applications for the Argonaut Talc Mine, Ludlow, Vermont, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Rio Tinto Minerals' Argonaut Mine, Ludlow Mill and shipping center are located east of the town of Ludlow, in Windsor County, south-central Vermont (Figure 1). The mine is situated on the serpentinite-hosted Ludlow talc-carbonate trend, which trends roughly north-south and is part of a larger ultramafic belt extending through Vermont into eastern Canada.

The Argonaut Mine produces a unique talc ore, which is processed by dry grinding methods in the Ludlow Mill to produce a variety of specialized products that are utilized in value applications in the roofing, adhesives, flooring, and paint industries. The large and consistent resources of the Argonaut talc-magnesite ore body allows for year-round mining. Talc products from the Ludlow facilities are sold throughout North America, particularly in the eastern United States.

The Argonaut Mine is located at an elevation of 480 m (1575 feet) above mean sea level. Facilities at the Argonaut Mine include the Black Bear waste impoundment; the Rainbow ore pad; the Ludlow Mill and shipping center; the administrative building; and the Stone House mine office.

REGIONAL GEOLOGY

Geologic History

The complex geologic history of southern Vermont is primarily a result of the Taconic, Acadian, and to some degree the Alleghenian orgenies. The oldest rocks present in this region are exposed as the core of the Green Mountain physiographic province. These Precambrian Grenville gneisses, quartzites and marbles were metamorphosed between 1,100 and 1,300 million years ago (Zen, et al., 1968). The same series of rocks extends into the Grenville province of the Canadian Shield to the north (Bain, 1936).

The region experienced a period of quiescence until about 650 million years ago, when crustal extension began to form the Iapetus Ocean (proto-Atlantic). As the Iapetus Ocean began to widen, it further separated North America from Africa, until about 450 million year ago. At this time, a shallow sea covered New England and formed the shelf sequence of carbonate and siliciclastic deposits located in the Vermont Valley physiographic province. This Cambro-Ordovician shelf sequence grades eastward into shales, turbidites and breccias that record an eastward transgressive marine environment. This marine sequence was later faulted and folded during the Taconic Orogeny.

During the Early Ordovician, ultramafic magmas where emplaced within the Iapetus oceanic crust within a spreading center or island arc prior to the Taconic Orogeny. The natural magmatic segregation of these ophiolites produced layered dunite and peridotite lithologies, which were later hydrated and thus serpentinized during or shortly after cooling.

Prior to orogenic emplacement within the Taconic belt, carbonatization associated with carbon dioxide metasomatism altered the serpentinite host to a talc-magnesite body. Aluminum-rich zones within the serpentinite body were altered to chlorite, and schistose and gneissic country rock folded within the altered serpentinite became chloritized to form mafic "cinders". Additional hydrothermal alteration along the body margin between the talc-magnesite and the mica-quartz-feldspar schist country rock produced an enriched "steatite" zone and an alteration front of chlorite called the "blackwall".

During the Middle Ordovician, compressional forces affecting the crust caused the Iapetus Ocean to begin to close. A subduction zone formed offshore with an associated island arc system, known as the Bronson Hill anticlinorum. Exposed in southwestern Vermont in the Taconic Highlands province is the Taconic allochthon, a complex mass of rock emplaced during the late Middle to Late Ordovician (Ratcliffe, 1996). This mass is composed of deep-water argillaceous sediments with interbedded limestones, sandstones, and greywacke.

The Ordovician Taconic Orogeny represents the collision of the Bronson Hill island arc system with North America. Block faulting, prevalent during the early compressional phase, was followed by intense thrust faulting. During this intense phase of thrust faulting, oceanic crust was overthrust onto continental crust and deformed. These ophiolite sequences are represented by the north-south trending, discontinuous belt of ultramafic bodies located throughout New England and continuing into eastern Canada.

Talc ore resources in Vermont are confined within this north-south trending ultramafic belt. In certain areas within Vermont, these ultramafic bodies are now represented by a central core of serpentinite surrounded by a shell or rind of talc-carbonate rock and steatite (Chidester, 1962). Within the Ludlow talc-carbonate trend, talc mineralization formed from the alteration of serpentinite bodies result in an outer steatite and a thick talc-magnesite rind around the serpentinite bodies that can be up to 100 meters thick. Commonly, within the Vermont ultramafic belt, talc-rich zones may be present around the serpentinite bodies, but may only be several meters thick.

Parent Rock

The majority of the Vermont ultramafic belt rocks occur within schist, phyllites, and gneisses on the east flank of the Green Mountain anticlinorium. The talc-magnesite deposit of the Argonaut Mine resulted from the alteration of existing rocks under the effect of metasomatic fluids carrying one or several of the components needed to form talc (Mg, SiO_2, CO_2). Tectonics played a major role in the genesis of these talc deposits by establishing brittle fractures, which enabled metasomatic fluids to penetrate the rock through the micro-permeability. The size and shape of talc deposits depend upon structural control as well as the intensity of the metasomatic activity, which corresponds to low temperature metamorphism (Gillson, 1927). Pressure and deformation, both concurrent with and subsequent to this transformation, determine the crystallinity of the talc ore in the deposit.

The steatite zone observed in many talc carbonate bodies is comprised almost entirely of talc. The zone that miners use to call “grit” is a more massive, talc-magnesite rock with localized areas of pure talc. The less pure form of talc ore, commonly called "soapstone", is grey and is typically has a higher percentage of chlorite and carbonate than talc. Soapstone deposits are relatively common and widely distributed along ultramafic rock belts. Historically, serpentinite-hosted talc deposits have been mined in California, Texas, Vermont and eastern Canada. Amongst those deposits currently are those deposits in Quebec, Ontario, and Finland are being mined.

Alternation History

The Argonaut talc-magnesite ore body began as an ophiolite sequence made up of olivine-rich dunite or peridotite, which underwent serpentinization prior to or during overthrusting onto continental crust. The serpenitization process likely occurred at low temperatures, by means of the interaction of seawater with low CO_2 content under reducing conditions (Kretschmar, et al., 1986). A byproduct of the prograde serpentinization of the olivines in the dunite is the loss of iron as a result the formation of the mineral lizardite, and the resulting precipitation of finely disseminated magnetite within the serpentinite (O'Hanley 1996). Serpentinization of the primarily olivine-rich rock is represented by the equation below:

$$\underset{\text{Olivine}}{3Mg_2SiO_4} + \underset{\text{Silica}}{SiO_2} + \underset{\text{Water}}{H_2O} = \underset{\text{Serpentinite}}{Mg_6Si_4O_{10}(OH)_8}$$

The carbonate metasomatism likely occurred prior to orogenic emplacement within the Taconic belt. The metasomatism appears to have been concentrated in the zones around the serpentinite bodies from the country rock as evidenced by the alteration front evident along the serpentinite – talc carbonate interface. Carbonate metasomatism involves the addition of CO_2 and the removal of H_2O. The conditions for this type of metasomatism have been experimentally defined at a low total pressure of 500 bars and a temperature around 450° C over a variable range of CO_2 (Johannes, 1969). The CO_2 is likely sourced from enriched solutions coming from the heating of carbonates deposited upon the subducted oceanic crust. The carbonate metasomatism process can be represented by the following equation:

$$\underset{\text{Serpentine}}{Mg_6SiO_{10}(OH)_8} + 3CO_2 = \underset{\text{Talc}}{Mg_3Si_4O_{10}(OH)_2} + \underset{\text{Magnesite}}{3MgCO_3} + 3H_2O$$

The later carbonate metasomatism was likely concentrated along the margins of the dense serpentinite bodies. As regional tectonics folded and faulted the highly foliated country rock (schist), the much denser serpentinite bodies were likely rotated with little internal deformation, resulting in augen-like structure surrounding these ultramafic bodies.

Within the altered halos of the serpentinite bodies, there is the steatite zone. This is the portion of the body between the altered country rock and the talc-carbonate zone. This zone contains significant shearing parallel to the contact between the ore body and the country rock and also contains a higher degree of talc mineralization as a result of increased fluid movement and introduction of silica from outside of the ore body. The "blackwall" is at the interface of this reaction front between the talc -carbonate body and the gneiss or schist country rock. The "blackwall" is comprised of black, chloritized country rock at the outer border of the steatite zone. "Blackwall" is an old miner's term derived from the dark color of this chlorite-schist zone (Chidester, Billings, and Cady, 1951).

DEPOSIT GEOLOGY

Lithology

These talc-carbonate bodies typically include a core of serpentinite with an outer band of talc with magnesite. These talc-rich zones can vary between a few meters to a hundred meters thick. The talc-carbonate ore bodies are contained between the footwall and hanging wall of mica-chlorite-feldspar schist and are typically found within the noses of relict folds within the overall trend. At the Argonaut Mine, the talc-carbonate bodies represent a low temperature assemblage with the "blackwall" zone being composed primarily of chlorite, the steatite zone is composed of nearly pure talc and the outer zone is platy talc and massive talc-magnesite.

Within the talc-magnesite ore body, there are discontinuous bed-like lenticular bodies of chlorite, termed locally as "cinders". There are several theories on the origin of chlorite bodies, the first is that these features are thought to be early basaltic dikes injected into the ultramafic zone prior to, during, or after the thrust fault emplacement of the ultramafic bodies. These basaltic dikes would later be metamorphosed to greenschist facies chlorite-rich schists. Another theory of their origin is that these features are likely chloritized country rock that was folded tightly within the talc carbonate body during late stage orogenesis and lost most of its relic features. The cinders are typically present parallel to the north-south foliation and range from 1-3 feet in thickness.

A swarm of mafic lampropyhre dikes transect the ore body along the western margin of the serpentinite core at shallow dip to the east. These dikes were initially exposed in the south pit, but have recently been encountered within the lower benches of the North Pit as well. The origins of these mafic dikes are not well understood but are possibly associated with the failed rifting and associated volcanism represented in the Ascutney and Little Ascutney Mountains during the Mesozoic. This is evidenced in southern Vermont by numerous lamprophyre, diabase, trachydacite, and felsite dikes directly related to the intrusive stock at Little Ascutney Mountain emplaced during the Cretaceous (Stanley et al., 1984) The dikes swarm within the eastern Argonaut ore body consists of six dikes ranging from 1-5 feet in thickness and appear to have originated at depth as they do not leave the orebody to the north or south of their trend.

Mineralogy

Talc is a hydrated magnesium phyllosilicate with the idealized chemical formula $Mg_3Si_4O_{10}(OH)_2$. Its elementary sheet is composed of a layer of magnesium-oxygen / hydroxyl octahedra, sandwiched between two layers of silicon-oxygen tetrahedra. The main or basal surfaces of this elementary sheet do not contain hydroxyl groups or active ions, which explains talc's hydrophobicity and inertness. Talc is practically insoluble in water and in weak acids and alkalis. It is neither explosive nor flammable. Although it has very little chemical reactivity, talc does have a marked affinity for certain organic chemicals, i.e. it is organophilic. Above 900°C, talc progressively loses its hydroxyl groups and above 1050°C, it re-crystallizes into different forms of enstatite (anhydrous magnesium silicate). Talc has a relatively high melting point at 1500°C (Carr, 1994).

Trace Elements

Ore characterization commonly includes four-acid total digestion ICP trace element chemistry on 37 elements. This data is collected within the mine planning database in order to characterize and understand the minor chemistry that may have the potential to impact our customer's product applications. The primary trace elements within the ore zone are iron, chromium, nickel, and arsenic. These elements are relatively consistent in their distribution with the exception of arsenic that tends to concentrate in a series of east-west trending fractures and along the outer margin of the steatite zone.

MINE HISTORY

Exploration Identification

Talc ore and more commonly its massive, less pure form called "soapstone" has been mined in Vermont since the early 19th century. Initially, talc and soapstone was hand-mined at select locations and used commercially for water pipes. Pipes two to three feet long were cut from three and four inch blocks and bored hollow. The finished pipe sold at six cents per foot. By the late 1800s, the largest soapstone quarries in the nation were located at Grafton, Vermont and Franconia, New Hampshire (Vermont Geological Survey, 2006). Several studies were conducted in the first half of the 20th century by the U.S. Geological Survey and the Vermont State Geological Survey on talc occurrences within the state. The Eastern Magnesia Talc Company operated mines in Vermont and was the primary producer of talc in Vermont for nearly 50 years.

In the mid-1960s, Johnson and Johnson bought the land holdings for the Eastern Magnesia Talc Company, which included the area near the current Argonaut Mine. Johnson and Johnson operated their talc properties under the name Windsor Minerals. The Argonaut Mine itself is located on a privately held parcel, for which monthly royalties are paid to the landowner for total ore extracted. The Argonaut Mine began production as an underground mine in 1972. Underground drifts and stopes followed the high-talc content steatite zones along the margins of the ore bodies. Development of the underground workings used some conventional drill and blast technology, but primarily utilized continuous miners to extract the talc ore (Piniazkiewicz, 1988).

In 1975, Windsor Minerals built the Columbia Mill in Ludlow, Vermont, now known as the Ludlow Mill. During the 1980s, five mines along the Ludlow talc-carbonate trend were being exploited. There have been six mine sites located in the Ludlow area. From North to South, they are the Rainbow Mine, Black Bear Mine, Argonaut East Mine, Argonaut Main Mine, Frostbite Mine and the Clifton Mine. Only the Frostbite and Argonaut Mines operated underground, with both the Argonaut Mines later becoming open pit mines. Each mine has produced a slight variation of talc ore unique to Vermont.

In 1988, Cyprus Industrial Minerals acquired the Ludlow properties from Windsor Minerals. Ore was processed at two grinding mills and one flotation plant. In July 1992, Luzenac America Incorporated purchased Cyprus Minerals' Vermont operations. Luzenac America Inc. is a wholly owned company of Rio Tinto Plc. based in London. Shortly after acquiring the various mines and properties, Luzenac began a rationalization process which resulted in the closure of all Vermont mines with only the Argonaut Mine remaining in operation.

During 2003, the West Windsor flotation plant was closed. At the present time all remaining ore produced from the Argonaut mine is processed and ground at the Ludlow Mill. In early 2006, Luzenac America was combined with Rio Tinto Borax and Dampier Salt to form Rio Tinto Minerals.

Mine Operations

Current mining operations utilize a five-day work week, with one – eight hour shift per day. The current annual output of the Argonaut Mine is 140,000 short tons of talc ore. The open-pit mine development began in 1992 with the stripping and exposure of both the north pit and the South Pit. Initially the south pit primarily supplied the West Windsor flotation plant and the North Pit was the primary source for ores utilized at the Ludlow Mill. Benches have been developed on 20-foot levels to optimize ore recovery while balancing geotechnical and slope concerns. Blasting is typically scheduled on a weekly basis, with ore segregation occurring directly at the muck pile. The mine currently uses two 65-ton Caterpillar 773 haul trucks, one 55-ton Terex haul truck, one Caterpillar 365 excavator, and two Caterpillar 890 front-end loaders.

Ore is hauled approximately one mile to a covered ore shed, the Rainbow stockpile pad or directly to the primary jaw crusher. The covered ore shed allows for ore storage and segregation while keeping the ore relatively dry during the wet New England winter. The crushing and grinding of the talc ore become increasingly difficult when the moisture content of the ore exceeds approximately five percent.

Mill Operations

The Ludlow Mill operates year-round and exclusively processes the talc-magnesite ore from the Argonaut Mine. The mill is a dry process grind plant with a capacity of approximately 180,000 short tons per year. The mill has a primary jaw-crusher, secondary cone crusher, three roller mills, bagging equipment, and a loading facility for both truck and rail. The crude ore is loaded from either the ore shed or directly from a haul truck into the primary jaw crusher's feed bin. The ore output from the primary jaw crusher is transferred through the secondary crusher to two 800-ton roller mill feed bins. The first roller mill, Alpha, is dedicated to producing a 30-mesh product which is primarily used for the roofing industry. This roller mill is in closed circuit with a screen deck for top size control. The screened oversize is recycled to the mill, while the undersized material is transferred to a 1,200 ton silo. The second and third mills, Beta and Gamma respectively, share common feed and product bins. The products produced from these two mills can be adjusted for a variety of industry applications including adhesives, caulks, sealants, flooring and others.

The Ludlow shipping center can package final product in 50-pound, 1-ton bags or as bulk product in truck trailer or rail car. The final product from the Ludlow operation is shipped to customers throughout the eastern United States and Canada via truck or rail.

ORE CONTROL

Sampling Procedures

Sampling is performed on a regular basis by both pre-mining in-fill airtrack drilling, typically on 50-foot spacing as well as weekly blast hole sampling. Drill holes are logged for lithology and sampled on 20-foot bench composite intervals. Samples are ground to 40% -325 mesh and tested for mineralogy, color, brightness, and chemistry.

Mineralogy

Mineralogy is determined by X-ray diffraction techniques combined with loss on ignition (LOI) data and major element chemistry. The ore mineralogy is primarily talc and magnesite with common dolomite and minor trace minerals. Typical ore from the Argonaut Mine averages 55 to 65 percent talc, 30 – 35 percent magnesite, 1-4 percent dolomite, 2-4 percent chlorite, with minor chromite and magnetite and less than one percent quartz.

Color Components

The whole ore is ground and measured for color and tint using a Minolta CR-300 according to Rio Tinto Minerals internal standard test methods. The Minolta instrument measures a compressed powder plaque and generates a number for each of the three color axes: X, Y, and Z. The Y-axis represents the whiteness of the sample based on magnesium oxide as a reference of 100. The yellowness of the samples (yi) is calculated using a formula with X, Y, and Z values.

Specifications

Ore control results in the definition of three stockpile grades that are then blended into the Ludlow Mill in order to satisfy a variety of product specifications. Commonly end-product specifications are based upon insol, dry yi, and Minolta Y value. The LOI of the ore typically averages 25 percent. The dry yi, representing the strength of the yellow tint, typically ranges from 2 to 8. The Minolta Y value ranges from 63 to 75, with an average of 68. All ore control testing procedures are performed on whole ore at a 40 %, minus 325 mesh grind through a Bico mill.

MINERAL PRODUCTS

Product Properties

Talc is a soft, nonabrasive, inert mineral that can be easily ground to form a white and bright fine to micronized powder that acts as a functional filler for paint, plastics, paper, rubber, adhesives, joint compounds, stucco and pharmaceuticals. Uniquely, talc is organophillic and hydrophobic in nature and naturally has high oil and grease absorption capabilities while being water repellent.

The Argonaut Mine produces a unique, microcrystalline and very platy talc ore that has excellent characteristics for a variety of industrial applications. The following table lists some of the applications and advantageous properties of the Argonaut Mine ore.

Market Applications

Table 1 lists specific industrial applications of talc ore from the Argonaut Mine. The mineralogy and platiness of the Argonaut ore provides our customers with a unique and cost-effective mineral solution for numerous industrial mineral applications.
The Argonaut talc ore out-performs a variety of other minerals for a number of specific applications. Information contained in Table 1 was obtained from personal communication with Dr. Edward McCarthy (McCarthy, 2006) of Rio Tinto Minerals.

TABLE 1 Industrial Applications of Argonaut Talc Ore

Asphalt Roofing	Talc acts as a parting agent for shingles for rolled roofing. In this market, it competes with sand, slag and dolomite. Talc is far less abrasive and allow for higher production rates due to faster drying and better lubricity on the shingle machines. Talc is also used as a functional filler in modified bitumen roll roofing where it is less abrasive than limestone and has better weathing characteristics than the limestone due to reduced loss of volatiles.
Stucco and Putties	Talc is used as an additive in drywall joint compounds. These compounds are mainly 200 mesh carbonates. The added talc reduces mudcracking, improves application and anti-settling behavior.
Flooring	Talc is added in the felt backing for vinyl flooring. Talc also provides better reinforcing properties than limestone and better smoothness on the felt.
Paints	Talc is a key pigment in alkyd and automotive refinish primers. Talc is also a key pigment in latex industrial and latex stain blocking primers.

(Table modified after McCarthy, 2006)

In addition to the applications listed in Table 1.0, finished product from the Ludlow Mill is also used in other applications such as: anti-friction for cable fabrication, wallboard filler, mold liner for tire fabrication, mold release for ceramics, animal feeds, graphite molding, candle filler, plastic batch component, clutch-type antifriction parts, cardboard and decking board.

CONCLUSIONS

With the projected long life and unique product characteristics of the Argonaut ore body, the Rio Tinto Minerals operation in Ludlow, Vermont can be expected to produce high quality, high value products for the roofing, adhesive, paint and other industries well into the 21st century. Detailed grid drilling and ore control supported by long term mine planning will assure ore consistency and quality to support the ore blends required to produce the product concentrates to satisfy customer requirements now and in the future.

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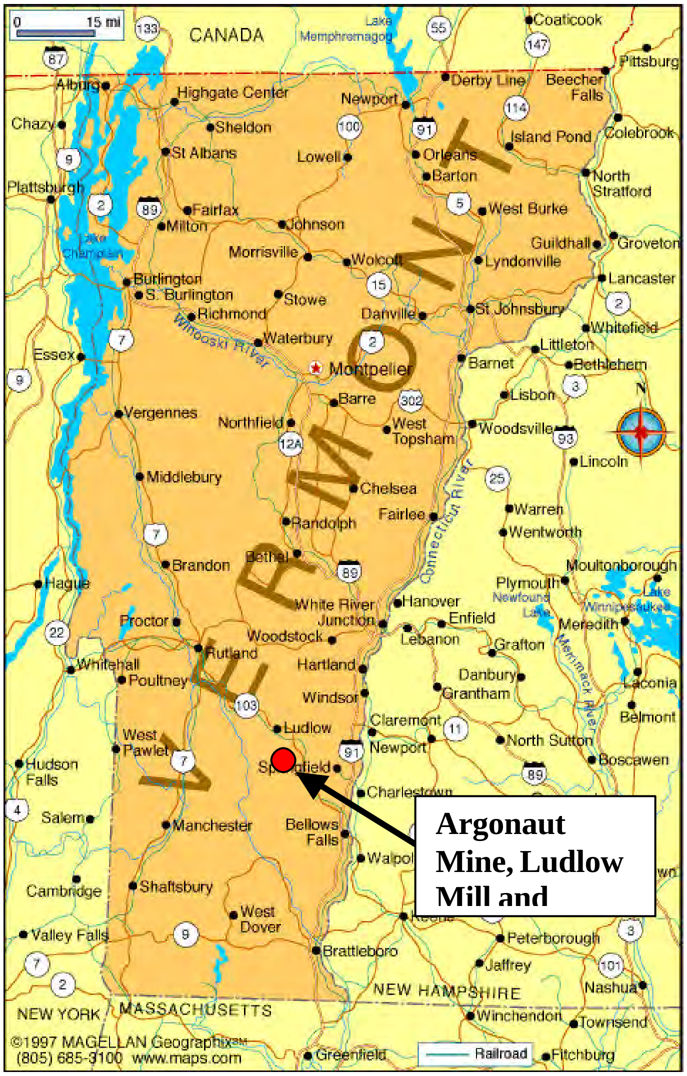

FIGURE 1 Location map of the Argonaut Mine, Ludlow Mill, and associated facilities near the town of Ludlow, VT.

FIGURE 2 Mine personel observe contact between the mafic lamprophyre dike swarm and the talc-magnesite ore.

FIGURE 3 Oblique aerial photograph of the north-south trending Ludlow talc-carbonate trend.

FIGURE 4 Loading ore into 65-ton Caterpillar haul truck.

The geology of and product applications for the Penhorwood Talc Mine, Penhorwood, Ontario, Canada

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ABSTRACT

The ore body of the Penhorwood Mine in Reeves Township, 74 km west of Timmins, Ontario is the largest talc mining operation in Canada. This open pit deposit was first developed by Johns Mansville in 1974, but was shortly sold to Steetley Talc in 1978. The mine, flotation plant and the Timmins micronizing plant have all been owned and operated by Luzenac Inc. since 1988. The annual production from this mine is currently at 230,000 short tons of talc magnesite ore, which feeds the adjacent flotation plant on the Penhorwood mine site.

The origin of this type of serpentinite-hosted ore body is related to the eruption and emplacement of extrusive dunitic komatiitic magmas within the Archean Abitibi Subprovince in a probable island arc tectonic environment. Magmatic segregation within these magmas produced layered dunite and peridotite lithologies, which were later serpentinized as they were cooling. Magnetite formed as the prevalent opaque mineral and crystallized during the serpentinization process.

Secondary carbonatization of the serpentinites, as a result of carbon dioxide metasomatism radiating out from major structural fault intersections, formed the talc magnesite mineralogy. Aluminous zones were altered to chlorite, and areas of intense carbonate alteration resulted in the conversion of the magnetite to hematite. This deposit does not display the typical blackwall alteration due to the lack of quartz-feldspar-mica country rock and the outward alteration pattern into the serpentinite on the margins of the talc carbonate body.

For almost 30 years high quality floated talc concentrates and micronized finished products have been generated from the Penhorwood and Timmins operations. Due to the platiness and whiteness of the Penhorwood talc, the products perform extremely well in specialty ceramic, polymer and coatings applications. Products are shipped throughout North America from the Ontario production facilities.

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INTRODUCTION

The Penhorwood Mine and milling facilities are unique within the Luzenac group in that they are well outside of their market area and that the processing utilizes flotation to concentrate and produce the finished talc product. The high quality talc product generated through the flotation process and the specialized micronizing milling capabilities at the sister milling facility in Timmins, combine to produce a special product that is utilized in value applications in paper, polymers, coatings and ceramics. The large and consistent resources of the talc carbonate ore body allows for seasonal campaign mining and low operational costs. Talc products from the Ontario facilities are sold throughout North America.

REGIONAL GEOLOGY

Host Rock

The Penhorwood Mine lies within the Archean Kidd-Munro assemblage along the northeastern edge of the Swayze Greenstone Belt in the western Abitibi Subprovince west of Timmins, Ontario (Figure 1). This assemblage appears to represent a series of stacked or thrusted subterranes formed during the evolution of paired active-arc-back-arc systems. Each episode is marked by the development of komatiitic, thoeliitic, and calc-alkaline igneous rocks. The Kidd-Munro assemblage is a steeply dipping and east-west striking, folded package of intercalated ultramafics, mafics, lesser felsic metavolcanic rocks and intrusions and associated sediments (Gibson et al., 2003).

The komatiites in the immediate area of the Penhorwood Mine are basal olivine cumulate dunites that erupted as part of large channelized komatiitic flows and were serpentinized shortly after emplacement. These flows were subsequently intruded by a gabbro/quartz diorite complex to the east. The komatiites are currently bounded to the west by mafic to felsic volcanic flows. Serpentinized komatiites bound the ore body to the south and southeast. Minor northeast-trending lamprophyre and carbonatite dikes cut the northern part of the talc carbonate ore body and an altered diabase related to the Matachewan dike swarm intruded along a north-south extensional structure to the northeast of the mineralized area.

Alteration History

It is postulated that the komatiites were extruded onto the base of a large marine basin and that the process of serpentinization took place shortly after deposition. Evidence to support this is found in the serpentinization patterns within the hexagonally jointed komatiite flows likely caused by rapid cooling. The degree of serpentinization decreases with distance from these joints. The serpentinization process likely took place in a stable tectonic environment at low temperatures by means of the interaction between the komatiites and seawater with low CO_2 content under reducing conditions (Kretschmar et al., 1986). A byproduct of the prograde serpentinization of the olivines is the loss of iron as a result the formation of the serpentine mineral lizardite. Lizardite can accept only a third of the iron that olivine can retain. This difference results in the precipitation of finely disseminated magnetite within the serpentinite (O'Hanley, 1996). Serpentinization of the primarily olivine-rich rock is represented by the equation below:

$$\underset{\text{Olivine}}{3Mg_2SiO_4} + SiO_2 + H_2O = \underset{\text{Serpentine}}{Mg_6Si_4O_{10}(OH)_8}$$

Later carbonate metasomatism was structurally controlled by the Porcupine-Destor Fault Zone (PDFZ), which crosses the ore body at its northern extension. The alteration was further concentrated in what became the Penhorwood ore body by crosscutting north-south structures and other tertiary oblique shear zones. The initial deformation regime within the serpentinite was brittle and involved thin fault zones. With further progressive alteration to talc carbonate, the deformation regime along this fault zone progressed from brittle to ductile deformation and involved a greater degree of shearing. The metasomatism appears to have been centered on a fault controlled source along the northern limits of current talc mineralization due to the fact that the ore is bounded by and transitions into magnesium-poor units to the east and west, beyond which no talc mineralization occurs. The talc mineralization progressively diminishes with distance from the PDFZ toward the south within the dunitic cumulate layers. The metasomatism involved the addition of CO_2 and SiO_2 the removal of H_2O. The conditions for this type of metasomatism have been experimentally defined at a low total pressure of 500 bars and a temperature around 450° C over a variable range of CO_2 (Johannes, 1969). The CO_2 is likely sourced from enriched solutions coming from the decomposition of carbonates deposited within the regional sea floor environment. In addition, it is likely that the spinifex textures within these komatiites increased the susceptibility to carbonate metasomatism as a result of the more open network structure of these olivines (Kretschmar et al., 1986). The carbonate metasomatism process can be represented by the following equation (O'Hanley, 1996):

$$\underset{\text{Serpentine (lizardite)}}{2Mg_3Si_2O_5(OH)_4} + 3CO_2 = \underset{\text{Talc}}{Mg_3Si_4O_{10}(OH)_2} + \underset{\text{Magnesite}}{3MgCO_3} + 4H_2O$$

It is likely that additional silica was introduced during the time of carbonate metasomatism as evidenced by enriched silica zones in several locations within the ore body. Metasomatism likely occurred throughout much of the Archean and Proterozoic along these faults as evidenced by the complete chloritization of the later Proterozic diabase dikes.

Structural and Metamorphic History

Several proposed tectonic models for the evolution of the southern Abitibi greenstone belt suggest that the deformation zone associated with Porcupine-Destor Fault is a crustal scale structure that developed in response to island-arc collision and subsequent rifting (Hodgson and Hamilton, 1989). Ultramafic and mafic metavolcanic rocks occur along the entire length of the fault zone (Berger, 1997). Movement and rotation along the fault zone has positioned the lithologic units in the area of the Penhorwood Mine as overturned with their stratigraphic tops toward the south and with units striking generally east to west and dipping steeply to the north. The metamorphic grade in the western portion of the southern Abitibi greenstone belt is typically greenschist facies with localized amphibolite facies in the contact aureoles of later intrusives (Jackson and Fyon, 1991). The metamorphic grade within the mine area is lower greenschist facies.

DEPOSIT GEOLOGY

Lithology

The primary lithology of the Penhorwood ore body is described as talc carbonate. The primary carbonate is magnesite with minor amounts of dolomite. The average percentage of talc within the ore body is 46%, with magnesite ranging from 42% to 49%. The ore body is bounded by a gabbroic intrusive to the east and aluminous mafic to felsic volcanics to the north and west. The talc carbonate alteration transitions into serpentinite toward the south representing the metasomatic alteration front. All of the basal cumulate dunitic komatiite units in the region have been serpentinized.

Within the ore body there are a number of dikes that are generally oriented either north-south or east-west. The dikes are of lamprophyre or diabase variety and are related to regional dike swarms.

Mineralogy

Talc carbonate ore bodies are lower grade in terms of talc content and globally are rarely exploited for talc as a result. In the Timmins region a number of talc magnesite or magnesite talc bodies have been identified. The Penhorwood ore body has the highest percentage of talc of the known altered and mineralized serpentinites in the region. However, the lower percentage of talc requires the ore to be floated to concentrate the talc to a marketable grade. The talc in this type of serpentinite-hosted ore body is classified as macrocrystalline. This type of talc has a coarse crystalline habit and the individual talc plates are typically greater than 20 microns in diameter. Talc plate thickness can range from 1 to 5 microns resulting in a high aspect ratio.

Minor minerals within the ore include chlorite, magnetite, hematite and dolomite in diminishing quantities. The magnetite is a remnant of the serpentinization process and it is believed that localized late stage intense carbonate metasomatism may be responsible for the localized transformation of magnetite to hematite, commonly concentrated as inclusions within the magnesite grains (Kretschmar et al., 1986).

Trace Elements

Ore characterization analyses commonly include four-acid total digestion ICP trace element chemistry on 37 elements. This data is collected within the mine planning database in order to characterize and understand the minor chemistry that may have the potential to impact our customer's product applications. The primary trace metals in the ore zone are iron, chrome and nickel. These elements are relatively consistent in their distribution but can be modeled along with the rest of the metals that are analyzed. Unlike many of the serpentinite talc carbonate deposits, Penhorwood does not have any significant levels or arsenic or other highly soluble metals that would require water treatment or additional ore control measures.

MINE OPERATION HISTORY

Exploration Identification

Johns Manville operated out of this region of Ontario and more specifically identified, developed and operated a chrysotile asbestos mine and plant on an adjacent property. They first became interested in these serpentinite bodies in 1951. During their term of exploration and development from the 1950's through the 1970's, Johns Mansville evaluated numerous serpentinite bodies in the region to determine their potential for asbestos mineralization. In 1973 the talc carbonate mineralization of the Penhorwood ore body was defined as part of one of their programs. The Penhorwood serpentinite body underwent a very complex alteration history and was converted to talc carbonate as a result of localized low temperature carbonate metasomatism in contrast to the low temperature hydrothermal CO_2-poor waters and tensional conditions that were the source for the formation of chrysotile deposits.

Development

Limited definition drilling was completed prior to the initial stripping and opening of the Penhorwood Mine. Mining was initiated at the southern limit of talc carbonate mineralization primarily due to the fact that glacial cover was thinnest there and mineralized outcrop was exposed at the surface. Since 1974, the development of mining has progressed to the north toward the flotation plant and will eventually expand to the east, where the ultimate pit limit has been defined.

Ownership

Johns Mansville operated the mine and flotation plant from 1974 to 1976. The nearby Reeves chrysotile mine had operated primarily in the 1960's and 1970's. In 1975 Johns Mansville made the decision to cease operations at both the Penhorwood mine and flotation plant operations and the Timmins mill. The operations were inactive until 1978 when Steetley PLC purchased both operations and resumed production. Steetley expanded the operations to be able to produce approximately 45,000 tonnes per year of talc product primarily for the paper, paint and plastics industry. Steetley operated the mine, plant and mill until 1988 when Luzenac Inc., in partnership with its parent RTZ (now Rio Tinto), purchased the operations as part of their North American expansion. The Ontario operations were added to the St.-Pierre-de-Broughton talc mine and mill near Thetford Mines, Quebec and the Canfield grinding mill in Canfield, Ohio.

The next large acquisition for the Luzenac group was the Cyprus Talc operations in Montana, Vermont, Alabama, Nebraska, California and Texas in 1992. The Canadian operations were operated under separate management from the Luzenac operations in the United States until 1998, when the corporate management in Denver became responsible for all North American operations. As of February 1, 2006 the Luzenac North America operations were merged with the Borax Americas operations to form part of a new global industrial minerals company within Rio Tinto, now called Rio Tinto Minerals.

Mine Operations

The ore body, as currently defined, is approximately 400 meters wide and 700 meters long in a north-south direction. The deposit has been defined by drilling on 50-meter centers with the deepest hole to date at a completed depth of 204 meters and still in ore. Benches are developed on 12-meter levels after glacial overburden has been removed. Current resources and reserves are estimated to be able to produce ore for over 100 years at the current level of production.

Mining operations are conducted on an annual basis with a contractor in a campaign during the winter season. Over a period of several months, a year's requirements for ore will be mined, graded, crushed and stockpiled adjacent to the Penhorwood flotation plant. Four stockpiles are created based upon yellow and red tints within the talc ore. Approximately 209,000 tonnes of ore are stockpiled during each campaign.

Any overburden removal required for pit development involving the surficial glacial cover is conducted with an excavator in the summer season prior to the mining campaign. The overburden is commonly placed on historic waste rock impoundments that are being reclaimed coincidently with the overburden program. The overburden serves as a vegetative substrate for the cover material required on the reclaimed waste rock impoundments.

An airtrack grid drilling program, based on a 12-meter grid, is conducted on the exposed resources following each campaign to provide ore characterization data. This data is utilized for modeling and planning prior to the next year's campaign.

Plant Operations

The flotation plant at the Penhorwood Mine operates year-round and can produce approximately 72,000 tonnes of talc concentrate on an annual basis. The ore is added to the plant through a Hazemag secondary impact crusher and is then ball milled and conditioned prior to flotation. After flotation the concentrate is de-watered using drum filters and is passed through flash dryer prior to being conveyed into one of a number of concentrate product silos. All of the concentrate product is conveyed to dual trailer bulk tanker trucks that transport the concentrate product to the Timmins micronizing plant approximately 70 km over the road to the east.

The Timmins plant utilizes Raymond vertical mills, an ACM (air classified mill) and PT9 jet mills to reduce the concentrate product to finished product specifications. The plant has the ability to ship product in 50-pound bags, 25-kilogram bags, bulk bags and bulk truck lots. Most of the product produced in the Timmins plant is shipped to customers in the United States by truck or rail.

ORE CONTROL

Sampling Procedures

Specific sampling for the annual mining campaign starts shortly after the last campaign is completed in the spring. A grid on 12-meter centers is laid out on the exposed resources in order to define the quality of the ore exposed and to guide the next year's campaign for both mine planning and scheduling. Each airtrack drill hole is 12 meters deep, is composited for the bench and is tested for mineralogy, LOI (loss on ignition), color and chemistry.

Mineralogy

The mineralogy of the ore is primarily talc with magnesite. The talc averages 46% with the magnesite content typically at 45%. Auxiliary minerals include chlorite and magnetite or hematite. Minor to trace amounts of calcite or dolomite are present as minor carbonate components but are commonly less than 2% of the total mineralogy. Transitional ore at the limits of the ore body that contains remnant serpentine minerals are excluded from the ore plan.

Color Components

The whole ore is ground and measured for color and tint with a Minolta CR-300 unit according to Luzenac internal standard test methods. The instrument measures a compressed powder plaque and generates a number for each of the three colors axes X, Y and Z. Y represents the whiteness based on a scale of 0-100 with 100 as pure white. The yellowness, or yi, is produced by calculating a formula, which utilizes the X, Y and Z components. Any number of additional hues or tints may be calculated from the base data, which is always X, Y and Z. These three numbers are entered into the database and yi is generated within the database as a calculated field.

Specifications

The ore control program generates four stockpile grades that are later blended into the flotation plant to satisfy a variety of concentrate and product specifications. The specifications are based on LOI, dry yi and Minolta Y. The LOI of the ore typically averages 28%. The dry yi, which represents the strength of the yellow tint, ranges from near 0 to a high of 20 with an average of 12. The yi range is divided into four subranges and this component is the primary controller on the feed into the plant. Minolta Y ranges from a low of 43 to a high of 70, with an average around 59. All of these controls are on whole ore samples tested at a 45% -325 mesh grind.

MINERAL PRODUCTS

Product Properties

The talc product that is produced as a result of the mining, flotation and micronizing grinding is a high aspect ratio, white and pure talc product. The finished ground products have a talc content of 98% minimum, a Minolta Y of least 84 and a yi of no greater than 3. The products are produced at the Timmins Mill and processed through a Raymond vertical mill, an ACM or micronized through a steam assisted fluid energy mill called a PT-9. The color of the product can appreciate with the finer grind up to an 88 Minolta Y on the finest PT9 grind. An alternative product stream is a flash dried talc concentrate that is sold directly from the Penhorwood flotation plant without additional grinding.

Market Applications

Two market applications are specifically well served by the unique products that are produced from the Penhorwood Mine and ground at the Timmins Mill. Although a wide range of customers are serviced from the operations here with a significant numbers of products, the engineered ceramics and polymers markets benefit the most from the characteristics of the Penhorwood product.

In polymer applications, the high aspect ratio micronized JetFil talcs from Timmins perform extremely well in polypropylene applications. The organophilic nature of the talc surface combined with the plate thickness and diameter provides enhanced performance when measured against other talc products. The Penhorwood talc generates superior stiffness to impact balance when compounded into plastics. These talc products also generate improved dimensional stability, increased heat deflection temperatures and improved barrier properties in polymeric materials (Clark, 2006).

In ceramic applications the product is sold directly from the flotation plant after flash drying. The low calcium, low alumina, high purity talc product extends consistent and high quality properties into cordierite ceramic bodies which are used for such applications as catalytic converters. The key factors in producing the product are controlling chemistry and mineralogy during flotation, maintaining morphology and talc structure and controlling particle size distribution. The platy talc and its lack of interlayer bonding is critical in allowing the very thin wall of the honeycomb to be extruded without too much distortion.

When talc, kaolin and alumina fuse to form the cordierite ($2MgO.2Al_2O_3.5SiO_2$), the processors control the thermal cycle so that the kaolin and alumina fuse first and then the talc diffuses into the fused kaolin/alumina to form the cordierite. Since there is a significant reduction in density from the starting materials, the relic structure of the talc remains in the final body as a micropore structure. Thus the particle size of the talc is absolutely critical (McCarthy, 2006).

CONCLUSIONS

With the projected long life and unique product characteristics of the Penhorwood ore body, the Luzenac operations in Ontario can be expected to produce high purity, high value products for the polymer, ceramic and other industries well into the 21st century. Detailed grid drilling and ore control supported by long term mine planning will assure ore consistency and quality by supporting the ore blends required to produce the product concentrates which will satisfy customer requirements now and in the future. The flotation capabilities will also allow the process to be flexible and control the costs and quality of the concentrate product. Although located in a remote part of Ontario, the customers that these operations service in the United States will be able to plan for a long-term supply of Luzenac talc products.

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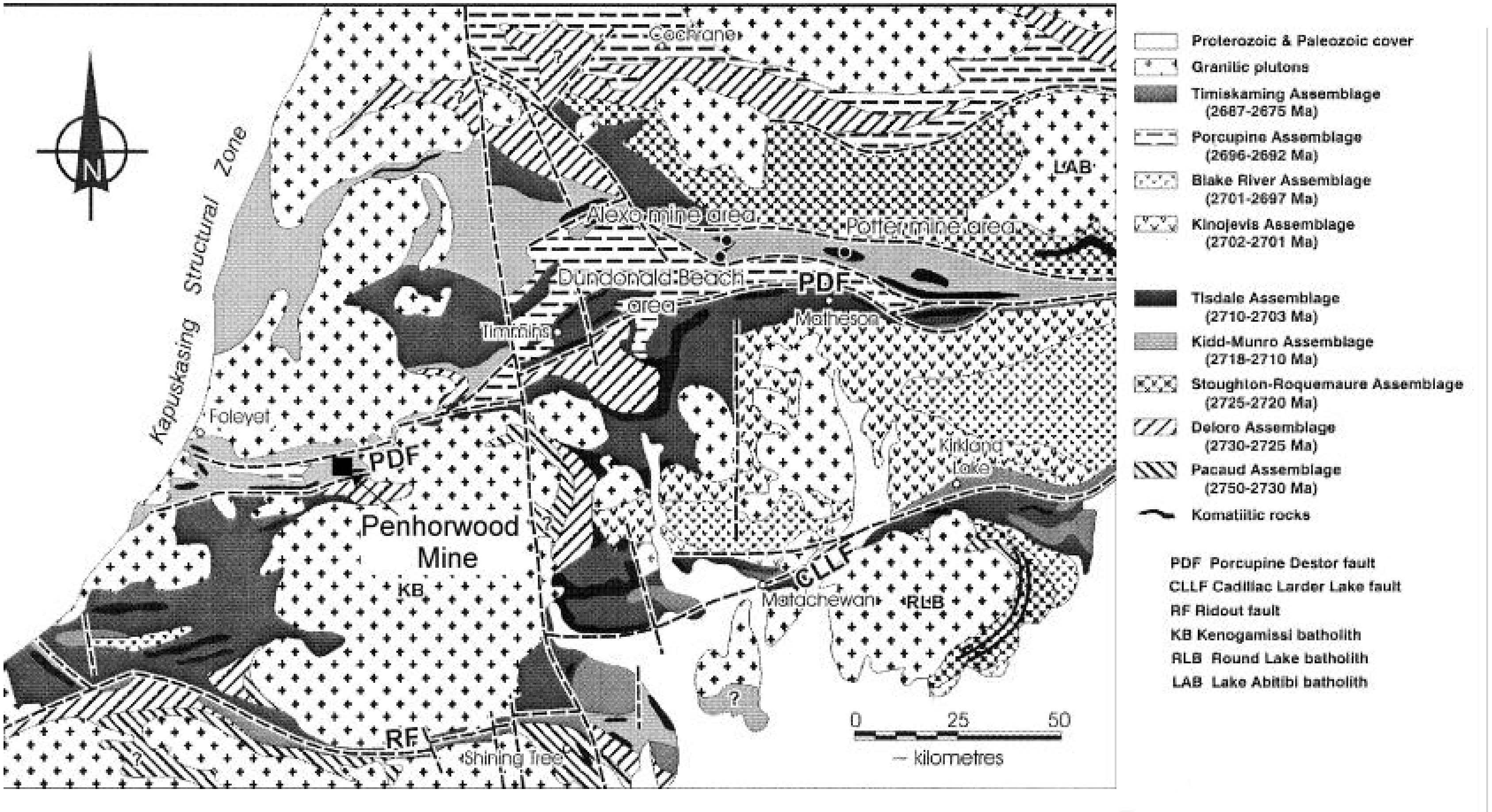

Figure 1. Location map for the Penhorwood Mine within the western Abitibi Subprovince (*modified from* Ayer et al., 2002).

The geology and product applications for the Yellowstone Talc Mine, Cameron, Montana

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ABSTRACT

The Yellowstone Mine in Madison County, Montana is the largest talc mining operation in North America. Talc deposits were first mined underground during World War Two. Surface mining began in 1950 to provide talc for ceramics, paint and paper applications. Over the ensuing years, operations have expanded and markets have diversified for Yellowstone talc products. Current annual production from the mine is 310,000 short tons of graded talc ore.

Talc ore bodies at the Yellowstone mine are hosted in Archean dolomitic marble belonging to the Cherry Creek Group metasedimentary suite found in southwestern Montana. Mineralization is controlled by the original carbonate stratigraphy and a system of chlorite filled faults that provided access for hydrothermal fluids to replace dolomite with talc. The three dimensional morphology of the orebody resembles northward plunging folds with satellite bodies of tabular mineralization that parallel the fold limbs. Talc mineralization is discordant to local foliation and major structure in the marble host.

Previous workers concluded that very large amounts of water were required to completely replace dolomite with talc. Ore forming fluids were derived either from connate brines in the bottom of the belt basin, or from Proterozoic seawater (Gammons, 2002). Temperatures of formation were 190^{o}C to 250^{o}C at burial depths of 3 km to 10 km. Rifting and intrusion of mafic dikes provided the heat and pressure gradients necessary to circulate waters through the adjacent Archean basement and drive metasomatic replacement of select dolomitic marble with talc. Later stage talc veins with abundant botryoidal structures that cut across primary talc masses in the main ore bodies are indicative of a direct precipitation mode of talc formation.

Microcrystalline talc textures and the characteristic micron scale "cabbage head" particle morphology of Yellowstone talcs are the result of relatively low temperature & pressure formation. The hydrophobic and organophyllic surface properties of micronized Yellowstone talc allows adsorption of organic pitch particles from the aqueous processes in pulp and paper manufacturing. Over 50% of the talc mined from Yellowstone deposits is sold for pitch control in pulp and paper. Yellowstone talc is also sold into paint, plastic, and rubber manufacturing, as well as a number of other niche market uses.

- **Note**: Paper not available at time of publication.

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Session Eight

Application of cathodoluminescence microscopy to industrial minerals

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ABSTRACT

Cathodoluminescence microscopy (CLM) is uniquely applicable to the study of industrial minerals. Most of the industrial minerals have a strong positive response to the electron microbeam and therefore they emit a variety of characteristic colors of catholuminescence (CL). CLM provides rapid identifications, effective examination of textural intergrowths, and an elegant means of recording those textures as CL micrographs. Cathodoluminescence is produced as a result of the emission of visible radiation when an electron shifts from an outer orbit to an orbit of lower energy level. Therefore, the color of CL is a function of the elements, especially minor transition and lanthanide elements, present in a mineral rather than the other properties of the mineral. Although a given mineral can exhibit more than one CL color due to the presence of various trace elements, certain colors tend to be most characteristic for each mineral. In contrast to the CL activator elements, other minor elements may act as CL quenchers.

Industrial minerals that typically exhibit characteristic CL include: potash feldspar, plagioclase, calcite, dolomite, fluorite, wollastonite, talc, tremolite, sillimanite, kyanite, andalusite, anthophyllite, apatite, collophane, zircon, corundum, barite, diopside, garnet, and quartz. Other minerals that exhibit distinctive CL include: scheelite, smithsonite, cerrusite, anglesite, baddeleyite, cassiterite, sphalerite, pitchblende, uranopilite, schroeckingerite, diamond, and emerald. Some of the minerals commonly grouped with the industrial minerals that typically do not exhibit CL include: ilmenite, graphite, chromite, olivine, and mica. CLM should be a routine tool in the study of most industrial minerals.

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INTRODUCTION

Cathodoluminescence (CL) microscopy is a microbeam technique that spreads the electron beam out over a sufficiently large portion of an uncovered thin section, polished section, polished thin section, polished slab, or loose grains that the CL emitted by the constituent mineral grains can be viewed under a petrographic microscope. The electron beam provides the energy input that causes the minerals to emit light in the form of visible CL. Most minerals emit CL as a result of the incorporation of minor or trace elements, called activator elements, incorporated in their structures. Electrons in the activator elements, typically members of the transition and lanthanide series, are excited by the electron energy input to shift to outer shells. The emission of light energy, observed as visible CL under the petrographic microscope, occurs when those electrons shift back to orbits of lower energy level. Thus, the ability of a mineral to exhibit CL is usually the result of mineral's minor or trace element content, rather than that of other properties of the mineral. However, some minerals possess intrinsic CL, a result of the character of their internal atomic structures, and they may show CL in spite of or in addition to that of activator CL. The presence of certain elements, called quencher elements, may inhibit or eliminate the emission of CL exhibited by a mineral.

CL microscopy (CLM) has been effectively utilized in the petroleum industry for quite some time to distinguish original calcite constituents in a limestone from subsequently deposited pore-filling sparry calcite (Amieux, 1982; Hollis and Walkden, 1996). Such information provides an understanding of the rock's porosity and probable permeability at the time of petroleum migration. Mariano (1978) has intensively used CLM to study a great variety of carbonatite mineralogical and exploration problems and has emphasized that the change from CL blue to CL red for potash feldspar can provide a useful guide to the presence of carbonatite intrusions. CLM has also been applied to problems in minerals exploration and beneficiation (Hagni, R.D., 1985, 1986). Barker (1986) has provided a bibliography of references on CLM through 1985. Marshall (1988) published a volume devoted to the CL study of geological materials. A chapter in Marshall's book prepared by Mariano (1988) discussed various applications of CL and especially emphasized the use of CL emission spectra to interpret the causes for CL. CL has also been applied to the study of refractory linings in the aluminum smelting (Hagni, A.M., 1998) and to fine-particle characterization (Hagni, A.M., 2002). Götze (2000) published a book devoted to the use of CL in applied mineralogy that featured many colored CL micrographs. More recently, Kempe and Götze (2002) have applied CLM to apatite in rare-metal deposits. Most recently, Karakus (2005a, 2005b) has extended the use of CLM to study a wide variety of ceramic materials. The purpose of the current contribution is to emphasize the value of CLM in the study of industrial minerals and to review various applications of CLM to industrial minerals in which the writer has been involved.

The writer uses two CLM units in the laboratory at the University of Missouri-Rolla, the Nuclide Luminoscope, and the Technosyn unit marketed by Cambridge Image Technology Ltd. (Citl) laboratories in Cambridge, England. Both instruments are optical-based, mounted on standard petrographic microscopes, and involve the insertion of samples into vacuum chambers. They differ from CL units mounted on scanning electron microscopes that do not produce visible colors (but rather false colors must be created).

CATHODOLUMINESCENCE OF INDUSTRIAL MINERALS

The presentation of CL shown by industrial minerals is organized here in the manner followed by Bates (1960). After a brief discussion of some of the features that can be revealed by CL examination, the sequence of organization is: 1) sedimentary minerals, 2) igneous minerals, 3) metamorphic minerals, 4) vein and replacement minerals, and 5) supergene minerals.

The CL results are presented in groups of six micrographs positioned on 10 plates. Abbreviations used in the figure captions for all of the plates are: UL = upper left micrograph, UR = upper left micrograph, ML = middle left micrograph, MR = middle right micrograph, LL = lower left micrograph, and LR = lower right micrograph. Types of microscope images include: PPL = plain polarized light, and CL = cathodoluminescence. All specimens were viewed as thin sections, except where noted. The long horizontal dimension for all micrographs is about 1.5 cm.

Features revealed or enhanced by cathodoluminescence

CLM typically provides a microscopic view that is greatly enhanced in multicolor beauty in contrast to that of many gray-only images under the regular petrographic or ore microscopes. The vivid multicolor CL views are not only more pleasant to the eye, but also commonly provide the enhanced ability to more readily recognize the presence and distribution of the various phases present. Some microscopic features are revealed, or at least markedly enhanced, under CLM.

Features that may be revealed only by CL include mineral zoning, twinning, degrees of alteration, etc. Minerals that are occluded under normal light by the presence of fine-grained opaque grains may become readily revealed under CL. Three examples (PPL-CL pairs) have been selected to illustrate this point (Plate 1). The upper pair exhibits difficulty distinguished apatite and quartz (both white) in Kiruna, Sweden iron ore on the left. Under CL apatite is readily distinguished from quartz. Phosphorus is a deleterious constituent in iron ores that must be separated by beneficiation from the resulting iron concentrates. The middle pair in plate 1 illustrates how CL brings out the full character of bryozoa fossils in Birmingham, Alabama iron formation despite their partial replacement by fine-grained hematite. The lower pair, also from Birmingham, illustrate that even where hematite completely prevents the passage of transmitted light through the thin section under the petrographic microscope, CL readily reveals the presence of abundant fossil and deleterious, very fine-grained collophane grains.

Sedimentary Industrial Minerals

Calcite, dolomite, potash feldspar, and collophane are some of the sedimentary minerals that exhibit prominent CL. CL is especially valuable to distinguish original calcite constituents, such as fossils and chemically precipitated calcite, from subsequently deposited sparry calcite that fills porosity (UL, Plate 2). The petroleum industry has used this feature to estimate the original rock porosity and probable permeability at the time of petroleum migration. The color and intensity of CL shown by calcite and dolomite are largely a function of the relative amounts of activator Mn^{2+} and quencher Fe^{2+}.

Deleterious dolomite can be readily detected in phosphorus concentrates from the Florida phosphate district (UR, Plate 2). Locking between collophane, dolomite, and potash feldspar can be easily studied in those concentrates by CL (ML, Plate 2).

As indicated earlier, the mineralogy of the Birmingham iron ores can be fully examined by CL despite the presence of abundant fine-grained hematite that occludes the passage of transmitted light under the petrographic microscope. The mineralogy and character of the nuclei of ooids (MR, Plate 2), character of bryozoa fossils (LL, LR, Plate 2), presence of dolomite and deleterious collophane with bryozoa (LR, Plate 2), faecal pellets (UL, Plate 3), and progressive replacement of clastic grains of potash feldspar by collophane (UR, ML, Plate 3) are especially well exhibited under CL. Abundant faecal pellets are present and are the main contributing cause to high deleterious amounts of phosphorus in the sedimentary iron ores of the Alsace-Lorraine district, France (MR, Plate 3). The chemical composition of collophane grains detected by CL can be further confirmed by SEM-RDS (LL, Plate 3) or EPMA. The activator elements producing the CL for a given mineral can be evaluated by CL emission spectra (LR, Plate 3).

Igneous Industrial Minerals

Igneous industrial minerals that typically exhibit strong CL include potash feldspar, plagioclase, apatite, zircon, corundum, and diamond. Potash feldspar usually exhibits blue CL due to minor element Ti activation and apatite may show yellow CL due to Mn^{2+} activation (UL, Plate 4). Plagioclase can be distinguished by its yellow green CL and corundum by its strong red CL (UR, Plate 4). Although the normal CL shown by quartz is dull brown (UR, Plate 4) or dull purple, the CL of quartz is enhanced under hot-cathode CL units.

Three micrographs showing synthetic minerals crystallized under high temperature igneous-like conditions are included. The minerals were studied to characterize deleterious ceramic build-ups in electric induction furnaces. They show abundant diopside in a melilite glass (ML, Plate 4), abundant forsterite with minor diopside (MR, Plate 4), and diopside, forsterite, and rare earth element phases (LL, Plate 4).

Zircon, a mineral that regularly exhibits intrinsic CL, is an abundant constituent in many heavy mineral concentrates (LR, Plate 4).

Four micrographs illustrate the application of CL to igneous carbonatite mineralogy and textures (UL, UR, ML, and MR, Plate 5). Apatite exhibits light to dark purple CL due to activation by Mn^{2+} and various, very small amounts and ratios of rare earth elements (REE). Fluorite shows intrinsic blue CL, perhaps modified by traces of REE (UR, Plate 5). Calcite exhibits yellow CL (ML, MR, Plate 5) and dolomite shows red CL (MR, Plate 5).

The lower pair of PPL-CL micrographs illustrates the detection of apatite in a magnetite concentrate from Pea Ridge, Missouri. Although the iron concentrates, so-called super concentrate, contained only about 0.3% contaminant minerals, the presence of apatite is readily recognized by CL.

Metamorphic Industrial Minerals

Metamorphic industrial minerals that typically show distinct CL include sillimanite, kyanite, andalusite, wollastonite, tremolite, anthophyllite, and the emerald variety of beryl. Fe-poor garnet may also show CL. The three forms of aluminum silicate tend to exhibit strong CL. Sillimanite may show blue Ti-activated CL (UL, Plate 6) or pink CL due to Fe^{3+} activation (UR, Plate 6). Kyanite shows light to medium blue CL (ML, Plate 6). Andalusite exhibits light to dark blue CL (MR, Plate 6). Wollastonite shows very strong yellowish white CL (LL, Plate 6). Both tremolite and anthophyllite exhibit distinct CL (LR, Plate 6).

Although most garnet varieties do not show CL due to Fe^{2+} quenching, Mn-rich (Fe-poor) garnet from the Adirondacks exhibits distinct blue CL (UL, Plate 7). Willemite from Franklin Furnace, NJ is known for its fluorescence and it shows strong green CL (UR, Plate 7). Deleterious apatite is readily recognized in iron ores from the Benson mines in the Adirondacks (ML, Plate 7). Emerald from the Gravelotte emerald mine in South Africa exhibits especially bright red CL (MR, Plate 7).

Vein and Replacement Industrial Minerals

Fluorite is a vein and replacement industrial mineral that exhibits distinct CL, and six micrographs showing fluorite from the Okorusu mines in Namibia are included. Growth banding in fluorite is especially well revealed by CLM (LL, LR, Plate 7). Fluorite usually shows medium to dark blue CL, but rims of some fluorite crystals exhibit blue-green CL (UL, Plate 8). Cubic fluorite crystals at Okorusu have been locally coated by subsequent hydrothermal quartz showing dark purple CL (MR, Plate 8). Thin veinlets of late, hydrothermal calcite traverse earlier deposited fluorite at Okorusu (MR, Plate 8).

Late hydrothermal calcite at Okorusu exhibits compositional zoning with yellow to orange CL (LL, Plate 8). That generation of calcite may also show colloform textures and it cements earlier-deposited apatite and potash feldspar that shows deep red CL (LR, Plate 8).

Mariano (1978) has emphasized the value of CL in detecting the introduction of carbonatite fluids. The next four micrographs illustrate the progressive change of potash feldspar from blue CL to red CL as a function of Fe^{3+} activation associated with introduced carbonatite fluids. The initial alteration of original potash feldspar in gneiss at Palabora, South Africa is shown by local change of blue to red CL (UL, Plate 9). Advanced introduction of carbonatite and alteration of the potash feldspar from blue CL to red CL is shown in images from Fen, Norway (UR, ML, Plate 9). Nearly all of the potash feldspar shows red CL with only minor remnants showing blue CL in the fourth micrograph from Fen (MR, Plate 9). Potash feldspar in carbonatite-related fluorite at Okorusu also shows deep red CL due to association with carbonatites intrusions (LL, LR, Plate 9).

Multiple generations of deposition of a given vein mineral may be distinguished in certain ore districts. In the Mittersill, Austria tungsten district, three separate generations of scheelite deposition have been distinguished by their contrasting colors of both fluorescence and CL (UL, Plate 10). In the Viburnum Trend Subdistrict of the Southeast Missouri Lead District, four generations of deposition of hydrothermal sparry dolomite have been distinguished by CL and recognized to be present throughout the entire length of the Trend (UR, Plate 10). CL has provided the means to detect a complex history of crystal form development during the growth of certain dolomite crystals even though they eventually formed external rhomb crystal faces (MR, Plate 10). Ordinary light examination of those rhombs had revealed little or no hint of the earlier crystal forms (ML, Plate 10).

Alteration minerals associated with vein deposits may also be effectively examined by CLM. Potassic alteration associated with molybdenum ore at the Henderson mine Colorado is represented by potash feldspar that shows distinct blue CL (LL, Plate 10).

Supergene Industrial Minerals

A number of supergene minerals show CL, including smithsonite, cerussite, anglesite, uranopilite, and schroeckingerite. Smithsonite from zinc deposits at Rush, Arkansas in selected here (LR, Plate 10). The smithsonite has formed by supergene alteration of sphalerite, which shows dull red CL. Sphalerite from most ore deposits contains sufficient Fe^{2+} to quench their CL, but current studies recognize CL-sphalerite at a surprisingly large number of classical ore districts that exhibits activation due to a wide variety of activator elements (Karakus et al., 2006).

SUMMARY AND CONCLUSIONS

CLM is uniquely applicable to the study of industrial minerals and is a technique that should be more fully utilized in their study under the microscope. Most industrial minerals exhibit strong and distinctive CL. The presence, distribution, amount, and textures of industrial minerals can be readily determined in thin sections using CL. The presence of certain industrial minerals and the recognition of their textures can only be observed by the use of CL.

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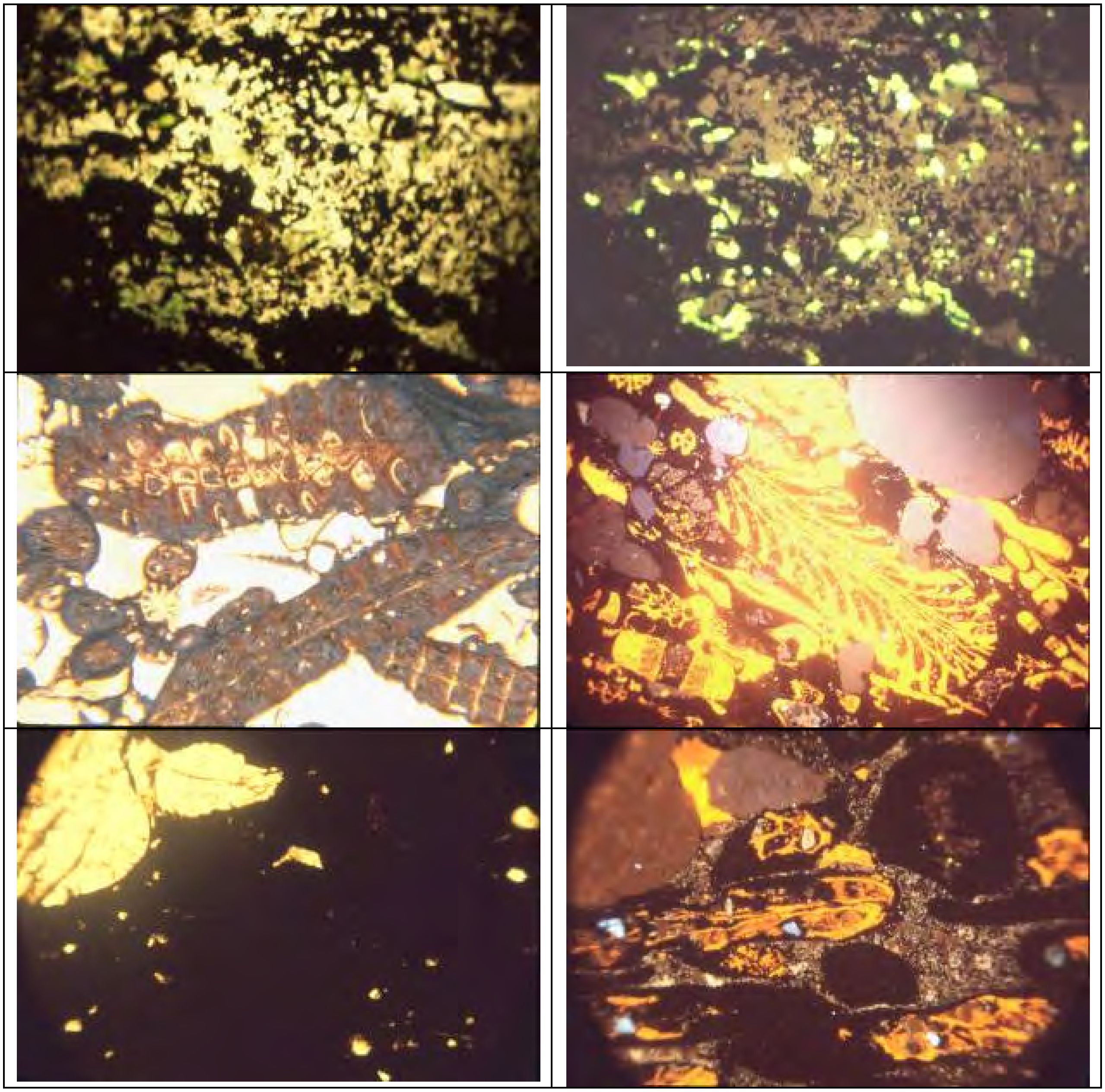

PLATE 1 Image pairs comparing transmitted light vs. cathodoluminescence (CL). UL. Kiruna iron ore showing magnetite (black) with quartz and apatite (white), PPL. UR. Same area with apatite (white) clearly distinguished from quartz (dull brown) and magnetite (non-CL, black), CL. ML. Bryozoa replaced by hematite (black and red), PPL. MR. Similar area revealing calcite (yellow) in replaced fossils, CL. LL. Mostly fine-grained hematite (black), PPL. LR. Same area revealing bryozoa (yellow), fine-grained collophane (light gray), and quartz (dull brown).

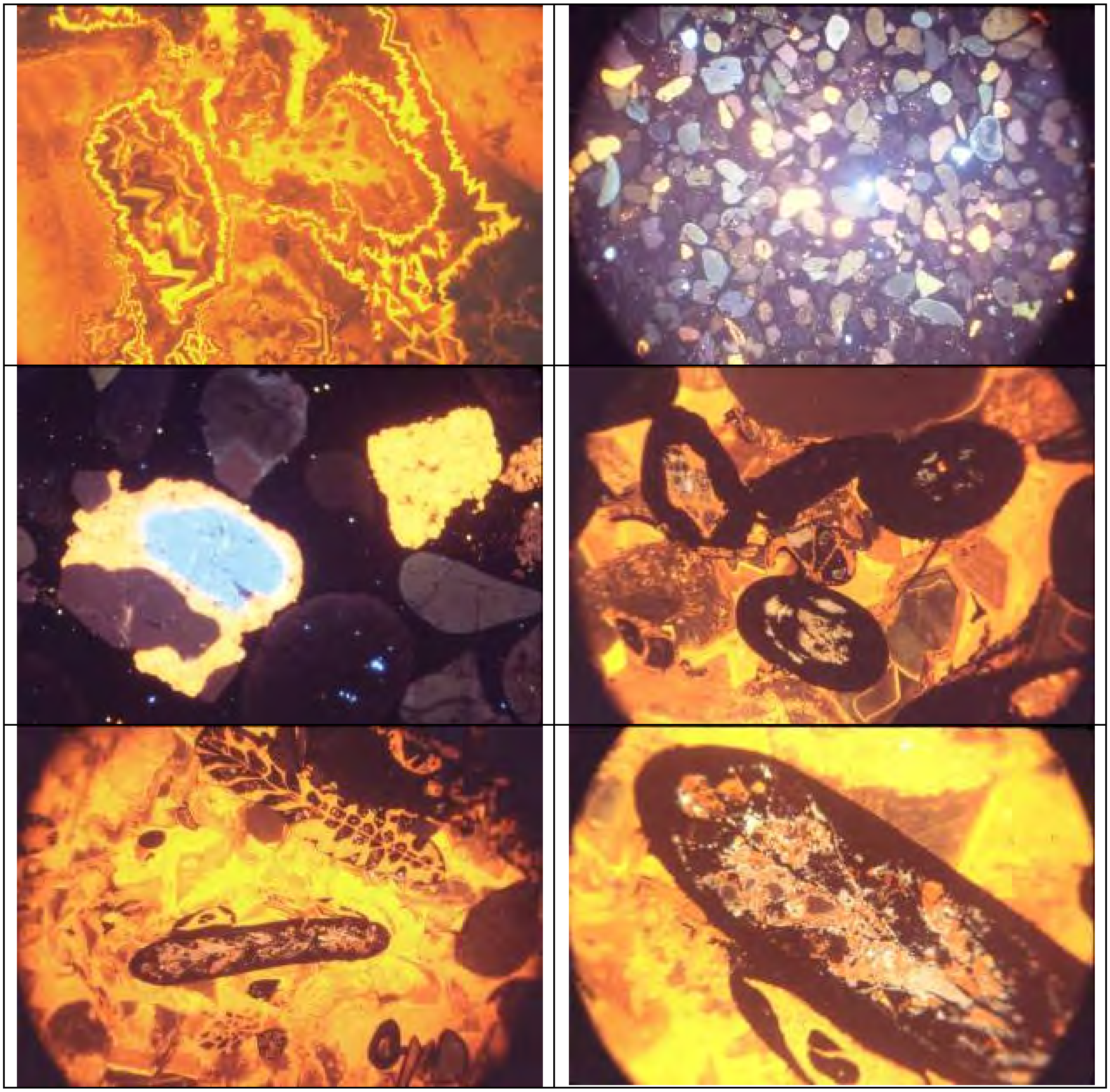

PLATE 2 CL micrographs showing sedimentary industrial minerals. UL. Original calcite (yellow, massive to cellular) and later sparry calcite (yellow, finely banded), Dewey Limestone, OK. UR. Dolomite impurity grains (yellow) in collophane (dull purple, blue, white) concentrate, FL. ML. Locked particle of KFd (blue)-dolomite (yellow)-collophane (dull brown) in phosphate concentrate, FL. MR. Hematite ooids (black) in sparry calcite (yellow, banded), Birmingham, AL iron ores (BIO). LL,LR. Calcitic bryozoa (elongate, cellular) replaced by hematite (black) dolomite (orange), and collophane (bluish white): all cemented by calcite (yellow), BIO. LR.

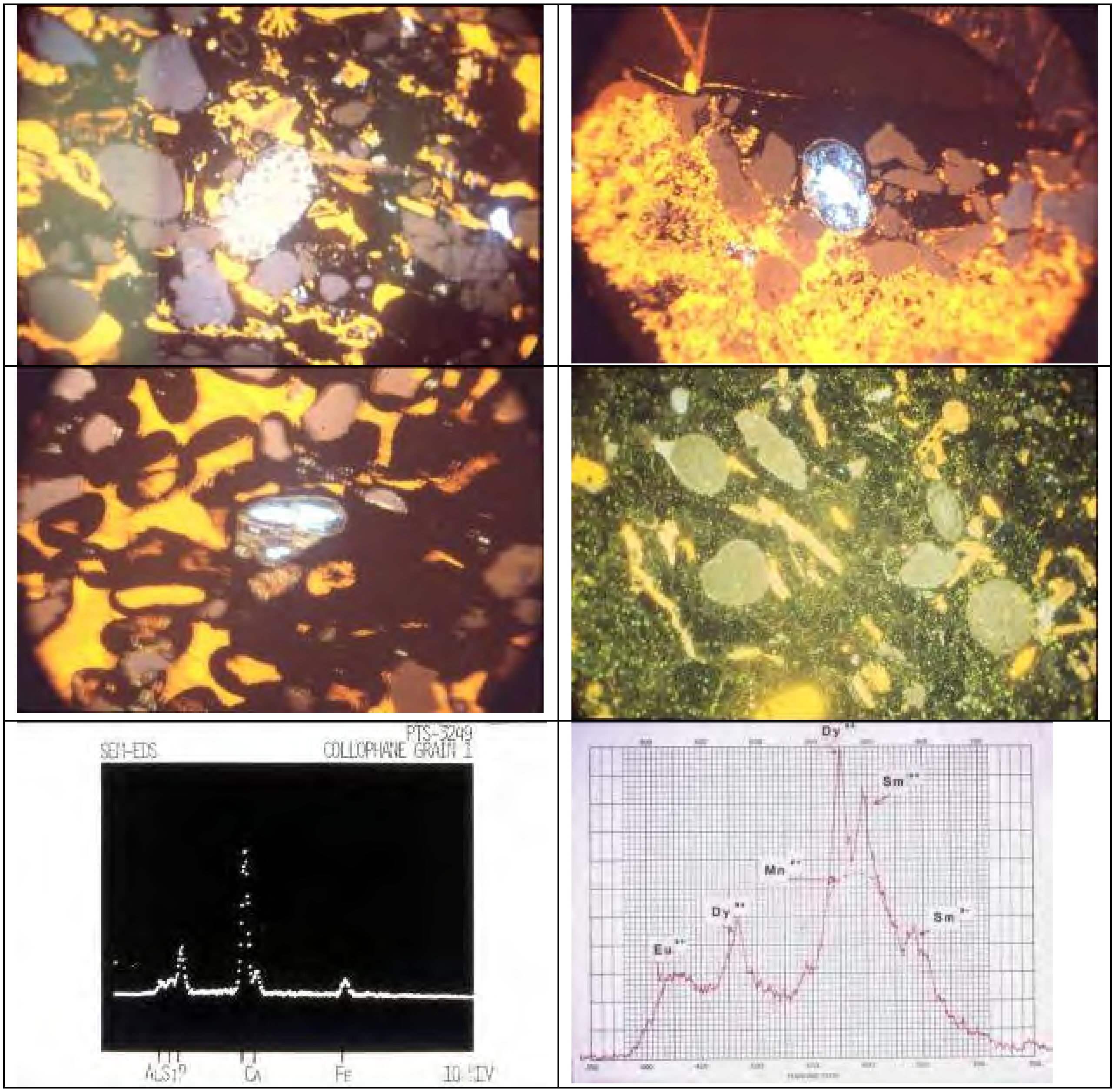

PLATE 3 CL micrographs showing sedimentary industrial minerals. UL. Single collophane faecal pellet (light blue) in BIO with quartz sand grains (dull purple), calcite (yellow), and hematite (black). UR. KFd (light blue) with initial outer replacement by collophane (gray); quartz (dull brown) and calcite (yellow), BIO, ML. Similar to UR but more advanced replacement of KFd, BIO. MR. Abundant collophane faecal pellets (light gray) in sedimentary iron ore with calcite (yellow), Alsace-Lorraine, France. LL. SEM-EDS analysis of BIO collophane showing Ca and P. CL emission spectrum showing activation by Dy^{2+}, Sm^{2+}, Mn^{2+}, and Eu^{2+}.

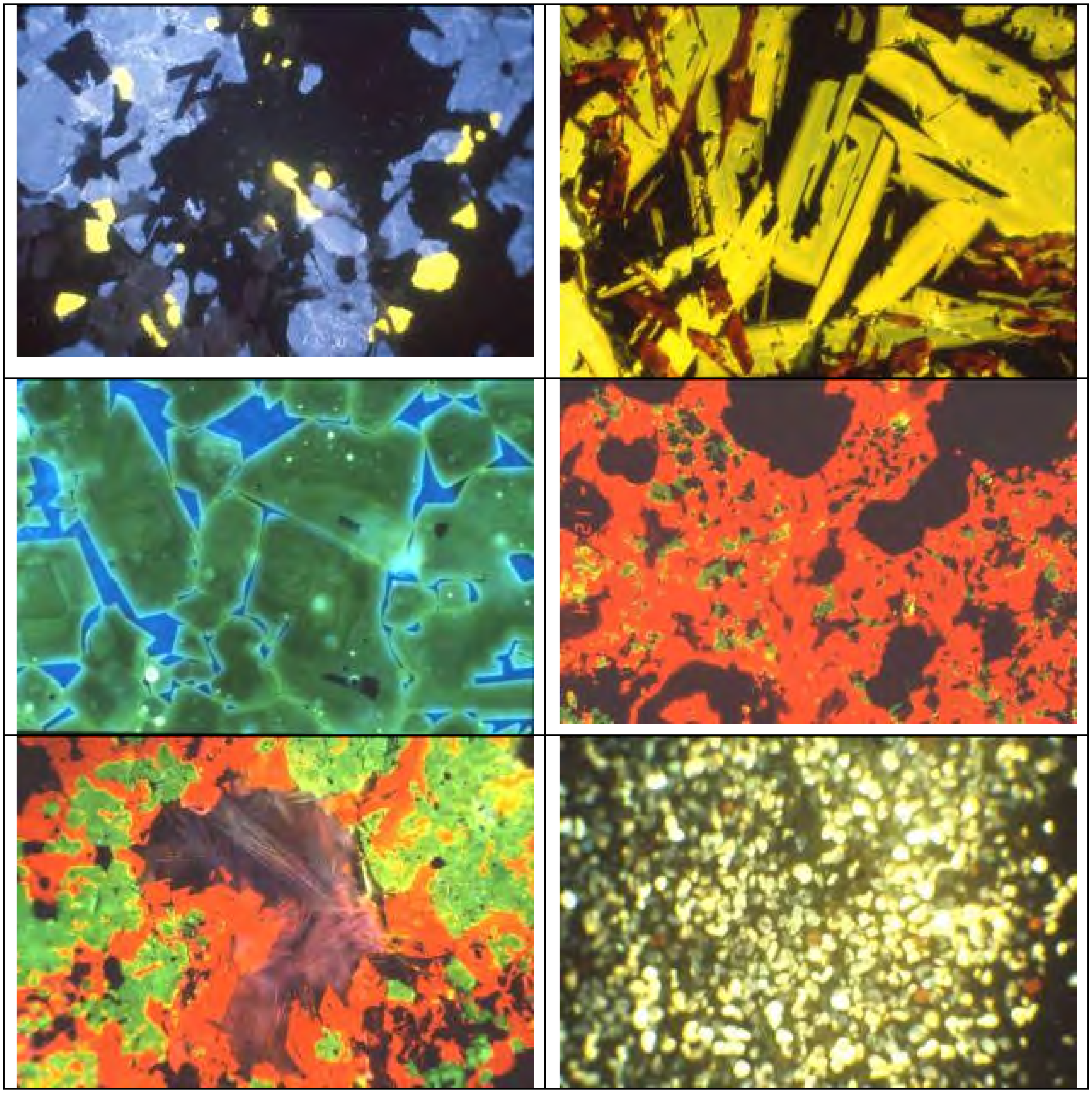

PLATE 4 CL micrographs showing igneous industrial minerals. UL. Charnokite with apatite (yellow), KFd (blue), biotite (black, platy), and quartz (dull brown), NY. UR. Plagioclase (yellow green, laths) and corundum (red) in high-temperature laboratory synthetic product (LSP). ML. Euhedral spinel crystals (green) in melilite glass (blue), LSP. MR. Abundant forsterite (red) with minor spinel (green) and pores (black), LSP. LL. Forsterite (red), spinel (green), and REE phases (purple), LSP. LR. Zircon (white) grain concentrate, Atlantic coast heavy minerals.

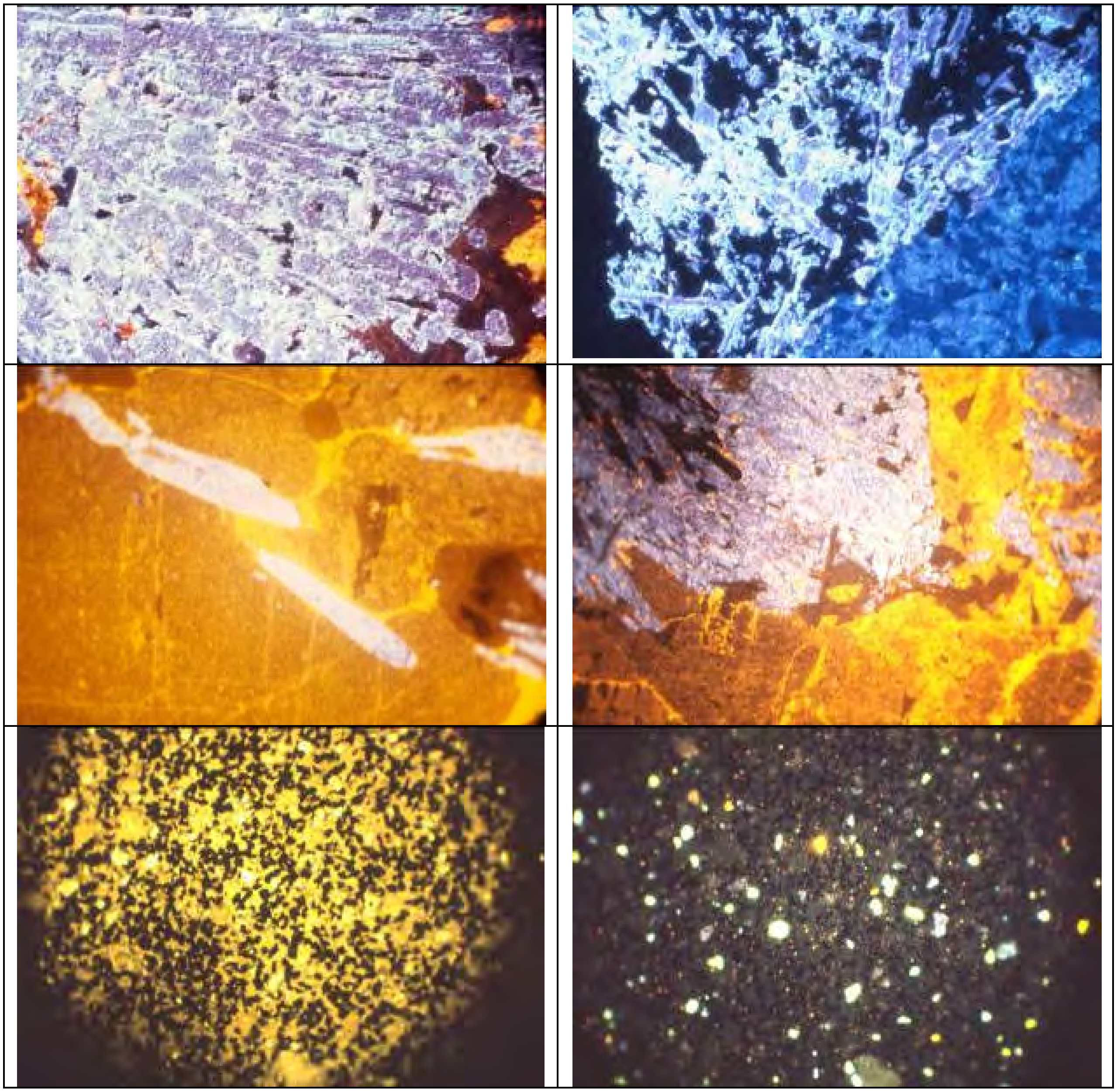

PLATE 5 CL micrographs showing igneous industrial minerals. UL. Apatite (purple to bluish white) with minor calcite (yellow) in carbonatite, Okorusu, Namibia (ON). UR. Abundant apatite (purple to white, upper left) and fluorite (blue, lower right), ON. ML. Apatite crystals (white, elongate) in carbonatite calcite (yellow), Magnet Cove, AR (MCA). MR. Apatite (purple to white, upper left) and calcite (yellow) with minor dolomite (orange) and biotite (black), MCA. LL. Magnetite (black) concentrate with quartz and apatite impurity particles in PPL, Pea Ridge, Missouri (PRM). LR. Same concentrate with apatite (bluish white) particles readily apparent, CL

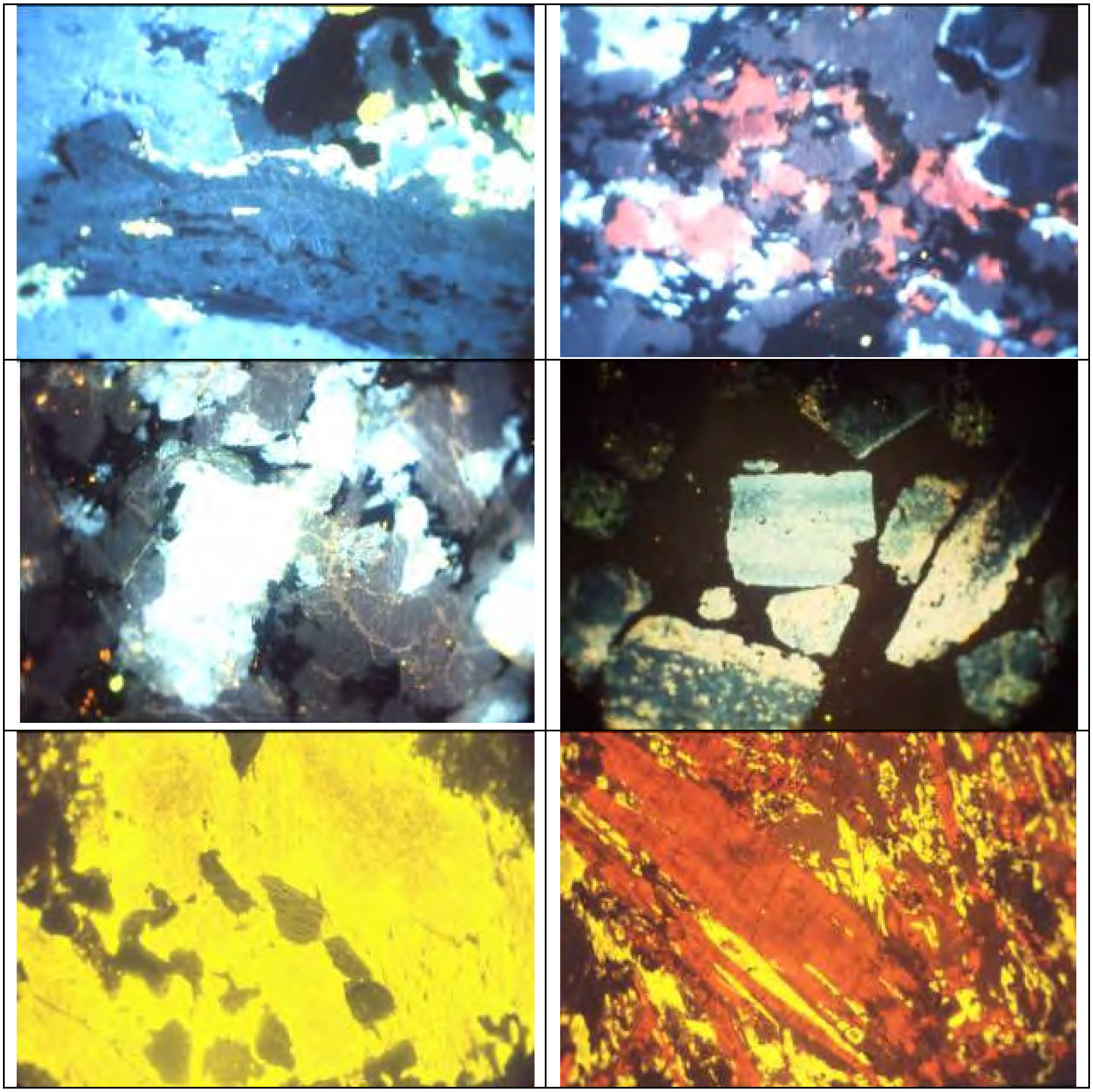

PLATE 6 CL micrographs showing metamorphic industrial minerals. UL. Sillimanite (dark blue) with KFd (light blue), plagioclase (white), and magnetite (black), Benson, NY. UR. Sillimanite (pink)-KFd (blue)-plagioclase (white)-biotite (black) gneiss, NY. ML. Kyanite (light bluish white) and microcline (medium gray), Graves Mountain, GA. MR. Andalusite (light to dark blue) grains, Cullinan mine, RSA. LL. Wollastonite (strong yellowish white) with diopside (dull green), Willsboro, NY. LR. Tremolite (red) and anthophyllite (yellow), Gouveneur, NY.

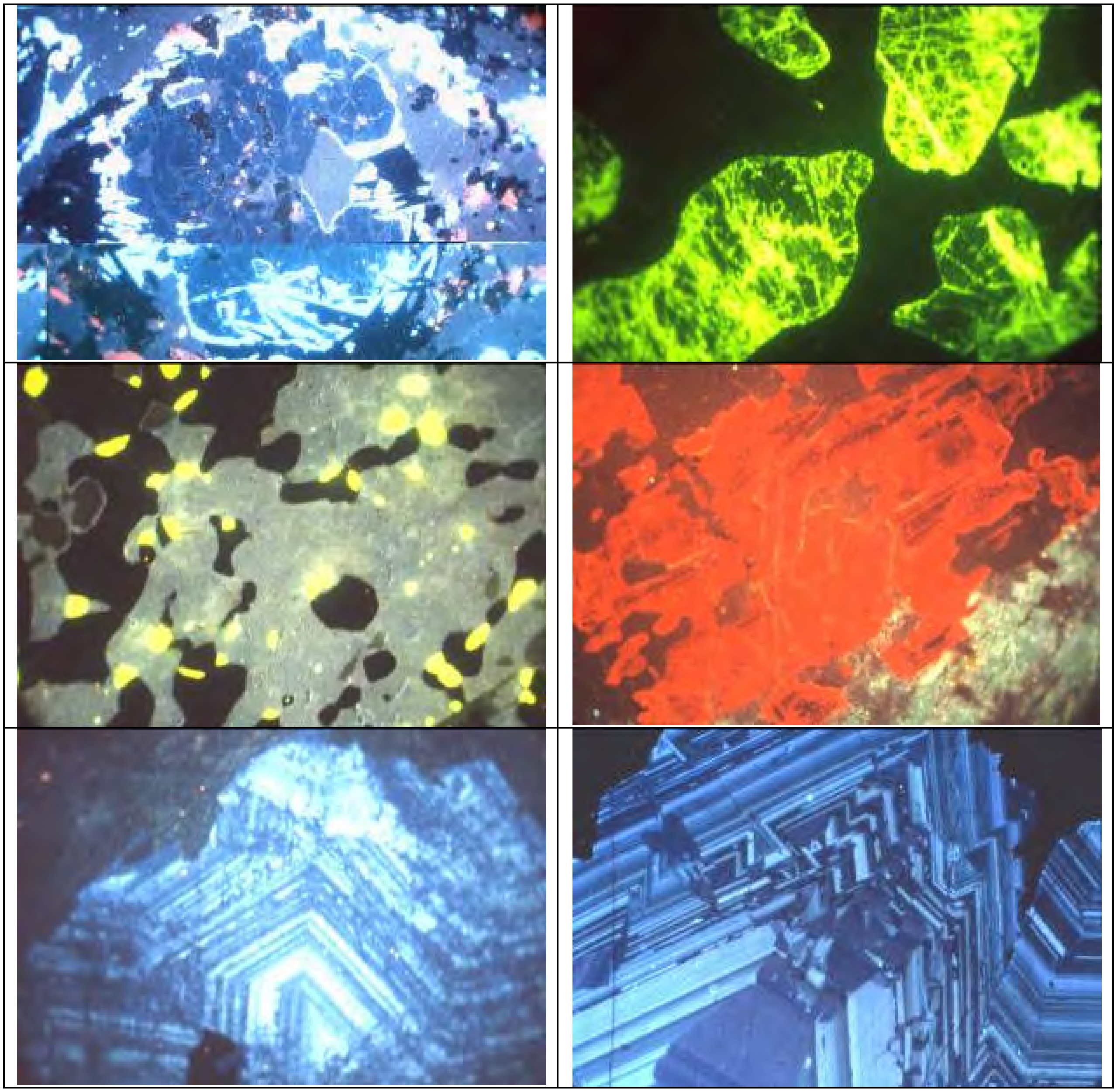

PLATE 7 CL micrographs showing metamorphic industrial minerals and fluorite. UL. Mn garnet (dark blue), potash feldspar (medium blue), plagioclase (white), and minor sillimanite (pink) and biotite (black), gneiss, Adirondacks, NY. UR. Willemite (green), Franklin Furnace, NJ. ML. Apatite (yellow)-microcline (blue gray)-hematite (black) gneiss, Benson Mines, NY. MR. Abundant emerald (red), Gravelotte mine, RSA. LL. Growth zoned fluorite (light to medium blue) and barite (dark green, lower right), Clara mine, Germany. LR. Growth zoned fluorite (medium to dark blue), Okorusu mine, Namibia

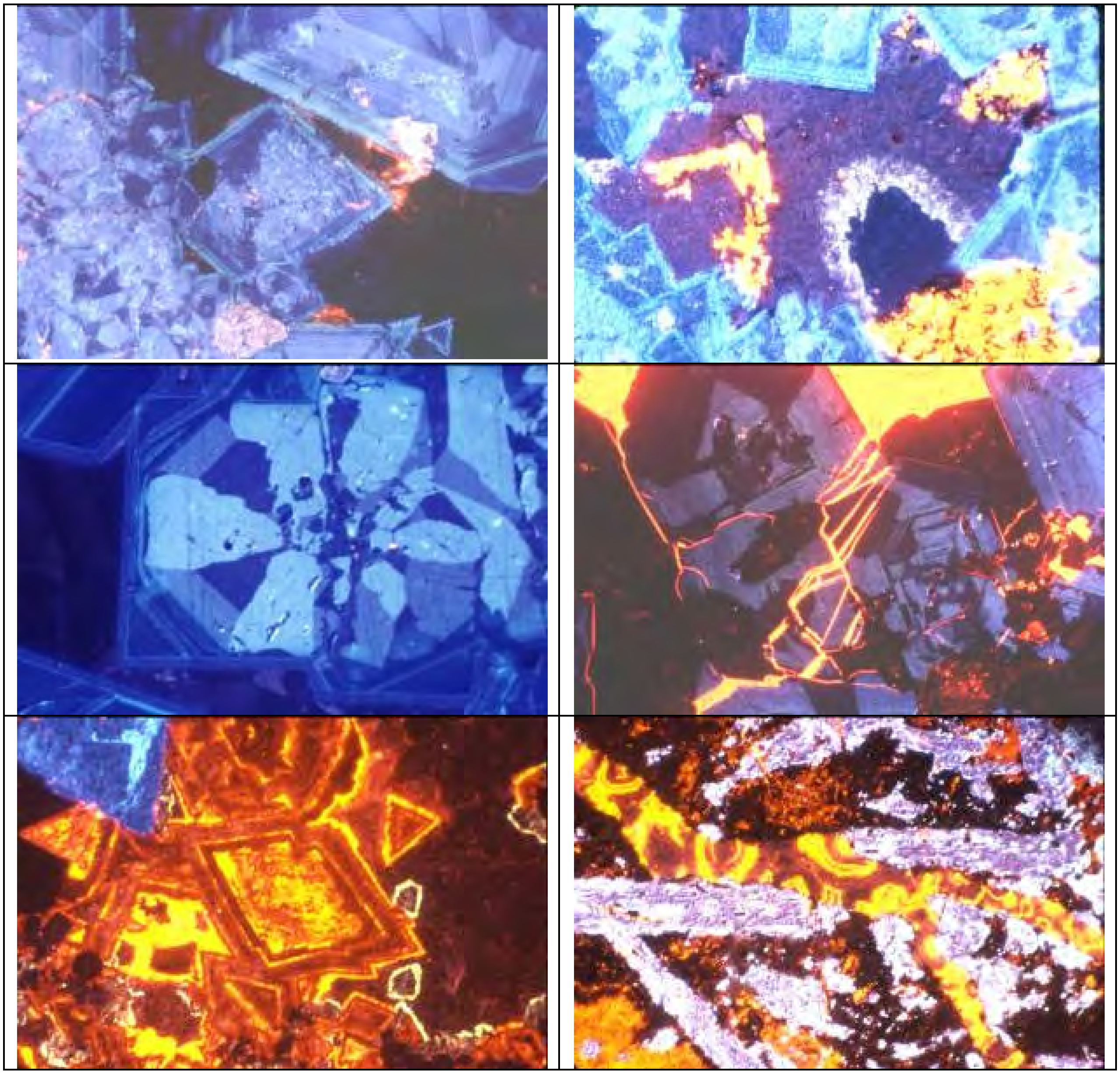

PLATE 8 CL micrographs showing vein and replacement industrial minerals from the Okorusu, Namibia fluorite mines. UL. Fluorite crystals (medium to dark blue with greenish rims) with minor apatite (purplish white) and calcite (yellow). UR. Fluorite crystals (blue, cubes) surrounded by late quartz (purple) with some calcite (yellow) and minor apatite (white). ML. Fluorite (blue) showing cyclic twinning. MR. Fluorite crystals (medium to dark blue) veined by late calcite (yellow). LL. Late calcite (yellow to red) crystals showing growth zoning and minor fluorite (blue). LR. Apatite crystals (purple to white, prismatic) associated with minor potash feldspar (dark red) and veined by late calcite (yellow to red, colloform).

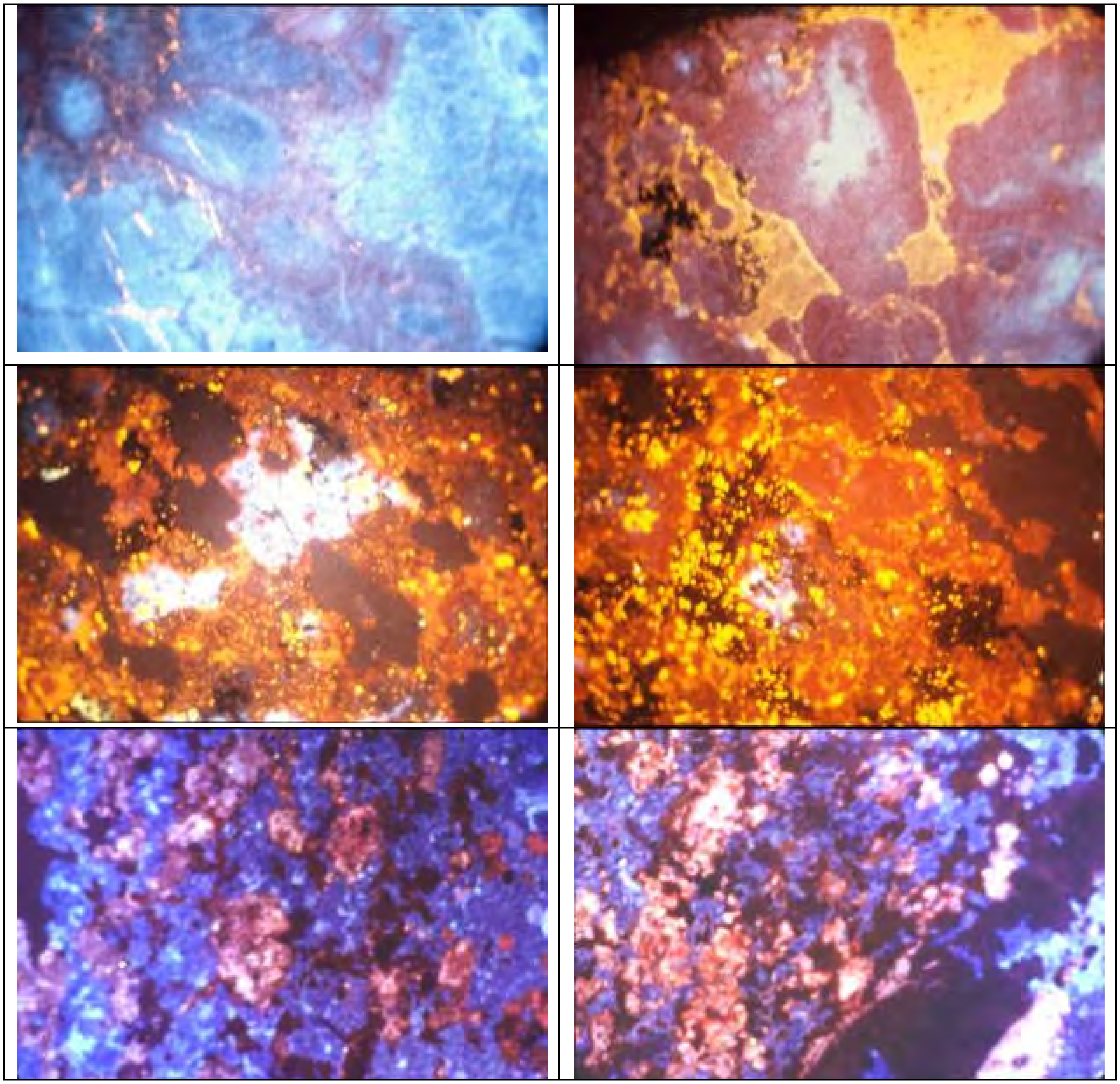

PLATE 9 CL micrographs of vein and replacement industrial minerals that show progressive effects of carbonatite fluids upon the CL color of potash feldspar (KFd). UL. Initial KFd (blue) beginning to turn red due to incipient carbonatite fluid introduction, Palabora, RSA. UR. Original KFd (blue) partly turned red and surrounded by carbonatite calcite (yellow), Fen, Norway (FN). ML. Most of original KFD (blue) has turned red due to progressive carbonatite introduction, FN. MR. Very small remnant of original KFD (blue) surrounded by red KFD and calcite (yellow), FN. LL and LR. KFD (red) in fluorite ore, Okorusu alkaline igneous carbonatite complex, Namibia (ON).

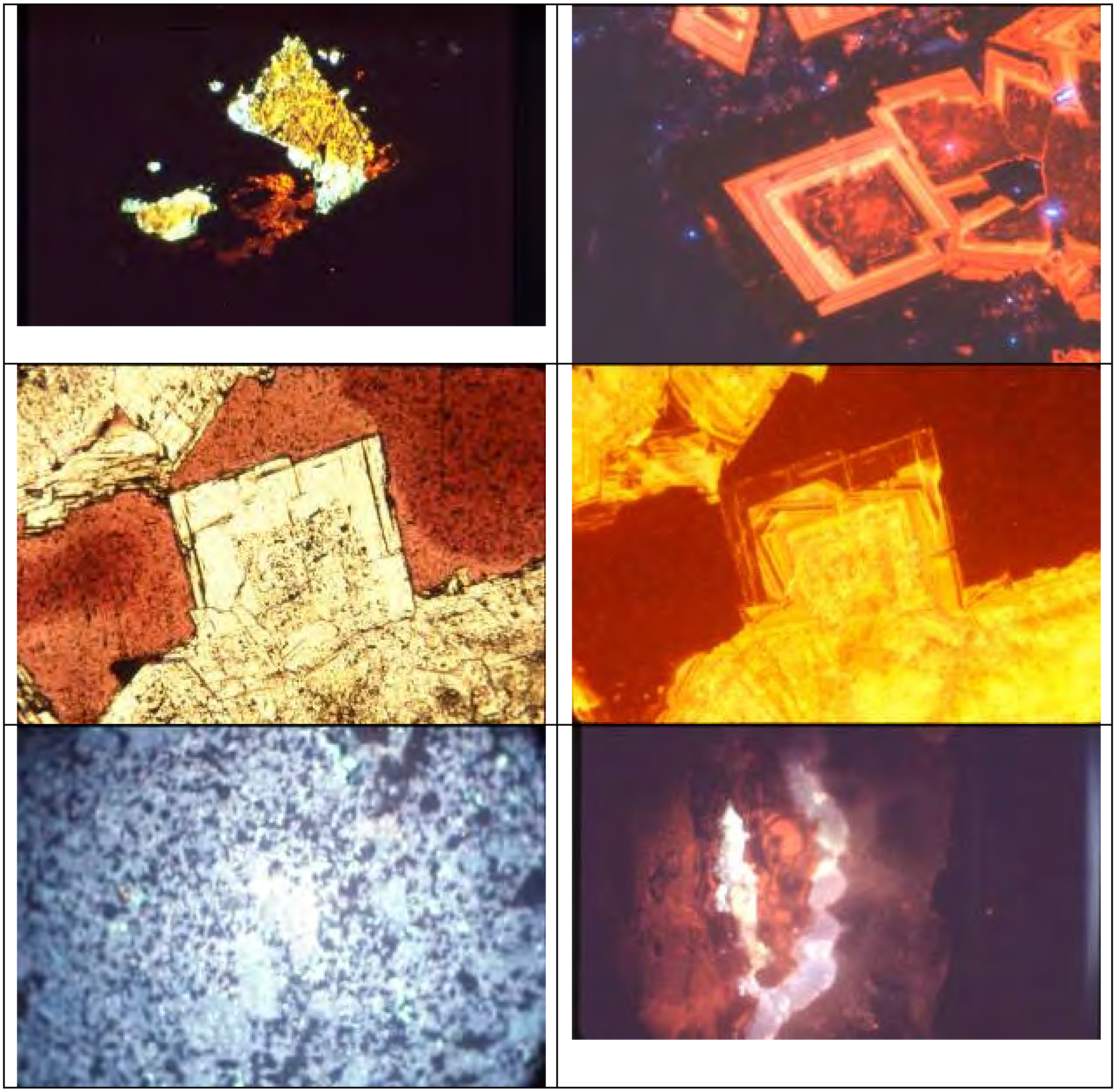

PLATE 10 CL micrographs of vein, replacement, and supergene industrial minerals. UL. An early generation of scheelite (yellow) coated by later scheelite (blue) and with minor calcite (red), Mittersill, Austria. UR. Growth zoned dolomite (yellow to dark red), Viburnum Trend, SE Missouri. ML. Euhedral dolomite rhomb (white) with PPL. MR. Same rhomb with CL showing a complex history of crystal growth forms. LL. Potash feldspar (blue) in potassic alteration material, Henderson mine, CO. LR. Supergene smithsonite (white, colloform) alteration of sphalerite (dull red), Rush, Arkansas

North Carolina State University Minerals Research Laboratory: Serving the mineral industry for over 60 years

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ABSTRACT

The sixty-year history of the Minerals Research Laboratory has been dedicated in helping commercialize the mineral resources of North Carolina. The work includes micas, feldspars, lithium ore, apatite, silica sands, primary kaolin, and high-purity quartz. Jasper Stuckey, State Geologist of North Carolina and H.S. Rankin, Head Regional Minerals Section of TVA, lead the creation of the laboratory in western North Carolina to develop the local mineral resources. Since its beginning the laboratory has expanded pilot plant capabilities into three other buildings. As a result, the laboratory has beneficiated ores from every continent on the globe. The ores have included industrial minerals, metals, as well as some fossil fuel. As the laboratory enters this century, it is changing its capabilities to keep pace with the changing needs of industry. The utilization of mineral wastes from mining operations as well as waste from mineral consuming industries will keep the laboratory challenged into the future.

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The influence of the ore deposit and product market on the design and operation of industrial mineral processing plants

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ABSTRACT

The design, construction, and operation of an industrial minerals facility is vastly different from a metallic processing plant. Many considerations must be given to the quality of the mineral concentrates recovered from the ore deposit and how these qualities will dictate the market and ultimately influence the design of the processing facility. This paper describes these considerations, the importance of defining them early in the evaluation process, and the critical role played by the process engineer. Examples of mineral commodities common to North Carolina are addressed, showing the diversity of potential markets and accompanying product specifications, and how both the quality and location of the deposit will play a critical role in the design of the process plant.

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INTRODUCTION

The mining industry is divided into mineral commodities that include metals, non-metallics, mineral fuels, and structural materials. Metals, both base and precious, are the most widely recognized, and include the sulfides such as sphalerite (Zn), pyrite (Fe), cerussite (Pb), and chalcocite (Cu), and the native metals gold, silver, platinum, etc. Mineral fuels include coal and oil sands, and are defined as implied - mineral resources that supply a raw energy source. The non-metallics and structural minerals are commonly referred to as industrial minerals, designating rocks used in industry.

The most common and abundant of the industrial minerals are the structural materials, which include sand, gravel, clay, and stone of various kinds. These construction minerals exceed all the metal and mineral fuel tonnage combined, and are typically low unit value. The industrial minerals to be addressed in this paper can be defined as any naturally occurring mineral or rock used as a raw material or additive in a range of manufacturing industries, such as paint, electronics, foundries and metal casting, paper, plastics, glass, ceramics, etc.

Over 200 minerals have been defined as belonging to the industrial minerals grouping, excluding the construction and structural minerals. Product markets can be as diverse as the groupings, in some instances becoming highly technical, requiring unique sales and marketing strategy and expertise.

Because the industrial minerals sector is so diverse, both in terms of mineral types and markets served, it is often found to be the least understood. It is near impossible to define, identify and develop economic, technical, and marketing characteristics in generic terms that would apply across the board. For these reasons, a general understanding of the industry is not enough to define the full potential, or avoid the hazards, of bringing a promising deposit into production. A working knowledge of the critical mineral characteristics and corresponding markets are necessary to make an industrial minerals venture a financial success.

GENERAL PRODUCT CHARACTERISTICS

Before the design and operation of an industrial minerals plant, it is imperative to understand the industry. In most cases, design parameters and processes employed for the beneficiation are dependent upon a specific marketable product and the quality of the mineral in the deposit. The importance of this fact cannot be under estimated.

Quartz is a prime example. In a sand deposit, a multitude of economic markets might be identified. If the deposit is located near an urban area and the sand quality is acceptable for construction purposes, such as concrete, markets within 10 to 15 miles should be targeted. Processing costs (crushing and sizing) would be minimal and the selling price of \$3 to \$5/ton plus any delivery costs would be attractive. If the sand can be processed into a glass grade product through flotation and/or magnetic separation, the sand could sell for \$20 to \$25/ton if there was a glass manufacturer within 150 miles or so. Yet again, if the sand is of exceptional quality and could be processed into the high and ultra-high pure grades, the quartz could be shipped anywhere in the world with pricing of \$500 to +\$10,000 per ton.

Although product specifications are very specific for any given industrial minerals market, several general factors apply to the majority of products as follows.

Ore Characteristics/Product Quality

The industrial minerals industry produces a commercial product that remains a mineral and is sold directly to a consumer on individual contracts or sales agreements. In contrast, the final product in the metals industry is normally a metal produced from the host mineral and is sold at published prices in the open market. Combine this with the fact that industrial minerals can be highly variable from one deposit to another, and natural ore characteristics become highly influential in determining market value.

Mica is an excellent example. Not all mica found in nature has equal economic value. Two mica concentrates can have equivalent concentrate grades, but because of the natural characteristics of the mica, can have drastically different market values. A mica suitable for wet ground products with low bulk densities will demand a much higher price than a mica deemed acceptable for dry ground products only.

It is important to determine these characteristics early in the evaluation programs, as these characteristics will influence the plant design. Mica suitable for the wet ground market must be concentrated without the use of chemicals, and therefore must be of a particle size amendable to these processes. In contrast, dry ground mica can be concentrated by flotation, and the design engineer must recognize these facts and reflect such in the final flowsheet.

Mineral characteristics that will influence product quality and the value and marketability of industrial mineral products include the following.

Particle Size – Particle size of the industrial mineral product is not defined for liberation purposes but rather to meet market specifications, and grinding circuits must be designed accordingly. For instance, if an ore requires a 100 mesh grind for liberation purposes, but the market calls for a 30 x 200 mesh product, the material cannot be sold.

Particle Shape – The shape (round or angular, platy, fibrous, etc.) of a mineral can define a market and mineral value. Wollastonite with a high aspect ratio demands a much higher price than those with low aspect ratios. Therefore, it is imperative that the plant design utilize unit operations that will maintain this property. If the wollastonite is not suitable for high aspect ratio uses, more conventional, and less costly, methods can be employed.

Color – Color becomes a critical factor in many industrial mineral markets. Kaolin, mica, limestone, feldspars, etc. can become more valuable with increasing whiteness. Whiteness may be dependent on the ore characteristics (impurities contained within the crystal structure) and beneficiation may not be able to improve the final color.

Chemical Composition – Because of the high variability found among industrial mineral deposits, chemical composition plays a role in value and marketing strategy. Feldspar can be classified as soda or K-spar, depending on the natural chemical composition. This will define the available markets and pricing.

Market Demands

The size of industrial mineral markets tend to be more restrictive and limited than those in the metals industry because the markets are more specific and directly connected with the consumer. The use of fillers is expanding into plastics in automobiles, and fertilizer markets are cyclic due to weather and world economies. Variable market conditions may be tonnage related, or apply to quality, and new industrial technologies can rapidly alter a market.

Therefore, the design and operation of the industrial mineral plant must be flexible to adjust to the variations in the market demands. In addition, an experienced and knowledgeable sales staff capable of recognizing and responding to the markets should be included in the cost evaluation, as process technology and marketing cannot be separated in the industrial minerals industry.

Location

Because industrial mineral operations are often high volume with low priced products (i.e.; construction materials), the geographic location of the deposit can become an influencing factor with transportation costs of the product to the market having a major impact on the deposit's economics. In many cases, the cost of transporting bulk solids can exceed those of mining and processing, and a thorough evaluation will include these factors. The investigation should determine if a rail spur is near, if the material could be transported by barge, or if trucking will be required. Current rail costs should be reviewed, as these can vary from location to location, and from commodity to commodity.

Product Consistency

All manufacturers, regardless of the industry, expect and demand consistent product performance from its suppliers. The same holds true for industrial minerals, particularly when attempting to enter a market with a new, unproven product.

Glass manufacturers present a great example. Glass is produced from large mixed batches of various raw materials (silica sand, limestone, feldspar, etc.), and the formulation of the batch is based on the chemical composition and physical properties of these raw materials. Batch formulations, as well as product specifications, will vary from producer to producer, and any variation in the quality of the raw materials can create serious and expensive problems in the glass maker's operation.

However, the glass industry, as with most industrial minerals consumers, is extremely competitive and willing to evaluate and test new raw material sources, especially if a cost advantage can be negotiated. Glass manufacturers may consider changing their formulation if a new product represents a significant cost reduction in their raw materials. Therefore, industrial mineral suppliers must go out of their way to insure consistent product quality, and must establish reliability with a client before a long term sales contract can be solidified.

By-Products

The profitability of many industrial mineral ventures are often dependent on the production of by-products beyond the primary product. For instance, many feldspar producers not only supply the spar, which is their bread and butter product, but may also produce mica and quartz for other industries. In most cases, these potential by-products must be removed during processing to meet the specifications on the primary product, and establishing markets for such products can add significantly to the bottom line, even if additional processing is required.

As most know, the high pure and ultra-high pure quartz from the Spruce Pine area of North Carolina were developed as by-products from feldspar production, and before the true potential of this quartz was developed, it was either waste or sold as low cost construction material. This is an extreme example where a waste product that was an expense to the company evolved into its primary product and highlights the potential of by-products.

An added advantage of by-product development which is often overlooked but must be included in the cost evaluation is savings in tailings disposal, not only financially but in land requirements. If a company is spending $3.00 per ton on waste disposal, but can develop a product that sells for $10.00 per ton, the true value of the by-product is $13.00 per ton. In this example, failure to include the savings in waste disposal detracts from the true value by almost a third, which can be significant in offsetting beneficiation costs or presenting an advantage in sales negotiations.

EVALUATION AND PRODUCT DEVELOPMENT

The test program implemented in any evaluation project is determined by several factors. The material to be tested could be from a new, unexplored deposit, or could be from an existing operation seeking to develop a new market, or create a value added product.

In the case of developing a new or value added product, much is already known about the material, and the evaluation may be as simple as characterizing the product to determine if it can meet imposed specifications for the targeted market. Some process development may be necessary if the material requires modifications to conform to the specifications.

In the case of an unexplored deposit, the evaluation becomes more complex. Often not much, if anything, is known about the deposit, and the development could require a multi-stage project, including several stages of bench testing, followed by pilot plant testing, and eventually flowsheet design and plant construction.

Bench Testing

Bench testing of a previously unexploited ore body begins with a preliminary program in which the feed is characterized and initial beneficiation tests are conducted. Caution must be exercised in obtaining a representative sample for any development program. It should be noted that it is never too early to begin investigating markets for any potential products, as well as shipping options and associated pricing. Good efforts in this area early in the development program can pay tremendous dividends down the road, particularly in establishing good relationships with possible consumers.

Feed characterization includes chemical analysis, mineralogical examination, and particle size distribution of either the feed as received, or crushed ore, depending on the nature of the deposit. Chemical analysis and mineralogical data allow identification of the minerals present, leading to identifying potential markets. The size distribution gives an idea to grindibility and examination of the size fractions will indicate liberation size. The latter is critical, as in most industrial mineral applications, mesh of grind is defined by product specifications and not ore properties.

Preliminary beneficiation tests are conducted to identify the primary product, determine how the material will respond to various processing techniques, give some insight to possible markets, allow the process engineer to become familiar with the material, and produce products on a small scale at relatively low cost. In most cases, the focus is to produce the highest grade product possible, while yields are secondary. Obviously, a working knowledge of the markets and pricing, product specifications, and process costs are essential to properly assess resultant data, draw accurate conclusions, and make appropriate recommendations.

Assuming the preliminary testing has been successful (i.e.; suitable product can be made, processing is reasonable from a cost standpoint, product yields are acceptable or can be improved, etc.), follow-up bench testing is recommended. The objective of this phase should be optimizing the process in terms of product grades and recoveries and costs. A small amount of concentrate may be produced and submitted to potential customers for feedback. The possibility of producing secondary, or by-products, is studied in detail, although an experienced engineer will have a good feel for by-products from the initial testing.

Although the preliminary and follow-up testing can be performed in a single stage, the resultant data should be accurate and complete enough to begin a reasonable economic feasibility study. This should include both operating and capital costs, current product pricing, and other incidentals such as environmental permitting, tailings disposal, and air and water treatment when applicable.

Pilot plant testing is the next step in the process development. This stage proves the bench process on a continuous basis and provides important scale-up data, such as more exact equipment and water requirements (percent solids, retention times, etc.). Process variables can be investigated, allowing the optimization of operating parameters and product grades and recoveries. Tailings and water treatment, becoming ever more important in new operations, can be thoroughly investigated, allowing these treatment circuits to be properly designed.

The pilot plant can produce tonnage of product for more stringent market evaluations that are often required by the eventual consumers of the product. It is not uncommon for a new raw material to be required to go through a qualification process performed by the consumer. This evaluation can range from the consumer determining key product characteristics in their own lab to actually utilizing the product on a trial basis in their manufacturing facility. In the latter, several tons of product may be requested.

The pilot plant can provide an excellent training ground for future operators. In industrial mineral plants, particularly if flotation is involved, variations in the operating parameters can significantly effect product quality. Because product consistency is critical, operators should be aware of the key parameters, how to maintain them, and recognize cause and effect disruptions so they can be corrected without major loss of production.

Because finances will be the final justification for proceeding with any development, all bench, pilot plant, and economic data must be reliable, and a lack of experience or proper information can be fatal to the investors. This again stresses the importance of being able to match the raw material to proper markets and processes based on product specifications, ore characteristics, and all associated costs.

PRODUCT SPECIFICATIONS AND PROCESS CONSIDERATIONS

Industrial minerals are used in a multitude of manufacturing industries, from construction materials to ceramics to silicon chips in the computer industry. Companies can vary in size from "mom and pop" type operations to large, multi-national corporations. The products are critical to the industries they serve, and are strategic to manufacturing and developing new products and applications. Each end use of these minerals will carry its own set of specifications that can vary from manufacturer to manufacturer. Add to the mix that all industrial minerals will have highly variable characteristics from deposit to deposit (if not in the same ore body), balancing all the critical factors is often a challenge.

To illustrate the diversity of the markets and how ore characteristics and product specifications apply, several examples of mineral commodities are offered below.

Silica Sand/Quartz

Silica sand is perhaps the most widely used of the industrial minerals. It enjoys a multitude of uses in the market place, all of which carry differing product specifications defined by the individual consumers. The ultimate use of the raw material must be considered in the process development phase.

Silica sand may also be referred to as sandstone, quartz, vein quartz, and quartzite. Although there are subtle geological differences associated with the terminology, this section will deal with silica sand as a group. Common uses, in addition to construction products, include trap sand, fracturing sand, casting sand, glass sand, filtration sand, blasting sand, electronics, opticals, etc.

Trap Sand

Use – Sand used in golf course bunkers.

Product Specs – Critical considerations are drainage, appearance, and consistent play by the golfer from the bunker,. Particle size is the key specification, with the United States Golf Association recommending a sand that lies between 0.25 mm to 1.00 mm, with 75% retained between 0.25 mm and 0.50 mm. This size range has been determined to allow the optimum playing conditions from the bunker. Other quality considerations include color/appearance for cosmetic effect, water permeability and porosity for drainage, and organic matter content.

Process Considerations – Processing will focus on producing the proper size range, and may include attrition scrubbing and washing for clay and silt removal, followed by classification into the specified size fraction. It is doubtful that any sand producer would base their process on this product, as tonnage and pricing would be low and seasonal. Instead, trap sand is usually offered as a by-product, leaving the consumer with perhaps a less than optimum choice, since costs would dictate a local supply.

Fracturing Sand

Use – Used in well drilling, frac sand is pumped at high pressure into subsurface rock to open fractures, thus increasing the permeability of the rock and increasing the flow of oil or gas from the well.

Product Specifications – Key quality considerations include sphericity and roundness of the sand grains, acid solubility, turbidity, and crush resistance. The sand is normally free of impurities, well classified, and composed of rounded grains. Typically offered by the supplier in a range of sizes from 3.5 mm to 0.1 mm, which are well defined and very tightly sized. The final sand can be resin coated for better crushing resistance, minimization of fines generation, superior wetability for pumping, and improved flowback control.

Process Considerations – Ore characteristics are important due to the requirement for rounded grains. Grinding via rod or ball milling should be avoided to prevent creating angular grains. Therefore, the deposits natural size distribution must be favorable to the imposed size specifications.

Processing may include attrition scrubbing and washing for clay and fines removal, followed by classification to produce the required size fractions. Some beneficiation in the form of flotation and/or gravity separation may be required to remove other impurities such as carbonates, feldspars, etc.

Foundry Sand

Use – Foundry sands are used in foundries to make the molds and cores that form the metal castings into a variety of shapes and sizes.

Product Specifications – A foundry sand must be able to withstand high temperatures (1300 - 1700^{o} C), high pressure, allow hot gases to escape from the molds, and produce the proper texture for a smooth casting without reacting with the metal. Therefore, the sand must meet rigid specifications regarding grain size and shape, size distributions, and chemical purity.

The grain size and shape of the sand will effect the rate of escape of gases and the surface texture of the casting. Fines and angular grains can cause plugging in the mold, decreasing the rate of gas flow out, and result in blistering and weakness in the final casting. Angular grains and coarse particles can cause pitting in the casting. Chemical purity focuses primarily on the presence of carbonates, which will react with the acid based binders used to form the mold, resulting in strength loss and higher binder consumption. In addition, other contaminants such as feldspar or mica can cause abrasions and weakening of the metal casting.

Process Considerations – Raw ore characteristics are critical given the shape requirements. Grinding (ball or rod milling) should be avoided to prevent angular shaped grains, so the raw material must possess a natural size distribution suitable for the defined size specifications.

Processing considerations should focus on fines and clay removal through attrition scrubbing and washing, followed by sizing into a product that broadly fits in a 30 x 100 mesh range. Additional beneficiation may involve flotation to remove carbonates, which if present, could increase the ADV, or Acid Demand Value of the green sand. However, removal of too many impurities via flotation could be cost prohibitive if multistages are required. Gravity separation techniques may be applied if mica is present.

Filtration Sand

Use – Filtration sand is used to create granular beds for separating suspended and colloidal impurities from water.

Product Specifications – Requirements for filtration sand are set by the American Water Works Association. The key consideration in producing a filtration sand is uniformity of size with a narrow size distribution. Two imposed specifications relating to the size of the sand are the effective size and a uniformity coefficient. Both are determined by the size distribution of the sand, and no rigorous demands are made on particle shape.

Process Considerations – Because fines can reduce the flow through the sand filter bed, attrition scrubbing and/or washing/desliming may be necessary. Classification through screening to meet the size specifications may be required if the raw material is not characterized by tight, narrow size fractions. Organic and micaeous material may have to be removed if present, but beneficiation may be limited due to cost considerations.

Glass Sand

Use – Silica sand is the most dominant raw material consumed in the glass manufacturing industry, which can be categorized into glass containers, flat glass, and fiberglass (excluding the high tech/high quality glasses). Each of these divisions utilize a glass formulation tailored to yield specific physical advantages for the intended purpose, and as a consequence, impose various chemical and physical specifications on the sand raw material. These specifications can also vary among the glass manufacturers.

Product Specifications – Although some variation will be found in the defined quality of the sand between the divisions and individual manufacturers, most impose specifications in 4 primary areas:

1) Chemistry
2) Colorant Minerals
3) Size Distribution
4) Refractory Minerals

Chemistry and colorant minerals are the most watched group in the raw material. Most emphasis is placed on the iron oxide (Fe_2O_3) content, since most sand deposits will contain iron. Iron values can range from 0.01 to 0.3% Fe_2O_3, depending on the product and manufacturer. Other oxides that are controlled include chromium, cobalt, and manganese, since they are extremely powerful colorants. Limits on alumina content can also be imposed.

An important note – Most glass manufacturers consider consistency of the raw materials of utmost importance, and will typically define variances allowed for the individual oxides if the sand supplier demonstrates a tolerable consistency.

Particle size distribution is also a critical component of the sand raw material. Glass manufacturers typically dictate a size range between 30 and 140 mesh, although again some variance is found among the glass makers, depending on the melting furnace, firing temperatures, and rate of batch fill.

Most will impose a coarse sand limit to insure complete melting of the sand based on the manufacturing parameters. Specifications imposed on the fine end relates primarily to health concerns associated with the fine silica. (**Note:** The one exception to the above size specifications is the fiberglass industry, which utilizes a silica sand ground to 200 mesh.)

Refractory minerals are of great concern to the glass manufacturer, and are defined as minerals that will not melt in the glass batch, leaving "stones" in the final glass product. Common refractory minerals are chromite, corundum, kyanite, silliminate, and zircon/zirconia. The presence of these contaminants are typically determined by heavy liquid separation at a specific gravity of 2.96.

Although limits imposed on these refractory minerals can be very strict, the glass producers are primarily concerned with those present in the +60 or +70 mesh sizes. Finer refractory minerals will melt out due to their size. The fiberglass industry is again the exception due to the already fine particle size employed.

Process Considerations – Due to the imposed specifications on the glass sand raw materials, the processing flowsheet can be fairly complex or relatively simple, depending on the ore characteristics. Therefore, characterization of the run of mine ore can assist in defining the required beneficiation, and should include initial chemical assays, size distributions, and heavy mineral determinations.

Typical unit operations employed in the beneficiation of glass sands can include sizing and/or grinding, attrition scrubbing and desliming, flotation, gravity separation, and magnetic separation. Electrostatic or high tension separations have been used on a limited basis.

Because shape of the sand grains is not critical in glass making, the sand can be ground to the -30 mesh specification if ore characteristics dictate. However, most glass sand producers avoid this comminution step if possible due to cost, and prefer to screen out any oversize unless the sand is produced as a by-product. The -30 mesh feed is usually subjected to attrition scrubbing and desliming to remove any surface stains (particularly iron oxide), eliminate fines and clays, and to prepare the mineral surfaces for flotation if required.

Flotation is usually employed when the sand contains refractory heavy minerals, as the introduction of chemical reagents to the process stream can complicate permitting and environmental concerns while adding to production costs. The refractories can be effectively removed through anionic flotation utilizing an acid circuit with a petroleum sulfonate based collector, or in a neutral or basic pH with cationic collectors (tall oils/fatty acids).

The acid based flotation has proven more effective, although success has been demonstrated in the neutral/basic circuits utilizing a sulfonate/tall oil blend. If successful, this scheme will eliminate the use of any acids for pH regulation, and can also remove any carbonates that may be present, in which case the use of an acid circuit is virtually impossible for obvious reasons.

Gravity separation can be an attractive alternative to the flotation. Spiral separators have proven successful in reducing the heavy minerals to meet product specifications in instances where the ore characteristics allow. The spirals are typically effective down to 50 or 60 mesh, so the distribution by size of the refractories is key when considering this option.

Magnetic separation can be utilized as a finishing step after the flotation and/or gravity separation, or as a main processing stage without the flotation, depending on the ore characteristics. Dry, high intensity separators that employee rare earth rolls have proven very effective in removing highly and para-magnetic minerals, which may be required to meet the imposed iron specifications. These minerals could include biotite, heavily stained sand grains, and iron bearing refractory minerals. Often a sand producer will use the high intensity magnets to produce a special product and will not necessarily treat the entire plant tonnage.

High Pure Quartz

Although high pure quartz could be included in the section on silica sand, the vast differences that exist in this area versus the more "common" sands dictates separate discussion. The primary difference is product quality, while others include the size of the markets, product pricing, availability of suitable raw material, processing requirements, and plant construction considerations.

High pure quartz products serve the higher end, high tech markets, which include electronics, opticals, semi-conductor, lighting, infrared, specialty glass, fiber optics, and the computer and communications industries. Fused silica, or more correctly fused quartz, are common terms applied to the silica for most of these applications, although they have become synonymous with the well known trade names of Quintas and Iota grade products, produced by the Unimin corporation from their facilities in Spruce Pine, NC. These products are also referred to as high pure quartz (Quintas grade) and ultra-high pure quartz (Iota grade).

Product Specifications – Because of the variety of end uses for the high pure and ultra-high pure products, exact product specifications are difficult to assign, and quality is ultimately determined by performance. In fact, it is often impossible for the consumers of such products to define chemical specifications. However, some typical guidelines can be applied to initially evaluate the quartz and control the process. Typical limits on contaminants are as follows.

High Pure Quartz (ppm)

Fe - 20 ppm max.
Na - 100 ppm max.
Mg - 30 ppm max.
Al - 200 ppm max.
Ca - 50 ppm max.
Ti - 5 ppm max.
K - 80 ppm max.
Li - 2 ppm max.

Ultra-High Pure Quartz (ppm)

Fe - 1.0 ppm max.
Na - 2.0 ppm max.
Mg - 0.5 ppm max.
Al - 15 ppm max.
Ca - 2.0 ppm max.
Ti - 1.0 ppm max.
K - 2.0 ppm max.
Li - 0.5 ppm max.

It should be noted that the above do not include all elements that could disqualify a quartz, but are instead listed as a basis for further evaluation. It should also be noted that while many describe the purity of quartz in terms of % SiO_2, these could be misleading, especially in the ultra-high pure grades. A quartz product may be described as 99.999% SiO_2, but still contain trace elements on a ppm or ppb level that could hinder its performance.

In addition to the chemical limits imposed, size specifications have been tentatively defined for the high pure and ultra-high pure products. Although these specifications may vary slightly among the consumers, the products are essentially maintained within a 50 x 140 mesh size range.

Process Considerations – High pure quartz products are typically produced through physical beneficiation techniques, including grinding, attrition scrubbing, flotation, and magnetic separation. The ultra-high pure grades, usually produced from the high pure products, receive additional beneficiation in the form intense acid leaching and chlorination.

Details of the technology are considered proprietary, and little data is available for publication. However, the ore characteristics will play a role in the degree of processing, specific types of flotation that may be required, etc. For example, a quartz to be recovered from a pegmatite deposit versus a vein-type quartz will almost certainly contain different types and levels of various contaminants, and must be beneficiated appropriately.

Comment – The key to any successful high pure quartz venture is finding a suitable raw material. It should be cautioned that basing any judgement of final quartz purity on feed analysis, or data generated from partially or unbeneficiated material could lead to wrong conclusions. Only after the raw material has been thoroughly processed and evaluated can the true potential be conclusively defined.

Mica

Mica, a group of aluminosilicate minerals possessing a sheet-like structure, has become a key industrial mineral due to its physical, chemical, electrical, thermal, and mechanical properties, and enjoys a multitude of industrial applications. Muscovite, a potassium-based mica, is the most common and widely used, along with the magnesium-based phlogopite mica. Phlogopite is usually a darker color than the muscovite, and is therefore used in non-color sensitive applications.

Mica's unique properties include high dielectric strength and uniform dielectric constants, making it an excellent electrical insulator. Its thermal properties include low coefficients of expansion, cold resistance, and is not affected by extended exposure to heat, allowing for high temperature applications. It is practically inert, and possesses high tensile strength, resulting in a high durability. These properties create a variety of markets for mica, which is ultimately determined by the mica's individual properties found in any given deposit, which can be extremely variable.

The majority of the mica consumed is in the form of dry ground and wet ground products. Dry grinding has a tendency to pulverize the individual mica flakes, resulting in more granular shaped powders, higher bulk densities, and lower aspect ratios. The wet ground mica creates more delamination, giving high aspect ratios, low bulk densities, and excellent sheen lubricity.

Common uses of wet ground products include paper applications, cosmetics, rubber coatings, paint and plastic fillers, and sealers. Value added wet ground mica that receives proprietary surface modifications find use in specialized markets, particularly in plastics. Dry ground uses include drilling muds, roofing shingles, joint compounds, and fillers in lower grade paints. Because of the lubricity, or “slip” produced by the delaminating, mica is used as lubricants and replacements for asbestos in applications such as brake pads and clutches.

Almost all industrial applications of mica benefit from the grinding process, which tends to enhance the physical properties of the mica. These properties improve proportionally to the degree of delamination that occurs, thus giving the wet ground products significantly better properties and higher pricing. However, not all mica’s are suitable for wet ground products due to inherent physical properties, such as bulk density, brightness, color, slip, etc., and may only find markets from dry grinding. In addition, the economics of wet versus dry grinding can dictate the use of the lower priced dry ground products, provided they possess the desired properties for the application. As requirements become more stringent, such as in composite reinforcement and cosmetics, wet ground micas are essential.

A third micaceous mineral is vermiculite, which is a highly weathered, hydrated boitite or magnesium-based mica. Because of its hydrated chemistry, it possesses unique expansion capabilities and high loss on ignition, transforming the mineral into a lightweight product. Vermiculite is used in various markets, including construction and agriculture, and is marketed according to various grades sorted by size.

Product Specifications – Chemical analysis is usually not of utmost importance to most of the mica consumers, although it is typically determined and listed on product spec sheets. The variation in chemistry between different mica’s force both producers and consumers to utilize other properties to evaluate a mica’s value.

Properties that are important to consumers (and thus the producers) are the particle size distributions, bulk density, moisture content, free silica content, brightness, surface area, oil absorption values, slip and sheen, and aspect ratios. These properties will ultimately determine the most suitable markets for any mica.

While the majority of the above characteristics, such as brightness, bulk density, chemistry, etc., are determined by standard methods, other properties are more subjective. Aspect ratios, or the relationship between the particle diameter and thickness, are difficult to determine and duplicate. Slip, which is an indication of the degree of friction between individual mica particles, and sheen, or luster, are determined initially by experience. These properties and their suitability for products that rely on them are often not deemed satisfactory without actual testing in the targeted application.

Process Considerations – Mica processing can include simply crushing and sizing with impact type crushers and screens, or can become more complex utilizing grinding and sizing, flotation, gravity separation, and magnetic separation.

Mica susceptible to crushing and sizing takes advantage of the differential grinding characteristics of the mica, employing the concept of reducing associated rock faster than the mica. This allows the harder to grind mica to be screened out as an oversize product. For a deposit to utilize this processing, it should be relatively high grade with coarser mica being the natural occurrence. It has the advantage of allowing relatively dry processing, producing a coarse mica concentrate with no chemicals that would be a good feed for wet ground processing provided it meets specifications. Disadvantages include lower grade concentrates, which could ultimately affect bulk densities, and high losses of finer mica, which would require additional processing for recovery.

Coarse mica (+40 mesh) is often recovered by spiral separation. This processing usually requires some crushing and grinding to liberate the mica from any host rock. The communition circuits should be designed to minimize fines and maximize the production of the coarse flake. This option allows mica production without the use of chemicals at a relatively coarse particle size, again producing an ideal wet ground feed. Often two spiral passes, including a rougher and cleaner, are required to produce mica grades of +90%. Concentrates may be subjected to screening to remove any fine grit to produce the final grades.

Mica flotation can be performed in either an acid or basic circuit. Both utilize amine-type collectors as the primary collector, although the basic circuit reagent scheme is more complex, requiring the use of a depressant (goulac) and other modifying agents such as kerosene and/or DLR, a highly refined tall oil. Flotation in acid circuits employes sulfuric acid as a pH regulator (pH = 2.5 - 3.5), with an amine collector. Fuel oil may be used as an additive to assist in floating coarser particles and where dirty feeds are a problem. In both flotation processes, cleaner steps are employed to produce the required grades, along with a classification circuit to remove any fine grit.

The flotation concentrates are typically used as dry ground feed due to the presence of the chemicals, which are a detriment for the wet ground products. If the mica in the ore is not of high enough quality to serve as a wet ground feed, flotation may be the only process used for concentration. If the mica does produce a quality wet ground product, the flotation is typically used as a compliment to the spirals, allowing the recovery of finer mica. This combination of processing produces concentrates for both wet and dry ground production.

Wollastonite

Wollastonite is a calcium metasilicate with the chemical structure $CaSiO_3$. Its most unique feature is its ability to cleave into needle like crystals, creating a high aspect ratio that is important for many of its industrial uses. As a matter of fact, wollastonite is the only naturally occurring nonmetallic, white acicular mineral. However, it has also found uses in low aspect ratio applications, although pricing is greatly influenced when the high aspect ratio characteristic can be used to its maximum advantage.

The high aspect ratios allow wollastonite to be used as reinforcers in composites and plastics, increasing tensile flexural, and impact strengths. Plastics appear to be its fastest growing application. Other applications include paint fillers, ceramics, asbestos replacements, sealants and caulks, and friction products. Some wollastonite may be surface modified to optimize its performance in composite materials, resulting in stronger bonding, enhanced mechanical properties, and increased weather resistance. Low aspect ratio products find uses in glass,adhesives, abrasives, metallurgical applications, and steel manufacturing. Depending on its use, the wollastonite may be supplied as fine ground products, or in coarser fractions similar to glass sands.

Product Specifications – Wollastonite specifications are market specific. Concentrate grades must be a minimum 90% wollastonite content, with some applications requiring higher grades of +97%. For higher end uses, the aspect ratios must be maintained as high as possible, giving more importance to processing choices.

Particle size distributions are critical on fine ground products, while color, whiteness, oil absorption, and bulk densities can be specified by individual consumers. Maximum iron content (Fe_2O_3) may be specified by certain consumers, although for the most part, these irons can be considerably higher than most "white", high end industrial mineral products.

Process Considerations – The most important processing consideration is creating and maintaining a high aspect ratio, as these products demand higher pricing in the market place. Most producers regard their milling techniques as well as fine grind technology, as proprietary, and guard them closely to maintain a commercial advantage. For production of low aspect ratio products, more conventional milling techniques can be employed.

For beneficiation purposes, the ore characteristics play a key role in the flowsheet design. Because high grade concentrates are required for most markets, the majority of associated gangue minerals must be successfully removed, and unit operations in the beneficiation plant must consider the type and amount of these gangue minerals.

Flotation is used to remove calcium carbonate, which is commonly associated with wollastonite deposits. This is especially critical for plastics applications. Quartz, if present, most also be removed to create the grades, bulk densities, and high aspect ratios. This is also done with flotation, utilizing amine-type collectors in conjunction with depressants and/or modifiers. High intensity magnetic separation is another common beneficiation practice, as many deposits are characterized by the presence of garnets and diopside.

Phosphate Rock

Phosphate rock is defined as a rock material that contains sufficient phosphate values for commercial usage. Grades are characterized by either its % P_2O_5, or by % BPL (bone phosphate of lime), which is a mathematical equivalency calculated from the phosphate content. The most commercially exploited phosphate rock is from the apatite family of minerals.

The most critical and largest of the phosphate markets is fertilizer, as phosphate rock provides the essential soil ingredients required for the agricultural industry. This requires the physical concentration of the phosphate rich minerals from the ore, followed by chemical processing of the concentrate to extract the phosphate. This places phosphate rock in a unique position, as consumption is governed by seasonal weather patterns and regulations controlling it use rather than periods of economic growth and recession, which characterizes most of the other industrial minerals markets.

Other uses of phosphate include the food, beverage, and animal feed industries. Non-fertilizer, non-food applications are found in the production of flame retardant materials, water treatment, textiles, pesticides, and plastics and rubber.

Product Specifications – Product specifications are difficult to quote for the phosphate industry for several reasons. Unlike most industrial minerals, the rock concentrations will more than likely be sent directly to the chemical processing facility for fertilizer and/or acid production.

Because the chemical facilities are essentially extensions of the beneficiation plants, owned and operated by the same Companies, the phosphate rock is not typically sold on the open market, and product specs are primarily for internal purposes. Often, the chemical plants are forced to except whatever concentrates are produced by the beneficiation plants, which can create internal friction amongst management teams. However, some general comments can be made that are defined as critical to the operation of the chemical treatment facilities.

Another consideration is the variability from one deposit to another. Commercial ore deposits currently being mined can run anywhere from 3 to 4% P_2O_5 to as high as 20% P_2O_5. Associated gangue minerals can vary just as drastically, ranging among various levels of silica, clays, and carbonates, as well as other trace mineral contaminants. These factors highly influence the concentrate grades that can be produced.

As a general statement, the beneficiation plant should produce as high a P_2O_5 content as possible for feed stock to the chemical plants. Silica content, or acid insols, in the final concentrate should be low (less than 2.0%). Another important product characteristic is the $CaO:P_2O_5$. If either of these are too high, the performance of the fertilizer and acid plants can be adversely affected.

Process Considerations – Most phosphate operations employee several steps of flotation as the primary beneficiation method. In the case of igneous deposits, some crushing and grinding may be required to reduce the rock to flotation size. Most sedimentary deposits contain phosphate pebble and the ore is typically classified to flotation size without any comminution.

Depending on the type and amount of clay slimes present, attrition scrubbing and desliming may be required ahead of the flotation. This will be defined by the ore characteristics, but typically the sedimentary deposits will contain more troublesome clays. If these clays are not removed, reagent consumption will increase in the flotation, and recoveries of the concentrate will decrease, thus influencing unit costs significantly.

Phosphate flotation is most commonly performed with fatty acid/tall oil type collectors. After conditioning at high solids, a primary froth concentrate is produced to reject the majority of the silica. Often a cleaner of this froth is employed to drop out additional silica. If silica content continues to be high, an additional flotation is required, consisting of a de-oiling step with sulfuric acid to remove the primary collector from the phosphate froth, followed by flotation of the remaining silica with amine type collectors. Both the fatty acid and amine flotation steps are conducted at neutral, or slightly basic pH.

Several major producers utilizing the above process have found it beneficial to split the flotation feed into two size fractions, thus resulting in fine and coarse flotation circuits. The size separation is determined by the ore characteristics and how the various fractions respond to the flotation.

A challenge in the beneficiation of phosphate rock is the removal of carbonates. The fatty acid flotation will float both the phosphate rock and the carbonate, and the amine flotation will not separate the two. Although much research has been done to effect this separation, at present there is no economic method available for most deposits, thus making the carbonate content of the ore an important consideration.

Feldspar

Feldspar is the most abundant of any mineral group, accounting for approximately 60% of the earth's crust. Commercially exploited deposits are of two main types: Orthoclase (or microcline), a potassium based feldspar, and albite, which is a sodium based feldspar. Feldspar concentrates containing over 10% K_2O are classified as potash spar, while Na_2O values above 6% are considered soda spar.

Feldspar is most widely used in the glass and ceramic industries, as well as fillers and extenders in a variety of manufacturing industries, such as paint, plastics, etc. The high alumina values associated with the feldspar are desired for flux purposes in both the glass and ceramic industries, although this is more critical to the glass maker. Ceramic producers, which use feldspar in both body and glaze applications, are typically more concerned with alkali ratios.

Product Specifications – A range of commercial feldspar products are available, but the key specification is chemical analysis. Alumina and alkali values are important for the key markets, as is iron content. For glass purposes, Fe_2O_3 should be below 0.10%. For ceramic purposes, a body spar is generally less than 0.08% Fe_2O_3, and feldspars used in glazes should be less than 0.06% Fe_2O_3. Alumina values are targeted at 18% Al_2O_3 minimum, and perhaps higher for glass applications.

Alkali values will range from deposit to deposit, and consistency is considered extremely important. Most ceramic and glass manufacturers will accept variations in the general specs listed above if the product quality is consistent and pricing competitive. Particle size distribution is important in all markets. Glass grade spar is sized to 30 x 200 mesh, while body spar for ceramics will carry a specification of a maximum percent coarser than 140 mesh. Feldspar used in glaze is typically finer than body spar, allowing only a small percentage on 200 mesh. Fillers will range from -325 mesh down to micron sizes, and are usually supplied in a range of top sizes.

Other critical properties include fired color and associated minerals for ceramics, and brightness and oil absorption for fillers. Filler grades are often characterized by a Hegman Grind factor, which essentially identifies the coarsest particles present. Average particle size and surface areas are defined for the finer products.

Process Considerations – Most feldspar deposits, originating in pigmatites, granites, or other hard rock ore bodies, require crushing and grinding prior to processing. The final comminution circuit design will depend on the ore characteristics, such as hardness of the host rock, degree of weathering, etc. Grinding circuits are typically designed to reduce the crushed ore to 20 or 30 mesh to meet the glass market specifications.

Flotation is utilized to concentrate the feldspar. The most common, and effective, reagent scheme includes hydrofluoric acid and amine collectors at a low pH (<3.5). Because of environmental concerns associated with the HF, other chemical regiments have been researched, and some put into practice, although none to date have proven to be as effective as the HF/amine combination in regards to grades and recoveries. Dry processing has also been attempted with little or no success.

Although the HF is an excellent activator of the feldspar, allowing for very sharp separations from associated quartz, it also tends to activate mica, biotite, and other iron bearing minerals, which will report with the feldspar froth product. Therefore, any associated minerals must be removed ahead of the feldspar flotation, particularly if they create problems for the anticipated markets. Common practice involves the removal of mica and biotite with standard flotation techniques, and the flotation of other iron bearing minerals utilizing practiced reagent schemes.

Following filtering and drying of the feldspar concentrate, the product can be shipped for glass purposes, or will require additional grinding for ceramic and filler applications. This grinding is performed in air swept mills in closed circuit with air classifiers, and the market will dictate the fineness of the grind. In the case of glaze and filler applications, the coarse glass grade feldspar may be treated with magnetic separators to produce the final iron and color/brightness specifications.

SUMMARY

The design, construction, and operation of an industrial minerals facility is vastly different from a metallic processing plant. Because the mineral products are market driven with exacting specifications, demanding long term sales agreements with clients, a market study and thorough evaluation of the product must be conducted before spending capital to develop a property.

The marketing study is critical, and should be one of the first exercises performed. It should include: 1) a survey of the potential use of the mineral; 2) size of the market; 3) price of the commodity; 4) available transportation and costs; 5) estimates of potential profitability based on the potential products; 6) by-product potential; 7) competition from other companies and/or minerals.

The process engineer must be aware of the general market conditions, product specifications, pricing, and associated costs. It is imperative that the development program characterize the ore, identify the key mineral properties and potential products, and match the beneficiation process to the corresponding markets. The resultant process flowsheet should be optimized through pilot plant testing, producing data for precise cost estimates, tonnage of product for customer evaluations and proving product quality and consistency. Failure to do so will lead to wrong conclusions and costly and erroneous recommendations

PULSEWAVE technology – A new and innovative processing technology for the minerals industry

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ABSTRACT

Pulsewave, LLC is a privately held firm involved in proprietary research aimed at mating its recently developed and patented resonance disintegration technology with potential commercial applications in several areas of materials science including the energy and mineral industries.

Unlike conventional milling processes that physically "crush" various material, the Pulsewave machine operates on the principle of resonance disintegration that reduces the particle size by the application of the physics of destructive resonance, shock waves and vortex-generated shearing forces that cause material to cleave along the internal planes of their structure that are the most susceptible to separation. This results in materials being fragmented from within rather than being crushed by impact or grinding. Therefore, in addition to efficient particle size reduction down to the micron level, this technology provides for the liberation of discrete particles in complex multi-phase materials as opposed to the simple size reduction that results from conventional milling methods. For example, pyrite can be liberated from coal by the Pulsewave process, hydraulic hose can be delaminated into separate steel wire and rubber fractions, and precious metals can be liberated from their host rock matrix. This process also produces a "cleaner" component particle than conventional milling because of the elimination of the smearing that normally accompanies the physical crushing of a material. This property of the Pulsewave processing technology could have a significant impact in the area of liberating and removing impurities from raw mineral ores.

Mica, talc, ore minerals, coal, limestone, oil shale, gypsum and quartz sands are among the mineral commodities Pulsewave has efficiently processed using its resonance disintegration technology.

Sumner, Richard L., 2006, Pulsewave technology – A new and innovative processing technology for the minerals industry, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey

INTRODUCTION

Pulsewave, LLC is a privately held Denver, Colorado corporation that has developed a new and unique milling process. Through experimentation and pilot projects, Pulsewave has demonstrated that its Pulsewave Resonance Disintegration (RD) Machine and associated patented technology can effectively micronize most solid materials and in many cases can also separate the individual components of a heterogeneous material.

The Pulsewave RD machine operates on the principle of resonance disintegration that reduces the particle size of various materials by the application of the physics of destructive resonance, shock waves and vortex-generated shearing forces. Multiple physical forces within the machine are applied in a timely fashion in order to maximize the disintegrative action. The design geometry of the Pulsewave machine provides for an incremental increase in the magnitude of the shock waves in the machine, and for the phasing of forces such that the efficiency of the process is enhanced while the energy transfer to the machine is minimized. This results in materials being fragmented from within rather than being crushed by impact or grinding. Therefore, solid materials will tend to cleave along the planes of their internal structure that are the most susceptible to separation, preserving the particle shape and integrity. The versatility of the RD machine is evident in the wide variety of materials it is capable of milling, from very hard crystalline materials to compressible soft elastic materials.

In addition to milling, the Pulsewave technology provides for the selective differential fragmentation of particles in complex multi-phase materials such as steel-reinforced tires, as opposed to the simple crushing and micronizing that result from conventional milling methods. Since different components of a heterogeneous material will tend to have different elasticity, they will tend to separate and fragment into different size fractions when processed in the RD mill. As examples, plant fiber can actually be liberated and separated from intracellular components, gold particles can be liberated from a rock matrix and small sections of hydraulic hose can be delaminated into separate steel wire and rubber fractions.

Description and Operation of the Pulsewave RD Machine

The weight of an assembled RD machine is approximately 2500 pounds (1140 kilograms), and an individual machine is approximately 15’ tall and has a footprint of approximately 4’ x 8’. The frame and the shaft of the machine are manufactured from standard stainless steel and the rotors and side plates are high-carbon steel. The machine parts are manufactured to a tolerance of 1/1000 to 1/10,000 of an inch, depending on the part, and many are balanced individually and again as a complete assembly. The mill is covered with a powdered coating rather than paint. Figure 1 below is a photograph of a Pulsewave RD Machine set up and operational at Pulsewave’s Denver, Colorado facility.

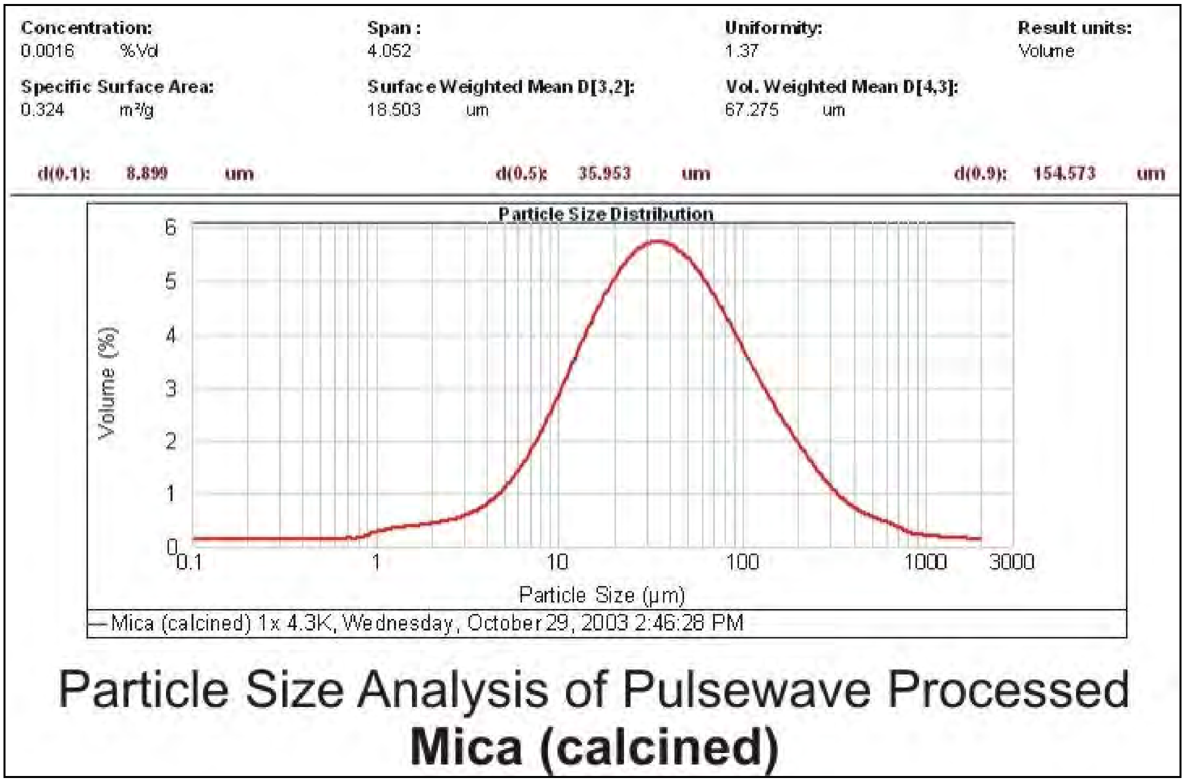
In addition to the basic components of the machine, accessories to a production operation could include vibrating feeders, feed chutes, discharge chutes, skids, ladder, and guard rails. The machine is powered by a 220/480-volt electric motor, and present units have been run with motors of from 10 to 100 horsepower. The amperage draw will vary with the material and the feed rate.

The basic operation of the RD machine entails feeding a material in the machine at a predetermined rate. The feed material needs to be approximately 2” or less in large dimension in order for an effective feed rate to be established. The material is carried in a stream vertically through the machine, from top (input) side to the bottom (output) end.

FIGURE 1 Pulsewave RD machine set up at Pulsewave's Denver facility.

The Pulsewave RD Machine has application in at least two areas of mineral processing: 1) general milling, and 2) as a simultaneous comminution/separation technology, where heterogeneous mineral commodities are micronized and certain internal components are liberated from each other, as in the case of liberating pyrite from a coal matrix.

As a general milling device, the Pulsewave machine excels at reducing material to 10-100 micron size, and generally does so at a lower energy consumption rate than conventional mills. Several mineral commodities have been tested in the Pulsewave machine, including mica, talc, limestone, gypsum, black sand and wollastonite, which are used as illustrative examples in this paper. Samples of these mineral commodities were crushed to a 2"-or-less input size and then fed into the Pulsewave machine. The particle size of the output of these processing runs was measured on a Malvern Laser Diffraction Unit and the graphical results are presented and explained in Figures 2-7 below. These graphs illustrate the particle size of processed material after one pass through the Pulsewave machine and are self-explanatory; the starting (pre-processing) size of all of these materials was between 1/6th" to 1" in large diameter.

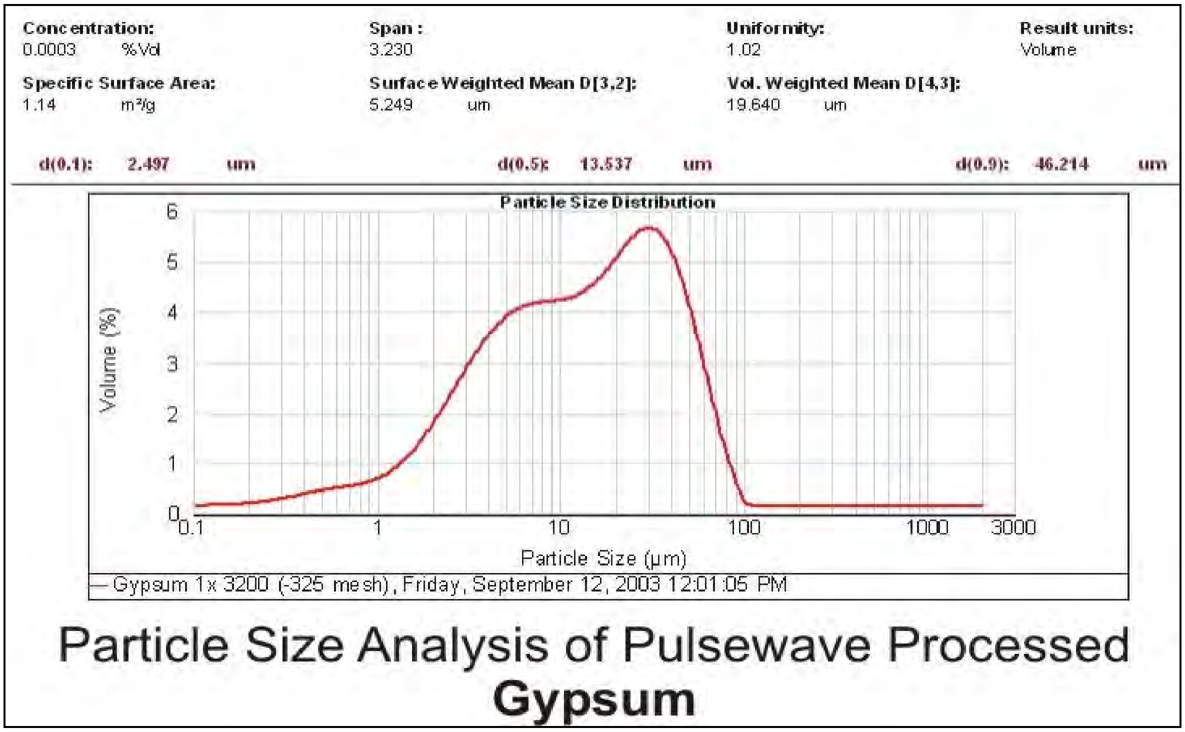


Concentration: 0.0016 %Vol
Span : 4.052
Uniformity: 1.37
Result units: Volume
Specific Surface Area: 0.324 m²/g
Surface Weighted Mean D[3,2]: 18.503 um
Vol. Weighted Mean D[4,3]: 67.275 um

d(0.1): 8.899 um
d(0.5): 35.953 um
d(0.9): 154.573 um

Particle Size Analysis of Pulsewave Processed **Mica (calcined)**

FIGURE 2 Particle size analysis of Pulsewave processed mica.



Concentration: 0.0003 %Vol
Span : 3.230
Uniformity: 1.02
Result units: Volume

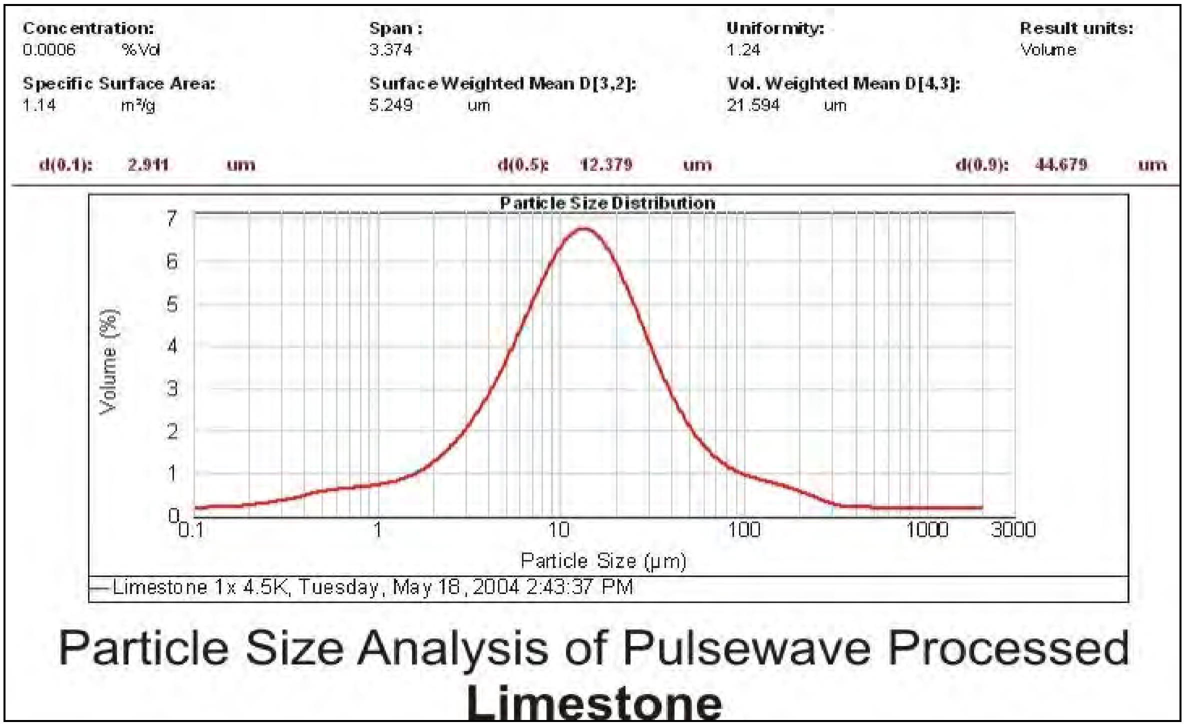
Specific Surface Area: 1.14 m²/g
Surface Weighted Mean D[3,2]: 5.249 um
Vol. Weighted Mean D[4,3]: 19.640 um

d(0.1): 2.497 um
d(0.5): 13.537 um
d(0.9): 46.214 um

— Gypsum 1x 3200 (-325 mesh), Friday, September 12, 2003 12:01:05 PM

Particle Size Analysis of Pulsewave Processed **Gypsum**

FIGURE 3 Particle size analysis of Pulsewave processed gypsum.



Concentration: 0.0006 %Vol
Span : 3.374
Uniformity: 1.24
Result units: Volume

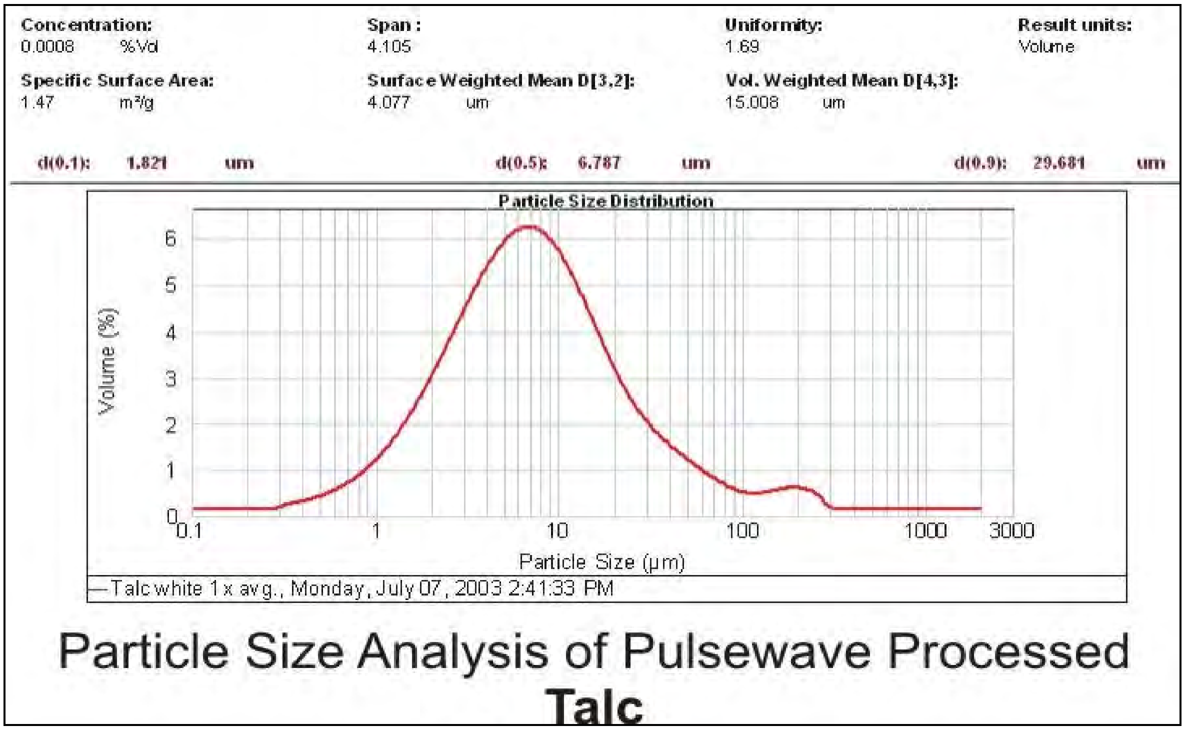
Specific Surface Area: 1.14 m²/g
Surface Weighted Mean D[3,2]: 5.249 um
Vol. Weighted Mean D[4,3]: 21.594 um

d(0.1): 2.911 um
d(0.5): 12.379 um
d(0.9): 44.679 um

— Limestone 1x 4.5K, Tuesday, May 18, 2004 2:43:37 PM

Particle Size Analysis of Pulsewave Processed **Limestone**

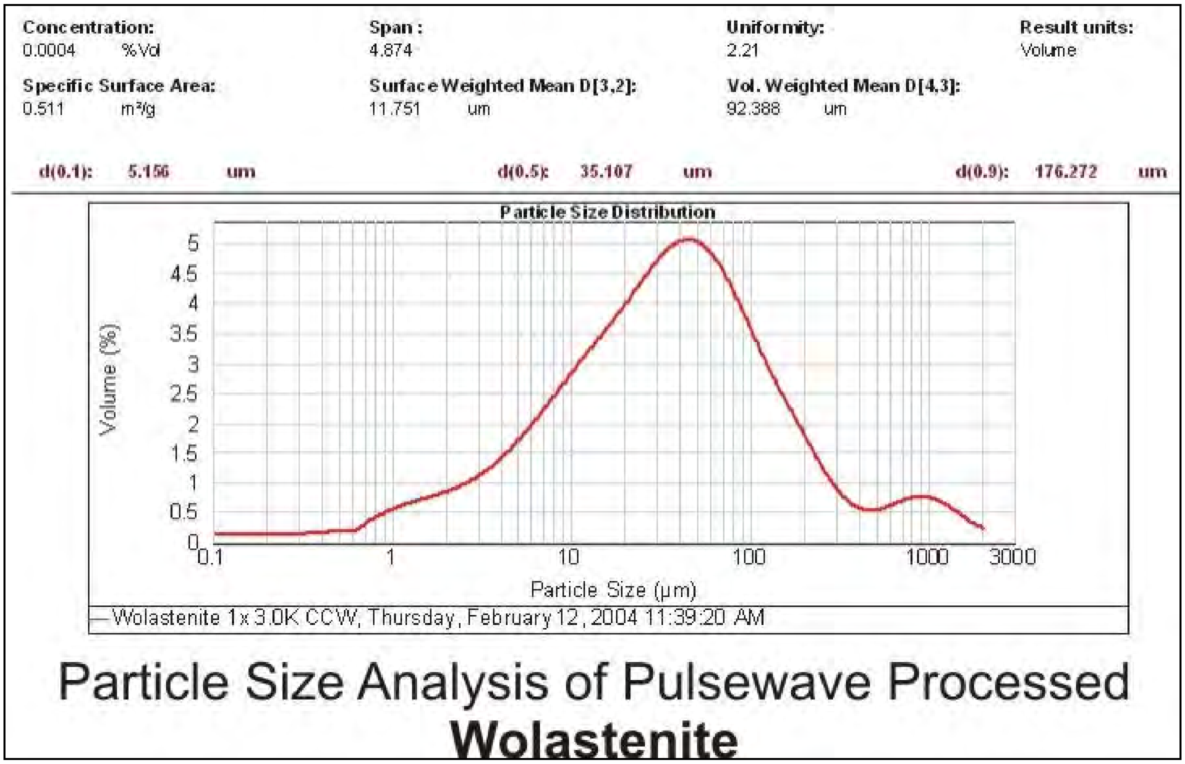
FIGURE 4 Particle size analysis of Pulsewave processed limestone.



Concentration: 0.0008 %Vol
Span : 4.105
Uniformity: 1.69
Result units: Volume
Specific Surface Area: 1.47 m²/g
Surface Weighted Mean D[3,2]: 4.077 um
Vol. Weighted Mean D[4,3]: 15.008 um
d(0.1): 1.821 um
d(0.5): 6.787 um
d(0.9): 29.681 um

Particle Size Analysis of Pulsewave Processed **Talc**

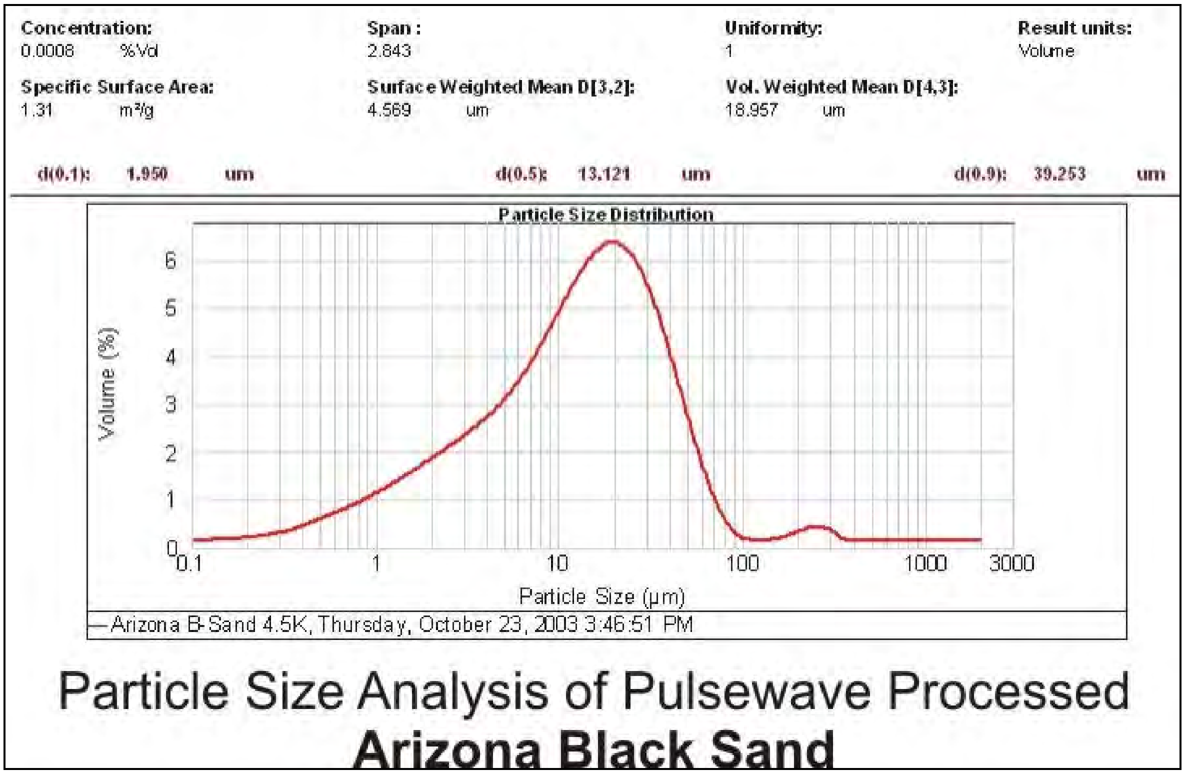
FIGURE 5 Particle size analysis of Pulsewave processed talc.



Concentration: 0.0004 %Vol
Span : 4.874
Uniformity: 2.21
Result units: Volume
Specific Surface Area: 0.511 m²/g
Surface Weighted Mean D[3,2]: 11.751 um
Vol. Weighted Mean D[4,3]: 92.388 um
d(0.1): 5.156 um
d(0.5): 35.107 um
d(0.9): 176.272 um

Particle Size Analysis of Pulsewave Processed **Wolastenite**

FIGURE 6 Particle size analysis of Pulsewave processed wollastonite.



Concentration: 0.0008 %Vol

Span : 2.843

Uniformity: 1

Result units: Volume

Specific Surface Area: 1.31 m²/g

Surface Weighted Mean D[3,2]: 4.569 um

Vol. Weighted Mean D[4,3]: 18.957 um

d(0.1): 1.950 um

d(0.5): 13.121 um

d(0.9): 39.253 um

Particle Size Analysis of Pulsewave Processed **Arizona Black Sand**

FIGURE 7 Particle size analysis of Arizona black sand.

As can be seen on these graphs, the processing of these mineral commodities in the Pulsewave machine resulted in a significant particle size reduction in each case. The Pulsewave technology has demonstrated that it is effective in reducing most single-phase materials to a particle size similar to those displayed above.

In addition to being an effective comminution technology, the Pulsewave system also has the unique ability to fragment and liberate particles in complex multi-phase materials, as opposed to the simple crushing and micronizing that result from conventional milling methods. Since different components of a heterogeneous material will tend to have different elasticity, they will tend to separate and fragment into different fractions when processed in the RD mill. For example, plant fiber can actually be liberated and separated from intracellular components, steel belted radial tires can be delaminated into separate steel wire and rubber fractions, pyrite can be liberated from coal and organic particles can be liberated from an oil shale matrix. The design geometry of the Pulsewave machine results in materials being fragmented from within rather than being crushed by impact or grinding. Therefore, material will tend to cleave along the internal planes of their structure that are the most susceptible to separation; for example, in the case of the components in coal, that is apparently the boundary between particles of the pyrite (mineral matter) and particles of the more elastic coal (organic matter). This process also produces a "cleaner" component particle than conventional milling because of the elimination of the smearing that normally accompanies the physical crushing of a material. Figures 8-10 below illustrate the ability of the Pulsewave machine to liberate internal components from a heterogeneous matrix; in this case pyrite from coal.

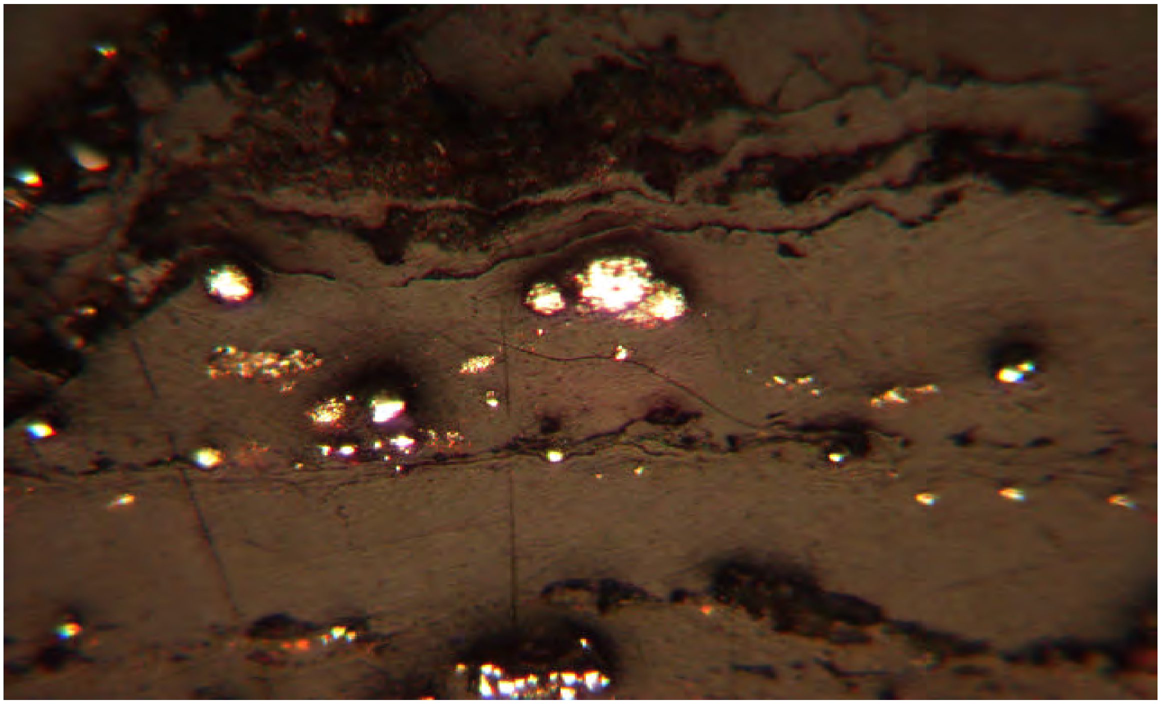


FIGURE 8 Microphotograph (~ 450x) of a raw sample of the Illinois #5 coal showing *in situ* pyrite crystals and framboids.

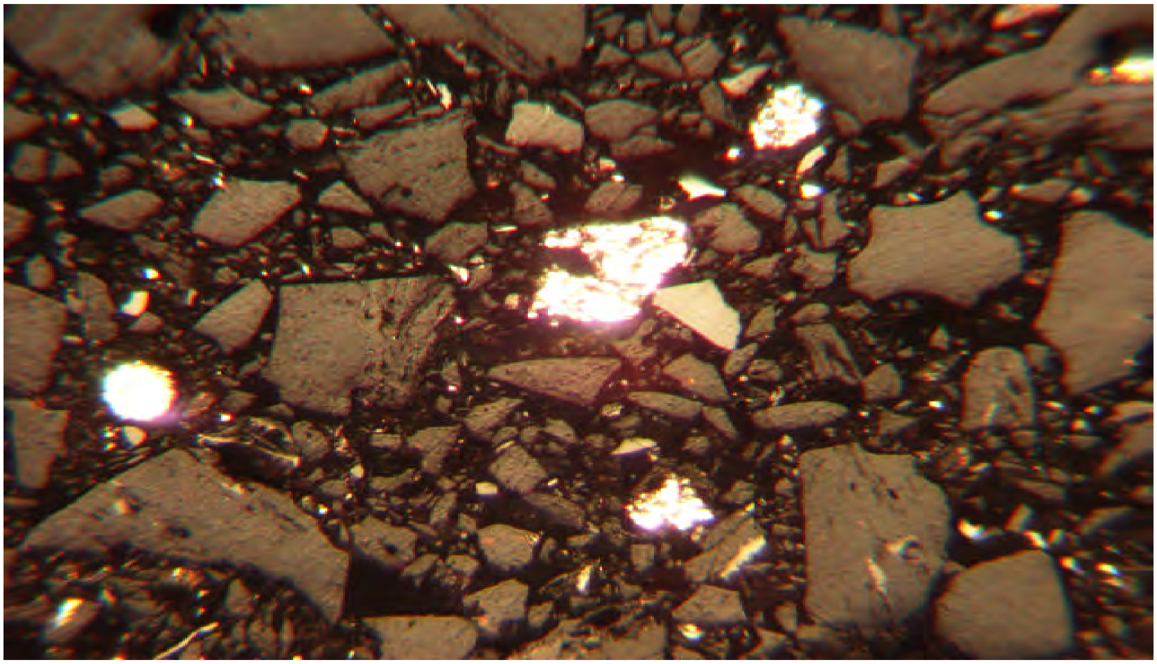


FIGURE 9 Microphotograph of the same Illinois #5 coal after processing through the Pulsewave machine. Note the degree of liberation of the pyrite from the organic phase in the processed material.

To illustrate the degree of clean liberation of the pyrite from the organic coal matrix in as illustrated by Figures 8 and 9 above, a sample of this processed Illinois #5 coal was separated into float (organics) and sink (pyrite) components in a Density Gradient Centrifuge (DGC). Microphotographs of the Pulsewave- liberated and DGC-separated pyrite are presented below.

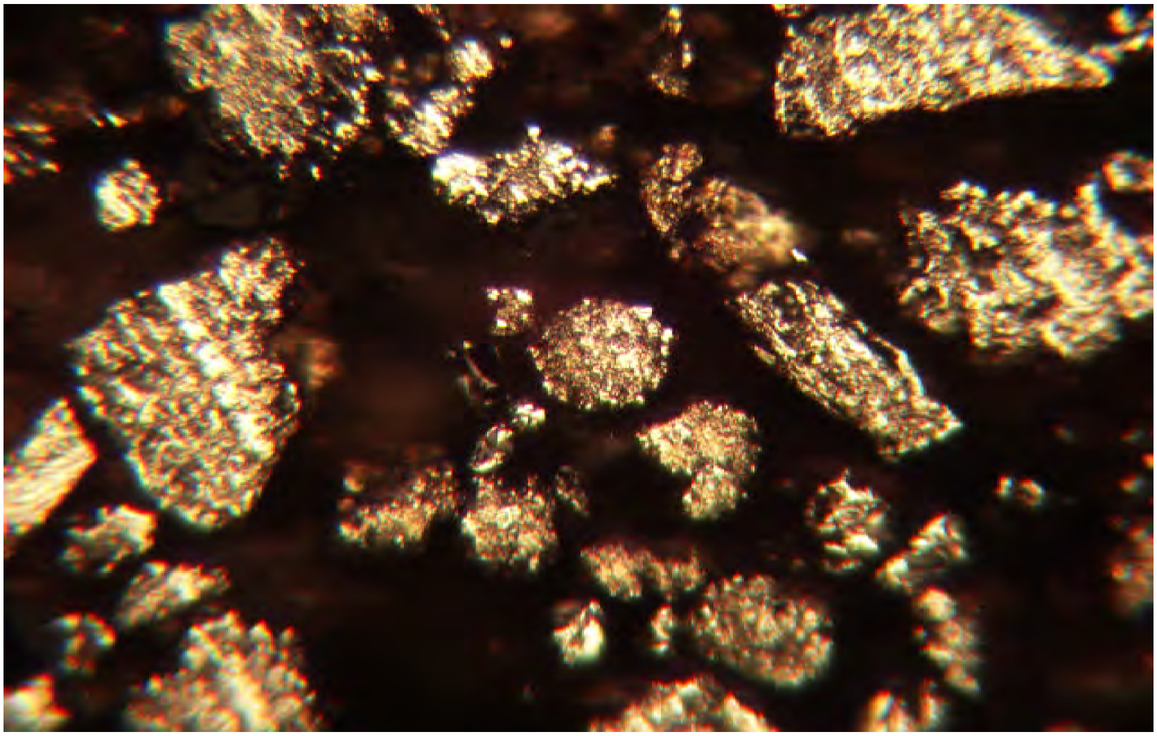


FIGURE 10 Microphotograph of Pulsewave-liberated and DGC-separated pyrite from the Illinois #5 coal. Note the lack of "smeared" coal on the faces of these particles.

This ability of the Pulsewave technology to liberate individual mineral components from a heterogeneous matrix has obvious implications in the mineral processing industry. Small discrete crystals or masses of certain economically important minerals could be cleanly liberated from their encasing host rock by the Pulsewave process and separated by readily-available separation technology. This would allow for the beneficiation of these mineral commodities without the use of chemical leaching, decreasing both the costs and environmental exposure associated with many mineral processing technologies.

SUMMARY

In summary, the specific benefits of the Pulsewave technology to the mineral processing industry include the ability to micronize certain single-phase mineral commodities to a very small particle size with a minimum expenditure of energy, and the ability to liberate certain discrete mineral commodities from a host rock matrix. We believe that the introduction of the Pulsewave technology to the mineral processing and beneficiation would be significant in terms of its potential economic benefit to companies involved in the exploitation of certain mineral commodities

Flotation of phosphate rock from North Carolina using Brazilian chemicals based on fatty acids

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ABSTRACT

Research has been conducted at the North Carolina State University Minerals Research Laboratory, in conjunction with Brazil's Center for Mineral Technology, to test a recently developed series of collectors for phosphate rock flotation on United States ore (Franca and others, 2002). The collectors, produced by *Hidroveg, Inc.*, a Brazilian Company, are marketed under the trade name *Hidrocol*.

The *Hidrocol* collectors, consisting of a biodegradable fatty acid produced by hydrogenation of vegetable oils, were originally manufactured for the Brazilian phosphate industry, which was facing challenges related to low P_2O_5 values, liberation, and environmental concerns. Because the collectors have several inherent advantages, among which include enhanced biodegradability, low residual oil content, and the potential to improve flotation performance, the collectors may benefit producers facing challenges related to ore grades, environmental concerns, production costs and water usage.

Initial bench testing at the MRL performed on North Carolina phosphate ore shows promise. Two of the collectors produced satisfactory results with single stage flotation *versus* the more common double flotation process utilized by most US producers. Overall, the best results on the North Carolina phosphate rock were obtained using *Hidrocol* and sodium silicate, producing enhanced selectivity between SiO_2 and P_2O_5. Results in the preliminary tests show P_2O_5 grades of 30-33% and recoveries ranging between 85-90%.

The *Hidrocol* series could lead to lower reagent consumption and operating costs, flotation circuit streamlining, and improved concentrate grades and recoveries while lessening the environmental impact of current practices.

Franca, S.C.A., Schlantz, John W., Lima, S.R.M., and Baldwin, Robert, 2006, Flotation of phosphate rock from North Carolina using Brazilian chemicals based on fatty acids, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Hidrocol is a biodegradable product manufactured by fatty acid hydrogenation in hydrogen cells. The chemical principle is based on improving the molecular structure by increasing the hydrogen chain lengths. This product is produced with combinations of fatty acids obtained from vegetable oils and, with specific catalysts, subjected to the hydrogenation.

Research using the *Hidrocol* collectors focused on increasing the efficiency of phosphate rock flotation, which was not satisfactory using traditional fatty acid based chemicals. It offers several advantages compared to other chemicals used in phosphate rock flotation, such as enhanced biodegradability and low residual oil content, both of which lessen environmental impacts while enhancing flotation performance.

Current ores have different characteristics from the first phosphate rocks studied for the development of flotation collectors. After several years of exploration at a particular mine, the raw ore became lower grade (P_2O_5 content) and presented liberation challenges, jeopardizing the productivity and quality of the phosphate concentrate.

Currently, HIDROVEG is the supplier to Fosfertil/Ultrafertil, the largest industrial group in Brazil producing phosphate rock, phosphoric acid and fertilizers, supplying 44.8% of Brazil's domestic market (Souza, 2004; Jasisnky, 2004).

OBJECTIVE

Because bench-scale flotation tests have traditionally been used for evaluating flotation reagents [4], a test series was designed to produce comparative data between the reagents in question, allowing HIDROVEG Chemicals to study the efficiency of *Hidrocol* in the NC phosphate rock flotation. Research objectives were defined as producing equivalent or better grades and recoveries while supplying cleaner chemicals that can increase production and product quality, and lessen the environmental impacts.

Major differences related to geological origin (Harben, 1996) exist between Brazilian and American phosphate rock. Brazilian phosphate rock was formed by volcanic action while American deposits are sedimentary, resulting in different grain size distributions and P_2O_5 content (Bartels and Gurr, 1994). These typological differences may require a chemical restructuring of the *Hidrocol* family of reagents to achieve optimum surface interaction given the rock characteristics.

MATERIAL AND TEST PROCEDURES

A phosphate rock sample, originating in North Carolina, was tested.

About the Concentration Process

Current processes produce concentrates with average P_2O_5 grades and recoveries of 27% and 90%, respectively. The phosphate rock is floated in two stages, consisting of rougher flotation with fuel oil and fatty acid reagents, followed by a scavenger step with amine and fuel oil for residual silica removal (Technical reports, 2002). A de-oiling step is included between the flotation steps, utilizing sulfuric acid to remove the fatty acid collector.

A challenge at this facility is water quality. Process water comes from rivers and rainwater reservoirs, plus recycled water, creating low pH values of approximately 5 to 6, which adversely affects the flotation process. The low pH requires the addition of soda to control the flotation pH, which must be maintained between 8 and 9. Consequently, the soda and other reagents necessary to obtain the flotation conditions will remain in the water after the flotation process and eventually return to the plant via the recycled water, further decreasing the water quality.

If the pH value is not maintained in the specified range, reagent consumption (both collectors and depressants) increase, thus increasing production costs. Wastewater from the plant is pumped to the dam and insufficient retention time is available in the ponds to reduce the impact of this water, rich in residual reagents, creating a strong interference to the surface phenomena required for good flotation.

Sampling

The test sample consists of flotation feed, acquired in January 2002, which was dried and split into 500 g representative samples for the bench testing, all of which were conducted in a Denver laboratory flotation cell. The chemical analysis of the feed used in the flotation tests is shown in Table 1.

TABLE 1 Assay for the Studied Sample (Flotation Feed).

compounds	(%)	compounds	(%)	compounds	(%)
Al_2O_3	0.43	MgO	0.42	SiO_2	50.3
CaO	25.4	MnO	0.01	TiO_2	0.18
Fe_2O_3	0.56	Na_2O	0.62	L.I.	5.79
K_2O	0.14	P_2O_5	16.7		

Reagents

Flotation tests were performed with HIDROVEG Chemicals' fatty acid collectors *Hidrocol* A and C, with degree of hydrogenation being the distinguishing difference. This characteristic of the collector customizes its effectiveness based on rock typology. The concentration used was 5% ($w.w^{-1}$) for both collectors.

Cornstarch and sodium silicate were employed as depressants in concentrations of 2 and 5% ($w.w^{-1}$), respectively. Cornstarch was selected as the primary for the test program as it has shown good depressing characteristics on Brazilian ores when used in conjunction with *Hidrocol* collectors.

Bench Flotation Tests

The bench flotation tests were run in a 4.5L Denver lab cell. General conditions in the flotation tests are presented in Table 2. These tests were run in January-September, 2002, at the North Carolina State University Minerals Research Laboratory (MRL/NCSU) in Asheville, NC, with follow-up tests conducted at CETEM's facilities in Rio de Janeiro, Brazil. All tests consisted of single stage flotation with rougher and cleaner steps (no 2nd stage amine flotation).

TABLE 2 Experimental Conditions in the Batch Flotation Tests.

Conditioning
Percent Solids – 70%
Retention time (pulp + depressant) – 4 min pH = 9.5
Retention time (pulp + depressant + collector) – 1 min pH = 9.5 - 10
Flotation
Percent solids – 20 - 25%
Rougher - pH = 9.5 – 10
Cleaner - pH = 8.0 – 8.5

RESULTS AND DISCUSSION

Test results and procedures on the different samples are presented in the following tables and figures. Batch flotation tests were completed using the two *Hidrocol* collectors (*A* and *C*) with cornstarch or sodium silicate as depressants. Results are presented in terms of grade and recovery of P_2O_5, SiO_2 and CaO.

TABLE 3 Laboratory Conditions for Batch Flotation Tests.

Experiments	Collector (mL)		Depressant (mL)		Comments
	A	C	Corn starch	Sodium silicate	
1	11.0	-	25	-	-
2	11.0	-	-	25	-
3	11.0	-	25	-	add attrition scrub
4	11.0	-	-	25	add attrition scrub
5	6.0	-	25	-	decrease Hid. A
8	-	11.0	25	-	-
9	-	11.0	-	25	-
10	-	11.0	-	-	no depressant
11	-	8.0	-	-	no depressant
12	12.5		-	25	increase Hid. A
13	14.0		-	25	increase Hid. A
14	11.0		-	30	increase sodium silicate

Tests employing collectors A and C showed significant improvements in flotation performance in both grade and recovery. Figures 1 and 2 show that tests 9, 10, and 11, using *Hidrocol* C produced the best results with grades over 30% P_2O_5 and plus 90% recoveries. Cornstarch was not effective on US ore as a silica depressant because of the typology of this phosphate rock.

Overall, the best results were obtained using *Hidrocol* and sodium silicate, producing enhanced selectivity between SiO_2 and P_2O_5. Sodium silicate is often used as a silica depressant by phosphate companies in United States. Data presented in Figures 3 and 4 confirms the efficiency of *Hidrocol* A and C in the phosphate rock flotation and the ability to attain satisfactory P_2O_5 grades and recoveries in the float products and tails. The best results were obtained with *Hidrocol* C.

The Table 4 contained reagents consumption and production costs data related related to the flotation of NC phosphate rock using *Hidrocol* chemicals.

TABLE 4 NC Phosphate rock beneficiation process: reagents consumption and production costs.

Grade (%)			Mass recovery (%)	P_2O_5 Recovery (%)	Reagents consumption (lb.ton feed^{-1})	Production costs (US$.ton feed^{-1})	Reagents consumption (lb.ton product^{-1})	Production costs (US$.ton product^{-1})
CaO	P_2O_5	SiO_2						
43.5	30.7	9.0	50	91.2	2.2	0.80	4.4	1.58

DISCUSSION AND CONCLUSIONS

Preliminary results obtained from US phosphate rock batch flotation tests using HIDROVEG collectors were satisfactory. *Hidrocol* A and C produced good P_2O_5 grades and recoveries. However, the process can be optimized and improved results anticipated through structural adjustments of the reagents (hydrogenation) to create a better match with the typology of each phosphate rock.

Two different silica depressants were used in the flotation tests, and results allow the conclusion that sodium silicate performed better than cornstarch, probably due to the rock typology.

Although *Hidrocol* A and C have different degrees of hydrogenation in the chemical structure, both produced very good and similar results in the flotation tests. However, results obtained in the flotation tests with *Hidrocol* C show better grades and recoveries.

It is important to emphasize that all results documented in this paper were obtained using a single flotation stage, with rougher and cleaner steps (no amine/silica float). In comparison to the industrial plants, the use of *Hidrocol* reagents shows a strong potential to improve the flotation circuits in terms of reagent additions and consumptions, plant equipment, operating costs, and environmental concerns.

RECOMMENDATIONS

Although the bench testing of the *Hidrocol* reagents was limited, the data generated indicates a true potential for improvement in the phosphate flotation circuits. Therefore, the following are strongly recommended to conclusively determine the full potential of the *Hidrocol* family of collectors on NC phosphate rock flotation.

1. Follow-up bench testing using current plant reagents to establish baseline parameters for direct comparison to the *Hidrocol* performance;
2. Follow-up bench testing to determine benefits of attrition scrubbing and its effects on reagent consumption, product quality, and recovery;

3. A preliminary economic evaluation once baselines are established to justify additional testing;
4. If economics warrant, pilot plant testing should be conducted to optimize all process parameters and supply data for projected plant performance and scale-up;
5. Final economic evaluation to determine if plant changes are warranted.

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Contribution of high resolution X-ray computed computer tomography to industrial minerals

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ABSTRACT

High resolution X-ray computed tomography (HRXCT) is the industrial equivalent of medical CAT scanning and provides a mechanism for non-destructive, in-situ studies of the distribution of minerals within rocks or synthetic products. HRXCT is a powerful extension of traditional petrographic analysis as it allows observations and measurements in three-dimensions of grain size, shape, and associations. HRXCT produces two-dimensional images ("slices") that reveal the interior of an object as if it had been sliced open along the image plane for viewing. A HRXCT image is generated by differences in X-ray absorption that arise principally from differences in density within the object. By acquiring a contiguous set of slices, a density map for all or part of a sample volume can be obtained, allowing three-dimensional inspection and measurement of features of interest. Because the HRXCT technique differentiates mineral grains largely based on their contrasting densities, these studies are particularly effective in the study of metallic mineral grains in contrast with typical rock-forming minerals, but it also is effective in differentiating minerals with limited density contrast.

The University of Texas at Austin HRXCT laboratory is a NSF-supported multi-user facility that has been used for the past decade to produce information for a wide variety of geological, biological, and material science problems. Descriptions of the facility, HRXCT principles, and examples of applications are available at http://www.ctlab.geo.utexas.edu/. The facility includes two subsystems that are used to image geological specimens across a range of sizes. The high-resolution subsystem uses a 420 kV X-ray source and a pair of linear array detectors to image samples from 5 to 50 cm in diameter, with slice thickness down to 0.25 mm. The ultra-high-resolution subsystem uses a 200 kV microfocal X-ray source with an image intensifier detector sampled by a 1024 X 1024 CCD video camera to image samples from 3 to 70 mm in diameter at slice thicknesses down to 10's or 1's of micrometers. Both UTCT X-ray sources are polychromatic, producing X-rays over a continuum of energies from about 30 keV up to their operating voltage, e.g. up to 420 keV for the 420 kV source.

While HRXCT studies at UTCT have not been directed specifically at industrial minerals problems to date, prior studies of rocks and industrial products provides relevant information on potential uses of these techniques. Examples include studies of metamorphic rocks with variable amounts of garnet, kyanite, and staurolite, as well as gold-bearing ores and industrial products such as asphalt. Scanning protocols and software have been developed to routinely extract quantitative measurements from volumetric data. Data sets totaling hundreds to thousands of measurements of the size and spatial distribution of mineral grains or clasts commonly result from these studies.

(continued)

These investigations suggest considerable potential for HRXCT studies to contribute to the understanding of mineralization systems and to practical applications such as mineral processing and product evaluation.

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Session Nine

Chromite from deposits in southwestern Oregon as a foundry sand

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ABSTRACT

Black sands along the southern Oregon Coast contain potentially valuable minerals such as chromite, zircon, garnet, ilmenite, gold, and platinum. These sands are found on modern beaches as well as beneath terraces ranging from 35 to 1500 feet in elevation. Some geologists believe the deposits found above present sea level are beach deposits associated with terraces that are assumed to be of marine origin. Others believe the deposits are not beach deposits related to the formation of the present raised terraces, but rather are deposits formed either during a period of land submergence or a period of rising sea level. Establishing the origin of the deposits - whether they formed along a beach, or during a period of submergence or sea level rise, or have some other origin - will influence future exploration, will help confirm known resources, and will influence the development of mining plans.

Historically, gold was produced from the placer deposits at Whiskey Run Beach beginning in the mid-1800s. Since that time there has been sporadic exploration and mining activity in the area. During World War II chromite concentrates were produced from the black sands and were purchased by the United States Government. Some zircon concentrates were made and used by the U.S. Bureau of Mines in metallurgical research. Also, some garnet-rich concentrates, suitable for water jet cutting, have been produced. In more recent years, interest has been sparked in producing chromite concentrates from these black sands for foundry applications.

A 10-ton per hour pilot spiral plant has been purchased and modified to make a chromite rich heavy-mineral concentrate from these black sands. A dry mill flowsheet consisting of high tension electrostatic separators, electrostatic plate separators, low intensity (400 gauss) rare earth magnets and 5,000 gauss rare earth drum magnets has been developed to produce a chromite product for use in foundry applications. This chromite product does not need to be crushed. The chromite grains are sub-rounded and therefore require the use of less binder. The grain structure allows the grains to pack tightly, reducing the opportunity for the molten metal to penetrate into the formed cores and molds. This packing also may allow for the elimination of refractory coatings. Heat transfer evaluations have shown that the increased grain-to-grain contact provides a higher heat transfer rate and chilling capacity. Core tensile strengths, scratch hardness determinations, core permeability, and core density tests performed on the Oregon chromites suggest this new chromite product will function as an additive to, or replacement for, the current specialty aggregates used in the metal casting industry.

Pirkle, Fredric L., Pirkle, William A., Stouffer, Norman W., Hoyt, Daryl F., and Pirkle David L., 2006 Chromite from deposits in southeastern Oregon as a foundry sand, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

The chromite mineral sand deposits discussed in this paper are often referred to as "black sands" because of their dark gray and brown to black colors (Hornor, 1918; Griggs, 1945). These deposits are part of a mineral sand province that extends a distance of about 50 miles from Cape Arago, Oregon, on the north to Port Orford, Oregon, on the south (Figure 1). These deposits lie in a series of raised terraces along the Oregon coastline. The terraces were named and defined by Griggs (1945). He states that terraces are found as high as 1,500 feet above sea level, but the lower terraces are better preserved. Griggs also states that most of the black-sand deposits occur in the terraces that are less than 400 feet above sea level. He named the lower terraces, going from lowest and presumably youngest to highest and presumably oldest, Whisky Run (25 to 125 feet above sea level), Pioneer (100 to 250 feet above sea level), and Seven Devils (275 to 375 feet above sea level). A fourth terrace is named the Metcalf (Adams, 1984) and a fifth terrace has been informally designated the Arago Peak terrace by McInelly and Kelsey (1990), (Figure 1). Timber company concessions, private land holdings, county controlled holdings, and some farming properties occupy the land.

MINING HISTORY

In addition to chromite, the black sands also contain zircon, garnet, ilmenite, gold, and platinum. Gold was discovered in 1852 and mining has occurred sporadically for many years. Semi-finished chromite concentrates as well as by-product concentrates of zircon, used by the U.S. Bureau of Mines in metallurgical research, and some garnet-rich concentrates, suitable for water jet cutting, have been produced from these black sand deposits (Ramp, 1973).

In 1943 the Krome Company of El Paso, Texas, and Humphreys Gold Corporation of Denver, Colorado, later known as Humphreys Mining Company, produced a total of 46,500 tons of semi-finished chromite concentrates from these deposits. The United States Government purchased these concentrates in support of the war effort (Ramp, 1973). The Krome Company erected a gravity concentration plant at the Seven Devils (Last Chance) mine (Figure 1). The plant contained Overstrom tables each capable of processing 4 tons per hour. The plant had a total capacity of 2,000 tons per day. The tables were considered the largest in the world measuring 8 feet x 30 feet (Huttl, 1943). Krome Corporation mined the property from February to December 1943. The Lagoons, a small lake that was filled with black sand tailings from sluice boxes being used to recover gold on Cut Creek, was also exploited (Figure 1). In the spring of 1943, Humphreys Gold Corporation built a gravity concentration plant capable of processing 1,000 long tons per day of chromite-bearing sands and mined The Lagoons under a contract with Metals Reserve Company. The sands were concentrated in a gravity device that had just been developed by I. B. Humphreys, one of the partners in Humphreys Gold Corporation. This device was a spiral consisting of three to five turns, down which a slurry was caused to flow. Under centrifugal action the light minerals were forced toward the outside lip of the spiral while the heavier minerals dragged the bottom and stayed in a path near the inside edge of the spiral, from which they were collected through conveniently spaced ports. The gangue minerals stayed near the outside lip of the spiral until they reached the bottom (Gillson, 1959). This gravity concentration plant was the first commercial spiral plant. The November issue of Engineering and Mining

Journal (Anonymous, 1943) reported that Krome Corporation was eliminating their tables and replacing them with 64 of the new Humphreys spirals. According to Humphreys and Hubbard (1945) this revamped flowsheet required less floor space than the original plant, needed less manpower, reduced the cost of power and repairs, and improved mineral recovery. In addition, the feed to the spirals did not need to be deslimed. The concentrating action of the spirals was not affected by a moderate amount of slimes.

A favorable turn in World War II and satisfactory negotiations for Turkish chrome allowed Metals Reserve Company to accumulate ample stockpiles of chemical chrome from abroad. Purchase contracts with Humphreys Gold Corporation and Krome Corporation were cancelled and mining at both sites ceased in December 1943. In seven months of operation, Humphreys Gold Corporation produced 42,842.6 long tons of chromite concentrate with a grade of 25.67 percent Cr_2O_3 (Humphreys and Hubbard, 1945).

GEOLOGY

A narrow strip of coastal plain exists along much of the southwestern Oregon coast approximately between latitudes 42° 20’ and 43° 00’. The coastal plain is up to four miles in width, and is bounded by the coastline on the west and the Coast Range and Klamath Mountains on the east. Except for areas near the mouths of rivers and a 14-mile stretch between Bandon and Port Orford, most of the coastal plain is composed of marine terraces (Figure 1).

General Geology

Griggs (1945) provides a general description of the geology of the southwestern coast of Oregon, including the terraces. He divides the mineral sand province into two sections. The first section extends from Coos Bay on the north southward to the Coquille River (Figure 1). It contains most of the known chromite mineral sand resource and is underlain primarily by Tertiary sandstones and shales. South of the Coquille River, the areas that contain potentially economic chromite mineral sand resources are underlain by rocks of greater age, including schists, sandstones, conglomerates, shales, partially altered periodotite and serpentine, and other intrusive and extrusive rocks mostly of basaltic composition (Griggs, 1945).

Pleistocene Terraces

Griggs (1945) did not assign formational names to the individual marine terraces. He treated the terraces as physiographic entities. Baldwin and Beaulieu (1973) provide a description of the Pleistocene terraces of the southwestern Oregon Coast. According to these workers the terraces form flat benches that can be recognized at various elevations along the southwestern Oregon coastline. Locally, recent alluvial fans or tree-covered dunes modify the topography (Baldwin and Beaulieu, 1973). Tectonic processes have affected the higher terraces that have elevations up to 1,500 feet and that may be late Pliocene in age. Tectonic processes have affected the lower terraces as well, but to a lesser extent (Baldwin, 1945; Baldwin and Beaulieu, 1973). According to Baldwin (1966) the Whisky Run Terrace is found at an elevation of 125 feet at Cape Arago. It is found at a lower elevation at Shore Acres and Sunset Bay and at approximately 25 to 30 feet above sea level at Fossil Point (Figure 1). Peterson *et al.* (1987) state that the Pioneer and Seven Devils terraces are cut into turbidite mudstones of Paleocene to Eocene age.

Beaulieu and Hughes (1975) state that terrace ages vary from 2 million years at the highest terrace to approximately 30,000 years along the seaward edge of Whisky Run Terrace. The 30,000-year age is based on radiocarbon dates. They believe a majority of the terraces are approximately 100,000 years old.

Peterson *et al.* (1987) report that a solitary coral from Whisky Run Terrace at Bandon has been Th/U age-dated at 72,000 ± 5,300 years. They report the age of Whisky Run Terrace, Pioneer Terrace, and Seven Devils Terrace as 83,000 years, 103,000 years, and 124,000 years respectively. Kelsey (1990) believes the terraces were formed during the 80,000, 105,000, and 125,000 high stands of sea level. The 80,000 and 105,000 ages of Kelsey are correlated ages and the 125,000 age is an inference based on the idea that a sea-level high stand occurred at this time.

Terrace Sediment Descriptions Sediment types include basal sands and gravels, compact horizontal layers of silt and fine-grained sand, river deposits of coarse sand and conglomerate, and a widespread mantling of unconsolidated medium-grained sand and fine-grained sand that is interpreted to be wind-blown sand (Beaulieu and Hughes, 1975). Most of the terrace deposits range in thickness from 10 to 50 feet. In some areas, however, the thickness may reach 100 feet or more. According to Hunter (1980), at some sites the Pleistocene coastal deposits can be divided into four stratigraphic units consisting of a basal gravelly unit plus three overlying sandy units. Each unit contains mud beds, a paleosol, or a modern soil in its uppermost part. The gravelly unit consists of gravel and sand in its lower part, sand, in part pebbly and cobbly, in its middle part, and mud and sand in its upper part. Black sand and transported pieces of wood are common in the middle part of the unit. Wood is common in the mud of the upper part (Hunter, 1980). Some of the sandy units appear aeolian in origin. Stream erosion and slumping disturb the terrace deposits (Peterson *et al*, 1987). River deposits located in the subsurface between the mouth of the Coquille River and Whisky Run reflect an ancestral Coquille River course (Baldwin and Beaulieu, 1973).

Mineral Suites The heavy-mineral resource is quite extensive and consists of an unconsolidated mixture of chromite, zircon, garnet, ilmenite, rutile, leucoxene, magnetite and other commercially valuable minerals such as staurolite and kyanite. Griggs (1945) reports that zircon constitutes 1 to 2 percent of most of the deposits. Buckovic and Associates, Inc. (1989) completed a review of known data and calculated a weighted average of 11.2 percent chromite for the known deposits. They also indicated that, even though actual zircon grades are not known for the deposits, their preliminary data suggests that zircon grades range between 0.2 and 2.6 percent. Readings (1991) analyzed a natural heavy-mineral concentrate from the Shepard deposit and reported 44.6 percent chromite/ilmenite, 2.2 percent zircon, 21.1 percent garnet, 0.4 percent rutile, 0.3 percent leucoxene, 5.4 percent quartz, and 26 percent other minerals. Based on the amount of chromite/ilmenite present, this sample seems to be high grade. Hines *et al.* (1993) reported the following mineral suite from a bulk sample collected from the South Seven Devils deposit: chromite 14.03 percent, garnet 3.91 percent, zircon 0.91 percent, other heavy minerals 23.86 percent, quartz 43.62 percent, and slimes 13.67 percent. As weight percent of the heavy mineral fraction, chromite is 32.85 percent, garnet is 9.15 percent, zircon is 2.13 percent, and other heavy minerals are 55.87 percent. Hines and Dawson

(1993) report results from drilling the South Seven Devils, North Seven Devils, and Shepard deposits. Table 1, modified from their report, illustrates the mineral suites of these deposits.

TABLE 1 Mineral Assessment of Areas Drilled, Assayed and Bulk Sampled

Deposit	% Chromite	% Garnet	% Zircon	% Hi - Ti	% Ilmenite	% Magnetite	% Kyanite & Staurolite.	% Others	% Over-size	% Slimes	% Quart
South Seven Devils	**15.30**	**4.40**	**1.20**	**0.36**	**2.53**	**1.50**	**5.80**	**11.10**	**8.00**	**14.00**	**35.81**
North Seven Devils	**15.20**	**2.50**	**1.00**	**1.26**	**1.75**	**1.50**	**7.80**	**12.30**	**8.00**	**9.00**	**39.69**
Shepard	**13.70**	**8.30**	**0.80**	**1.71**	**3.51**	**1.75**	**17.40**	**20.80**	**6.00**	**4.00**	**22.03**

RESOURCES

Buckovic and Associates (1989) reviewed the known data and confirmed an indicated resource of 7,318,000 short tons of mineralized sand with a weighted average grade of 11.2 percent chromite. Hines and McTavish (1991) reviewed data collected during a 1991 drilling program involving deposits referred to as South Seven Devils, North Seven Devils, Shepard, and Westbrook. Hines and Dawson (1993) made a more extensive review of available data. Table 2 is taken from Buckovic and Associates (1989), Hines and McTavish (1991), and from data provided by Hines and Dawson (1993).

TABLE 2 Summary of Resources

Deposit	Mineralized Sand (Short Tons)	Chromite Grade in %	Chromite (Short Tons)	Zircon Grade in %	Overburden (Short Tons)	Stripping Ratio	Area (Acres)
South Seven Devils[1]	848,000	11.0	93,280		95,400	0.11	17.1
South Seven Devils[2]	603,000	15.3	92,259	1.2	163,000	0.27	16.1
North Seven Devils[1]	1,623,399	11.7	189,938		1,992,000	1.23	30.3
North Seven Devils[2]	490,000	15.2	74,480	1.0	1,421,000	2.90	16.0
Sec. 33 Deposit[1]	1,726,145	8.3	143,252		1,270,800	0.74	53.7
Sec. 33 Deposit[3]	1,656,000	8.9	147,384				
Section 9 Deposit[1]	1,070,000	5.5 - 16			765,000	0.94	52
Shepard[1]	277,600	13.7	38,031		894,000	3.90	11.7
Shepard[2]	289,000	13.7	39,593	0.8	901,000	3.11	16.2
Shepard Extension[3]	1,867,000	7.6	141,892				
Sec. 4 Deposit/Westbrooke[1]	659,000	10.3	67,877		635,700	0.96	77
Westbrooke[2]	729,000	9.0	65,610	0.5	216,000	0.30	49.7
South Slough[3]	2,593,000	7.4	191,882				
Pioneer-Eagle[1]	800,000	13.8	110,400		3,918,000	4.9	29
Rose[1]	38,900	14.4	5,600		374,000	9.6	4.1
West Section 10[1]	32,580	10.8	3,519		91,400	2.8	3
Section 36 Deposit[1]	121,400	7.3	8,862		69,400	0.57	5.2
Butler[1]	121,480	15.7	19,072		140,000	1.77	4.8

[1] From Buckovic and Associates, 1989; [2] From Hines and McTavish, 1991; [3] From Hines and Dawson, 1993.

Deposit Location

The heavy-mineral sands province located along the coast of southwestern Oregon contains a number of individual heavy-mineral sand deposits. Figure 1 shows that the largest number of deposits thus far discovered is located within a 51 square mile area between Coos Bay and Port Orford (Buckovic and Associates, 1989). These deposits occur on at least three different terraces. Seven Devils Terrace hosts seven deposits, Pioneer Terrace hosts 3 deposits, and Whisky Run Terrace contains two deposits. The deposits on Seven Devils Terrace include the South Seven Devils deposit, the North Seven Devils deposit, the Section 33 deposit that also is referred to as the Westbrook deposit, the Section 4 deposit, the Section 9 deposit, the West Section 10 deposit, and the West Bohemia deposit.

MINING AND MINERAL PROCESSING

Mining

The Oregon chromite orebodies lie south of Coos Bay on land that currently is involved in sylvaculture production. Mining will interrupt the tree planting cycle in any given area for approximately 2 years, allowing time for the tree harvest, ore extraction, tailings return, and site reclamation, so that tree planting can resume.

Current planning calls for mining 400,000 tons per year of the chromite-bearing ore. After removal of topsoil and overburden, the exposed ore will be excavated dry with backhoe and shovel, and then loaded onto trucks for transport to the wet mill for further processing. The tailings and clays, separated from the raw ore by the wet mill processing, will be returned to the mining area for placement in their approximate original locations. The overburden will then be put back over the tailings, and graded to mimic the pre-mining contours of the land (Figure 2). Restoring the topsoil and revegetation will reclaim the land for continued productive use.

Wet Mill Processing (Gravity Separations)

The wet mill is the initial processing stage. For the Oregon chromite ore, the 60-ton per hour wet processing stage will include:

1. A hopper and belt system to feed the raw ore into the process at a near-constant rate;
2. A vibrating screen to reject material over one quarter inch in size from the raw feed;
3. A hammer mill to liberate the individual mineral grains from the plus quarter inch agglomerates in the screen oversize, prior to recycling back to the screen;
4. A head feed sump to slurry the screen undersize material and pump it to the cyclones;
5. Cyclones to remove minus 45 micron slimes ahead of the gravity processing; and
6. Several stages of spirals that use gravity to concentrate the valuable heavy minerals while rejecting quartz and many of the lighter gangue heavy minerals.

The wet mill process described above represents the composite knowledge gathered from the processing of this ore during World War II, updated with several recent and extensive processing studies. These later studies include Readings (1991), Hines *et al.* (1993), and Domenico *et al.* (2005). The inescapable conclusion of this prior work is that the Oregon Chromite ore can be readily concentrated using the conventional mineral dressing technologies described above. Current estimates for percent recovery of chromite in the wet processing are in the low 90's.

This spring, a small 10-ton per hour pilot wet plant will begin operation in Coos Bay. This plant will gravity concentrate test quantities of the Oregon ore for the dual purposes of generating concentrates from which market quantities of mineral products can be made, and to finalize the wet process prior to construction of a full-size mill.

Dry Mill Processing (Mineral Separations)

The dry mill is where final mineral products are separated from the wet mill concentrate (Figure 2). A dry mill feed rate of 18 tons per hour is planned, with chromite and garnet as the primary products. Expected annual production is 40,000 tons of chromite, and 9,000 tons of garnet. All minerals not included in the final products become the dry mill tails, which are the composite of the rejected gangue minerals and those desirable minerals not recovered to their appropriate product (yield loss). For the present, dry mill tailings will be stockpiled in Coos Bay pending the results of the work described below.

As is the case with the wet processing, there is the same abundant previous work on designing a process for the dry mill. From these prior studies the dry mill process can be conceptualized. The dry mill process will follow a general template of acid attrition scrubbing, followed by drying to an elevated temperature, separation of conductors from non-conductors by roll high tension, and then magnetic gradation of both the conductor and non-conductor fractions.

Further work to finalize the dry mill process is scheduled for 2006. This work will examine the potential for additional mineral products, as well as complete the details on the chromite and garnet circuits. In the case of the pilot plant concentrates, these will be contract processed to make market quantities of chromite and garnet products.

OREGON CHROMITE AS A FOUNDRY SAND

The initial focus has been on the chromite portion of the deposit for use in the metal casting industry. The foundry industry has been using chromite for many years as a specialty sand to produce high quality castings poured with various high temperature alloys of steel. Currently all the chromite used in the U.S. metal casting industry is supplied from South Africa.

The chromite sand from the Oregon mineral sands deposit is significantly different from that supplied by the South African producers. The grain structure of the South African chromite has a rhombohedral grain shape, formed when the mineral is crushed during the mining operation. The Oregon chromite does not require crushing and has an American Foundrymens Society Grain Fineness Number (AFS GFN) of 80 to 85, which is finer than the South African chromite with its AFS GFN of 50.

The grain structure of the Oregon chromite is sub-rounded, with a smooth and highly polished surface, allowing the foundryman to use less binder to achieve the desired core and mold handling properties. The rounded grain structure allows the grains to pack more tightly, reducing the opportunity for the molten metal to penetrate into the formed cores and molds, even at high ferrostatic pressures. This packing characteristic may also allow the foundryman to reduce or eliminate the need for refractory coatings. The increased grain-to-grain contact of the Oregon sand has shown a higher potential for the extraction of the metal's temperature, affording a higher heat transfer rate and chilling capacity, than the other chromites or specialty sands (Hoyt, 2006).

To provide a credible comparison between the aggregates currently used in the metal casting industry, Oregon Resources Corporation funded an extensive study comparing the core and casting properties of five sands – the two current chromite sands from South Africa, an Australian zircon sand, a ceramic sand, and a silica sand – with the core and casting properties of the Oregon chromite sand. These comparisons include complete chemical analyses of the base aggregates, their particle size distribution, AFS GFN, pH, ADV (acid demand value) base permeability, surface area, coefficient of angularity, bulk density, pyrometric cone equivalent values as well as photomicrographs of the individual size fractions for all of the aggregates evaluated (Hoyt, 2006).

Comparisons of core tensile strengths, scratch hardness determinations, core permeability, core density and other core sand analyses were performed. Test castings were poured at 2900ºF/1593ºC using ASTM A216 WCB steel. The steel's nominal composition was 0.28 percent C, 0.55 percent Si and 0.80 percent Mn. Gertsman and Step Cone test castings were poured to evaluate the sand's resistance to metal penetration, potential for expansion related defects, and the casting's surface finish. In addition to the comparison between the six aggregates, blends of the Oregon chromite sand with the two South African chromite sands, the Australian zircon sand and the ceramic sand were investigated. In every case where the Oregon chromite was blended at a 75 percent test aggregate to 25 percent Oregon chromite ratio, the core and casting properties were improved. Although the ratios of addition in this study only included 25 percent of the Oregon product, the test results indicate the product can function at any level of addition or as a stand alone refractory. Due to the narrow particle size distribution of the Oregon chromite, mathematical blends at 10 percent increments indicate that blending the Oregon chromite sand at any ratio with any of the five other specialty sands investigated will not produce a bimodal or double peak sand distribution (Hoyt, 2006).

Comparisons of the average tensile strengths for the phenolic urethane nobake and phenolic urethane coldbox binder systems were evaluated (Hoyt, 2006). Table 3 and Figure 3 provide a comparison of average tensile strengths for the phenolic urethane coldbox binder system.

TABLE 3 Comparisons of the Average Core Tensile Strengths 24 Hours After Stripping from the Pattern. One Percent Binder Addition, Based on the Sand's Weight, 55:45 Ratio of Part #1 to Part #2

Sand Type and Source	Tensile (psi)	Rank #	Scratch (index)	Rank #
Oregon Chromite "O"	311	3	74	4
South African Chromite "A"	229	5	79	3
South African Chromite "B"	138	8	74	4
Australian Zircon "Z"	330	2	81	2
Ceramic Sand "C" (1.7%)	173	7	70	7
Silica Sand "S"	183	6	62	9
75% "A"/25% "O"	251	4	87	1
75% "C"/25% "O" (1.4%)	136	9	67	8
75% "Z"/25% "O"	351	1	74	4

The test castings were evaluated on the basis of metal penetration and casting finish. The rating system to determine the level of penetration used the following scale: "0" No Penetration; "1" Slight Penetration; "2" Moderate Penetration; "3" Severe Penetration; "5" Fused Metal.

The core sections in the Step Cone casting ranged from a 4" diameter to a 1" diameter in ½" increments, with the lowest sand to metal ratio (1" core section) at the bottom of the test casting. The cores were placed in a mold cavity, with a 5" cross section, providing each core section with a different sand to metal ratio. The 1" diameter bottom ring of the core was surrounded by a 2" metal section. Each level of the Step Cone casting was evaluated for penetration and multiplied by a factor, based on the thermal input into the core section, with the 1" core section receiving the highest factor. The product of these calculations resulted in the determination of an overall "P" index (penetration value index), and ranking. Each section of the same Step Cone casting was evaluated for surface finish by comparing the casting's surface finish with a standard "Casting Surface Comparator" and assigning a "V" index (casting finish rating value).

The products of the "P" and "V" ratings were summarized to provide the overall ranking for the casting quality produced with the various aggregates, and are summarized in Table 4. All of the Step Cone cores were made with a 1.0% coldbox binder addition.

TABLE 4 Ranking of Casting Quality of Aggregates Investigated

Sand Type and Source	"P" Rating	Rank #	"V" Rating	Rank	Overall Rank #
Oregon Chromite "O"	5.5	2	840	3	2
South African Chromite "A"	11	6	1065	4	6
South African Chromite "B"	8	4	1080	5	5
Australian Zircon "Z"	20	8	1662.5	7	7
Ceramic Sand "C"	9.5	5	657.5	2	3
Silica Sand "S"	17.5	7	1722.5	8	7
75% "A"/25% "O"	5.5	2	1345	6	4
75% "Z"/25% "O"	4.5	1	645	1	1

The data shown above illustrate that the Oregon chromite product will function well as an additive to, or replacement for, the current specialty aggregates used in the metal casting industry.

EXPLORATION POTENTIAL

In order to develop exploration models for heavy-mineral sand deposits, the geologist needs to determine the source of the minerals of interest (a provenance), a means of transporting the mineral from its provenance to a site of deposition, a place for the minerals to be deposited and to accumulate (a host), a means of concentrating the minerals of interest, and a means of preserving the mineral concentration. Often there are multiple cycles of erosion, deposition, and concentration before a final deposit is created.

Provenance and Transportation

In an attempt to determine the provenance of the black sands from Seven Devils Terrace, Pioneer Terrace, Whisky Run Terrace and modern Sacci Beach, Peterson *et al.* (1987) collected samples of the opaque minerals found in the rivers and streams along the coastline. Based on microprobe analyses of opaque minerals they determined that the two older terraces (Seven Devils and Pioneer) differed from Whisky Run Terrace and the modern Sacci Beach. The microprobe analyses showed that the opaque minerals found on the two older terraces resemble those in the Coquille, Sixes, and Elk rivers (local streams/rivers between Cape Blanco and Cape Arago shown on Figure 1). The opaque minerals from Whisky Run Terrace and Sacci Beach were found to resemble those found in more distant rivers such as the Rogue, Chetco, and Smith rivers. Ramp (1973) also believed the black sands of the Seven Devils and Pioneer terraces are derived from sediments of nearby rivers and creeks (intermediate sources), which drain into the ocean. The sediments are then reworked by the waves. The principal source stream according to Ramp (1973) is the Coquille River with less important sources of black sands from the Coos River, Twomile Creek, Fourmile Creek, Floras Creek, and the Sixes River (Figure 1).

The concept of local rivers supplying the sands found on the two older terraces does not agree completely with Clemens and Komar (1988). Clemens and Komar (1988) used factor analysis to conclude that the sands found on the terraces of the Oregon coast are composites from four source areas identified as the Columbia River, Coast Range rivers, the Umpqua River, and rivers draining the Klamath Mountains. At times of lower sea level, the sands were able to migrate freely to the north and south along the coast.

Griggs (1945) concluded that the ultimate source of the chromite in the black sands is the serpentinized ultramafic rock in the Coast Range and Klamath Mountains. Tertiary sedimentary rocks in the area served as intermediate sources for the chromite, especially for deposits located at the northern end of the province. According to Griggs, chromite in the deposits that are located in the southern portion of the province where Tertiary sediments are absent has been derived either directly from peridotite and serpentine bodies or from higher terraces.

Host and Concentration Mechanism

Twenhofel (1943) believed the chromite rich mineral sands were deposited in embayments where longshore currents and the energy of the incoming waves were sufficient to transport the black sands from offshore during subsidence of the coastline or a rise in sea level. These heavy-mineral sands were concentrated by means of selective sorting by the outgoing currents, which were less powerful than the incoming waves. These outgoing currents removed the lighter and finer materials.

Griggs (1945) divided the black sand deposits into two categories: (1) those formed on beaches that are found next to old sea cliffs; and (2) those formed offshore. The concentrating mechanisms were winds, waves, and currents. The "deposits of sufficient size and grade to be noteworthy appear to have formed by sizing and concentration effected by several cycles of erosion." (Griggs, 1945, p.122).

Ramp (1973) contended that fluctuations of sea level during the Pleistocene resulted in the formation of several wave-cut terraces. He believed gradual uplift of the region coupled with a number of sea-level still stands allowed erosion by small coastal streams to re-work portions of the mineral sands deposits located on higher terraces. Therefore, as sea level fell the succeeding lower terraces were enriched in the more resistant minerals such as chromite, zircon, and garnet. The winnowing action of the waves concentrated the heavy-mineral deposits in thin tapering layers or stringers mainly along the back beaches.

Peterson *et al*. (1987) thought the mineral sand deposits were formed and preserved during periods of marine transgression and high sea-level stand coupled with beach-face progradation. The younger terraces contain smaller accumulations of placers than do the older terraces. Peterson *et al.*, therefore, did not believe that reworking and concentrating pre-existing sea cliff or river mouth deposits of placer minerals was a controlling factor in the development of the terrace placers in the Cape Arago area. According to these workers, heavy minerals were transported northward and landward during successive marine transgressions, and were selectively sorted from lighter minerals during deposition in high-energy swash-zone and surf-zone environments. Peterson *et al.* (1987, p. 227) state, "Placer sand reaches twice the concentration, but only half the thickness, in progradational beach deposits relative to transgressive nearshore deposits in the Cape Arago terraces." Peterson *et al.* (1987) interpret the Seven Devils Terrace deposit (Figure 1; Table 1) to be part of a nearshore and inner shelf transgressive sequence. They believe the Eagle-Pioneer depositional sequence, located on the Pioneer Terrace (Figure 1; Table 1), represents a progradational beach sequence formed during a high sea-level stand.

In a transgressive sequence the maximum placer sand thickness is controlled in part by the platform gradient, with steepening gradients resulting in increased placer deposit thickness (Peterson *et al.*, 1987). The range of tidal elevation limits the thickness of beach placer deposits. Beach placer deposits thicken to the extent of the height of the fair-weather tidal range when there is onshore sand transport. Therefore, the thickness of beach placers formed by the selective removal of light minerals cannot exceed the maximum thickness of the beach sand produced under fair weather conditions (Peterson *et al.*, 1986).

Preservation

All of the deposits are preserved by a drop in sea level or tectonic uplift of the coast. Other factors also play a role in preserving each deposit. The thickness of the preserved sediments at the Seven Devils placer varies greatly, ranging from being a complete section to the more general 1 to 5 meters. The Seven Devils Terrace has neither the seaward nor landward margin preserved, while the margins of the Pioneer Terrace have been preserved. The eastern margin of Seven Devils Terrace terminates abruptly at a fault contact with Tertiary mudstones, while the western margin has been eroded by subsequent transgressions (Peterson *et al.*, 1987). These workers claim the western boundary of the Pioneer Terrace is poorly defined, but shows no evidence of erosion by subsequent transgressions.

Post deposition stream erosion has destroyed parts of some deposits. For example, the North Seven Devils deposit and the South Seven Devils deposit probably once were a single deposit that subsequently was separated by post-depositional stream erosion. Hines and McTavish (1991) state that the North Seven Devils deposit lies on a series of parallel plateaus separated by steep gullies. In this deposit, stream erosion has dissected the original deposit. Stream erosion has also played a significant role in the present configuration of placer deposits on the Pioneer Terrace. The Shepard Deposit is an excellent example that shows stream erosion modification of a deposit's geometry. Evaluation of the deposits on the terraces within the study area must take into account the effects of stream erosion.

Exploration Model(s)

Over time several hypotheses concerning the origin of the mineral sand deposits of southwestern Oregon have been advanced. Early investigators believed the Pioneer placers formed as onshore (beach) deposits, and the Seven Devils placers formed as offshore (shelf) deposits. Twenhofel (1943) believed deposits on the Pioneer Terrace formed along embayed shorelines, while Griggs (1945) suggested the deposits on Seven Devils Terrace formed in isolated sea-floor depressions. Peterson *et al.* (1987) thought the major concentrations of heavy minerals in the mineral sand deposits along the Oregon coast were found south of prominent headlands. They have shown that heavy minerals and drift logs are concentrated in zones where longshore currents decelerate (Peterson *et al.*, 1987), and along the southwest Oregon coast this deceleration generally occurs south of prominent headlands.

Ehlen (1969) reports the terrace sediments range from fine silt to sand and cobbles in a fine silt and sand matrix. Hunter (1980) reports the terrace deposits located near Gold Beach consists of a gravelly basal unit and three overlying sandy units. He further states that each unit contains mud beds, a paleosol, or a modern soil in its uppermost part. The lower part of the gravelly unit is described as consisting of gravel and sand, the middle part of the unit is composed of sand, pebbles, and cobbles, and the upper portion of the gravelly unit is comprised of mud and sand. The middle portion of this gravelly unit also contains "black sand" and transported pieces of wood. Wood is also common in the mud found in the upper portion of the unit (Hunter, 1980). Sonic drilling of the deposits in Seven Devils Terrace shows that up to 35 percent minus 45 micron material is associated with the heavy minerals. This depositional pattern is not typical beach type sedimentation.

From the descriptions of the mineral sands deposits provided in the literature (Hornor, 1918; Griggs, 1945; Ehlen, 1969; Baldwin and Beaulieu, 1973; Beaulieu and Hughes, 1975; Hunter, 1980; Peterson *et al.*, 1987), it seems prudent to consider the possibility that the mineral sands deposits located along the southwestern Oregon coast may be associated with a delta or a series of deltas rather than being strictly beach or offshore deposits. These deposits may have an origin similar to the heavy-mineral deposits currently being exploited in the coastal plain of southeastern Virginia by Iluka Resources, Inc. In this type of model one is not simply looking for deposits located south of headlands; rather, one is looking for slight variations in geomorphology, in stream patterns, or in magnetic intensities that might signal a slight basement high. A basement high might be sufficient to disrupt a stream current enough to cause sedimentation and might allow for the concentration of heavy minerals in a manner similar to that of a headland. This particular model might result in more of the terrace area having potential for containing significant chromite resources.

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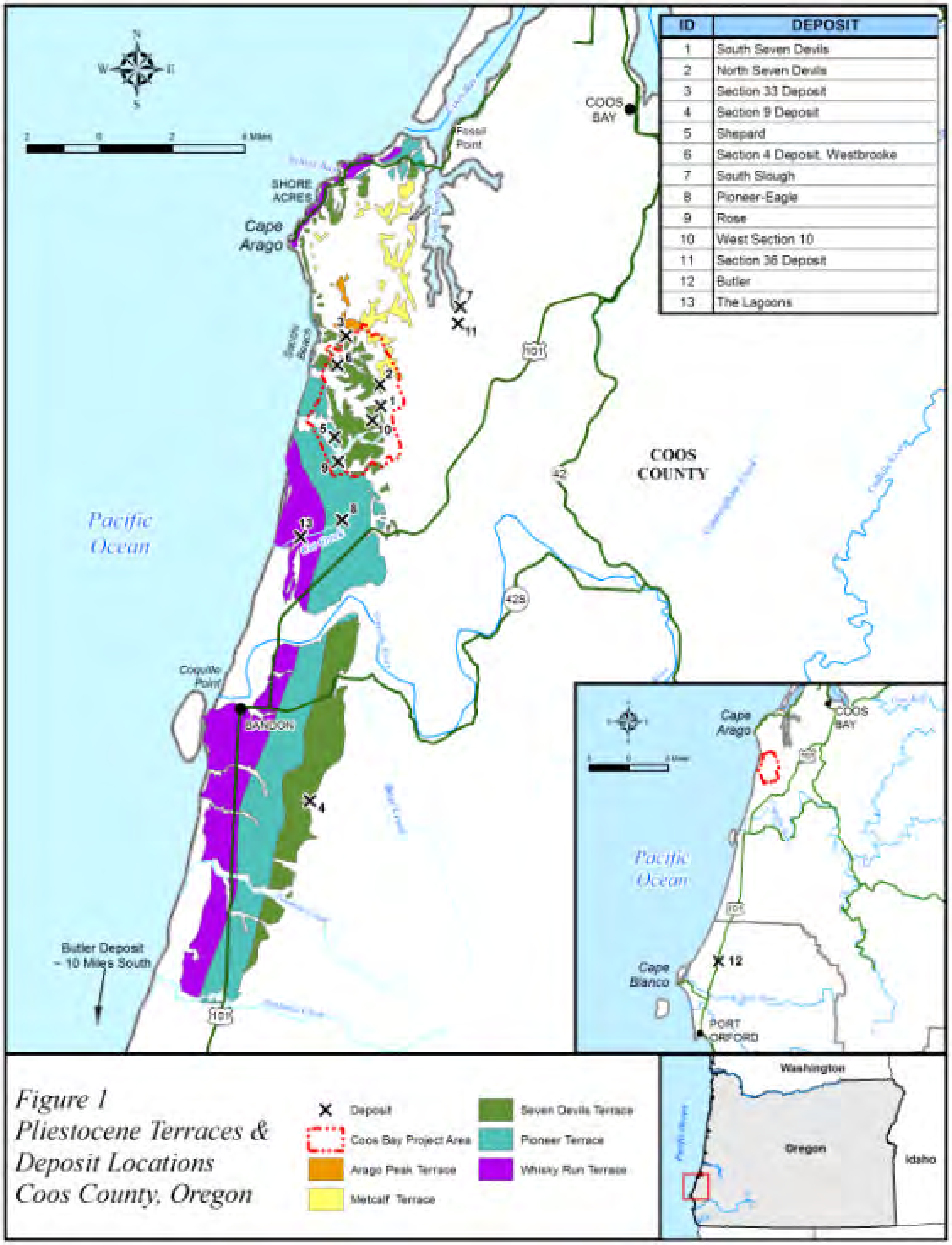

ID	DEPOSIT
1	South Seven Devils
2	North Seven Devils
3	Section 33 Deposit
4	Section 9 Deposit
5	Shepard
6	Section 4 Deposit, Westbrooke
7	South Slough
8	Pioneer-Eagle
9	Rose
10	West Section 10
11	Section 36 Deposit
12	Butler
13	The Lagoons

FIGURE 1 Location map showing physiographic features and the sites of heavy-mineral concentrations located in southwestern Oregon. Modified from Griggs, 1945 and McInelly and Kelsey, 1990.

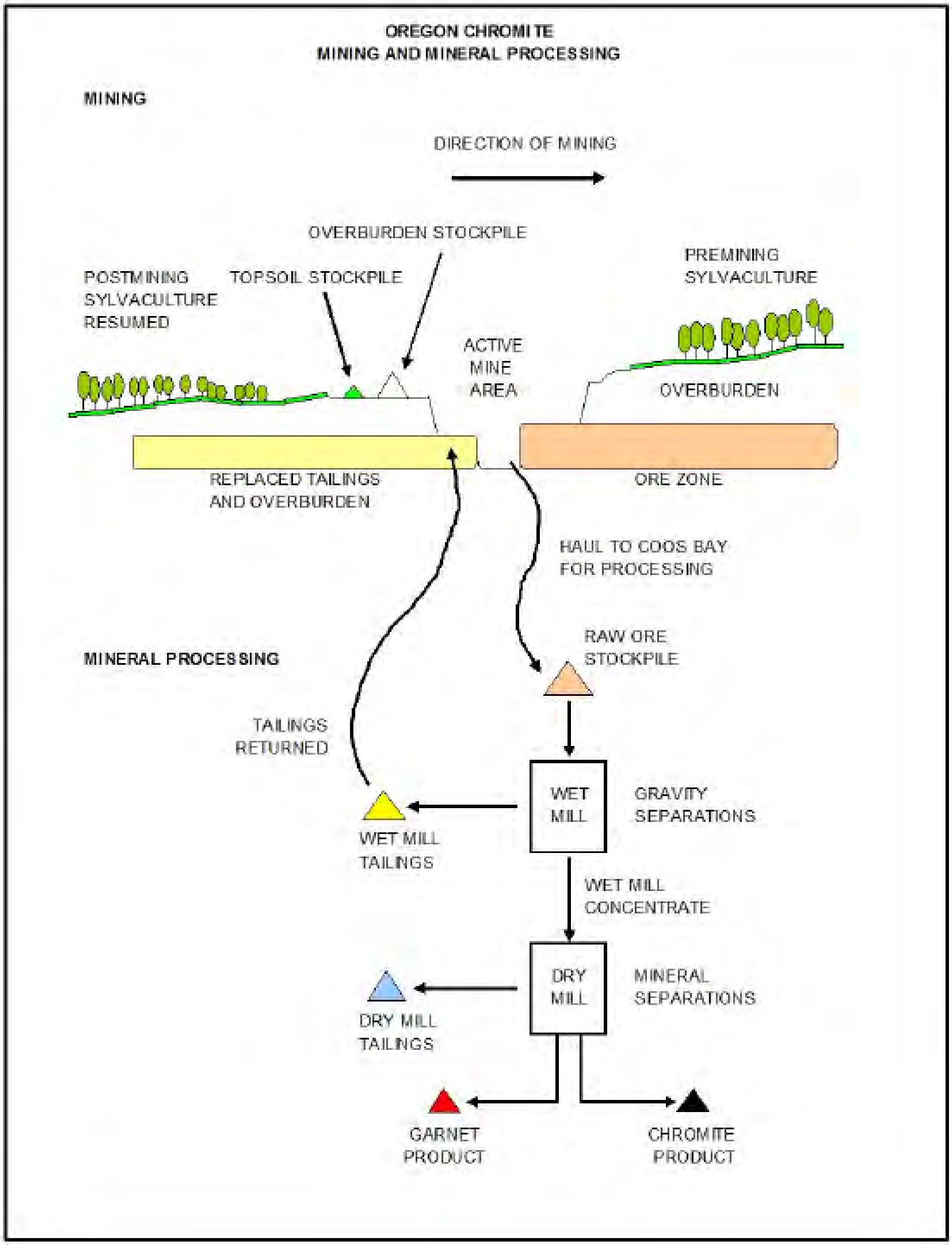

FIGURE 2 Typical heavy-mineral mining sequence.

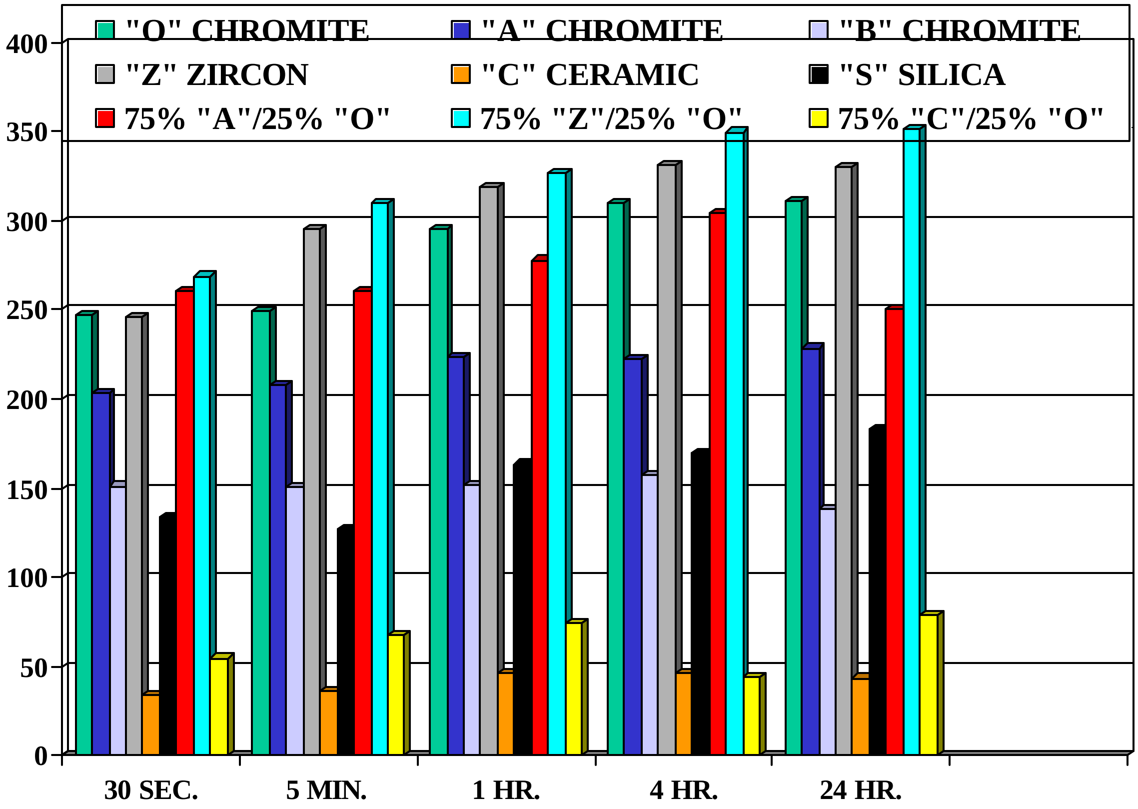

FIGURE 3 A comparison of core tensile strengths for 1% coldbox binder systems at a 4-minute cycle. From Hoyt, 2006.

Using the geology of asbestos deposits to predict the presence or absence of asbestos in mining and natural environments

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ABSTRACT

In the last several years, "naturally occurring asbestos" (NOA) has drawn the interest and study of many health and regulatory agencies, as well as the attention of a number of citizen groups. Asbestos has not been mined as a primary commodity in the United States since the last asbestos mine (a chrysotile mine) closed in California in 2002. Recently, there has been a renewed focus upon the potential for airborne releases of NOA caused by: (1) the disturbance of asbestos-bearing bedrocks through man's activities or natural weathering, and (2) the mining and milling of some mineral deposits in which asbestos occurs as an accessory mineral(s). Whether assessing an undisturbed natural setting or an excavation site, the geology of known asbestos deposits should be considered when developing plans to evaluate, monitor, regulate, and remediate asbestos exposures. Because asbestos forms in specific rock types and geologic conditions, this geologic information can be used to focus on areas with the potential to contain asbestos, rather than devoting effort to areas with minimal NOA potential.

All asbestos minerals contain magnesium, silica, and water as essential constituents, and some also contain iron and (or) calcium as major constituents. Predictably, the geologic environments that host asbestos are enriched in these components. Most asbestos deposits form by the metasomatic replacement of magnesium-rich rocks. The local asbestos-forming environments typically display shear and evidence for significant influx of hydrothermal silica-rich fluids. The asbestos-forming processes can be driven by regional metamorphism, contact metamorphism, or magmatic hydrothermal systems. Thus, asbestos deposits, from commercial-grade ore bodies to thin veinlets, are typically hosted by magnesium-rich rocks (often also iron-rich) that have been metasomatized by a metamorphic or magmatic process. Rock types known to locally host asbestos include serpentinites, altered ultramafic and some mafic rocks, dolomitic marbles and metamorphosed dolostones, metamorphosed iron formations, and alkalic intrusions and carbonatites. Other rock types appear unlikely to contain asbestos. Hence these geologic insights can be used by the mining industry, regulators, land managers, and others to focus attention on the critical locales that seem most likely to contain asbestos.

Van Gosen, Bradley S., 2006, Using the geology of asbestos deposits to predict the presence or absence of asbestos in mining and natural environments, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

ASBESTOS

"Asbestos" is not a mineralogical term, but rather a commercial and industrial term used to describe a group of specific silicate minerals that form bundles of long, very thin mineral fibers. When crushed or handled, asbestos bundles readily disaggregate and release microscopic mineral fibers. Asbestos fibers are typically less than a micrometer in diameter and range from several micrometers to hundreds of micrometers in length. The many different ways that asbestos and related terms have been described are summarized in Lowers and Meeker (2002).

The history of asbestos discovery and usage extends back at least 5,000 years (see Ross and Nolan, 2003). Commercial-grade asbestos is composed of long, thin, durable mineral fibers and fiber bundles that exhibit high tensile strength, flexibility, and resistance to heat, chemicals, and electricity (Ross, 1981; Zoltai, 1981; Cossette, 1984; Ross and others, 1984; Skinner and others, 1988). These properties, especially its exceptional insulation and fire-resistance abilities, have made asbestos widely used in a number of products and industrial applications in the past and present (see Virta and Mann, 1994; Ross and Virta, 2001).

Asbestos is most commonly defined as the *asbestiform* variety of several specific, naturally occurring, hydrated silicate minerals. Asbestos typically includes chrysotile, the asbestiform member of the serpentine group, and several members of the amphibole mineral group, including, but not limited to, the asbestiform varieties of (1) riebeckite (commercially called crocidolite), (2) cummingtonite-grunerite (commercially called amosite), (3) anthophyllite (anthophyllite asbestos), (4) actinolite (actinolite asbestos), and (5) tremolite (tremolite asbestos) (Table 1). Several other amphiboles are known to occur in the fibrous habit (Skinner and others, 1988), and some in the asbestiform habit, such as winchite, richterite (Meeker and others, 2003), and fluoro-edenite (Gianfagna and Oberti, 2001; Gianfagna and others, 2003), which have been linked to respiratory disease clusters. However, these more rigorous academic definitions for amphiboles (Table 2) have generally not been applied in regulatory language.

Historically, chrysotile has accounted for more than 90 percent of the world's asbestos production, and it presently accounts for over 99 percent of the world production (Ross and Virta, 2001; Virta, 2002). Mining of crocidolite (asbestiform riebeckite) in South Africa, Western Australia, and Bolivia, and mining of amosite (asbestiform cummingtonite-grunerite) deposits in South Africa account for most of the other asbestos production (Ross and Virta, 2001); all of these asbestos mines are now inactive. Relatively small amounts of anthophyllite asbestos were once mined in Finland (Ross and Virta, 2001). Anthophyllite asbestos was mined in North Carolina until 1979. Very small amounts of actinolite asbestos, anthophyllite asbestos, and tremolite asbestos still may be mined in some countries, such as India, but details on these operations are not available. Asbestos is no longer mined as a primary commodity in the U.S., since the last U.S. asbestos mine (a chrysotile mine) closed in California in 2002.

Asbestos as a Health Hazard

Inhalation of airborne asbestos has been linked to a number of serious respiratory diseases and health problems. Diseases such as asbestosis (scarring of the lungs), lung cancer, and malignant mesothelioma have affected many workers in certain asbestos-related occupations (Skinner and others, 1988; Mossman and others, 1990; Guthrie and

Mossman, 1993; Nolan and others, 2001; Plumlee and Ziegler, 2003; Roggli and others, 2004; Tweedale and McCulloch, 2004; Dodson and Hammar, 2006). As a result, during the latter decades of the 20th century, regulatory agencies in the U.S. and numerous other countries began to define asbestos and set limits for asbestos exposures, such as those that mine, process, manufacture, and handle asbestos-bearing materials, and also to a limited extent in environmental occurrences (Occupational Safety and Health Administration, 1992; Perkins and Harvey, 1993). Asbestos information is available online at http://www.epa.gov/asbestos/ and http://www.atsdr.cdc.gov/asbestos/index.html

The fibrous variety of erionite, a member of the zeolite mineral group, is another asbestiform mineral that has been linked to serious respiratory disease and mortality. Fibrous erionite is not regulated as asbestos, but is classified as a known carcinogen to humans. Studies have reported anomalous mortality from mesothelioma in residents of three Turkish villages, which has been linked to chronic exposure to erionite in the local volcanic rocks (Baris, 1991)

TABLE 1 Ideal Compositions of the Commonly Regulated Asbestos Minerals

Mineral	**End member cation ratios**
Serpentine group	
Chrysotile	$Mg_3Si_2O_5(OH)_4$
Amphibole group[1]	
Asbestiform riebeckite (“crocidolite”)	? $Na_2(Mg, Fe^{2+})_3Fe^{3+}{}_2\,Si_8O_{22}(OH)_2$ $Mg/(Mg+Fe^{2+}) < 0.5$
Asbestiform cummingtonite-grunerite (“amosite”)	?$Mg_7Si_8O_{22}(OH)_2$ to ?$Fe^{2+}{}_7Si_8O_{22}(OH)_2$
Asbestiform anthophyllite	? $(Mg, Fe^{2+})_7Si_8O_{22}(OH)_2$ $Mg/(Mg+Fe^{2+}) = 0.5$
Asbestiform actinolite	?$Ca_2(Mg, Fe^{2+})_5\,Si_8O_{22}(OH)_2$ $Mg/(Mg+Fe^{2+}) = 0.5 – 0.89$
Asbestiform tremolite	?$Ca_2(Mg, Fe^{2+})_5\,Si_8O_{22}(OH)_2$ $Mg/(Mg+Fe^{2+}) = 1.0 – 0.9$

[1] Cation ratios from Leake and others (1997)

? Empty “A” site in the amphibole structure

TABLE 2 Ideal Compositions of Other Asbestiform Amphibole Minerals Reportedly Linked to Respiratory Disease Clusters (Meeker and others, 2003; Gianfagna and others, 2003)

Mineral	**End member cation ratios**[1]
Amphibole group	
Asbestiform winchite	? $(CaNa)Mg_4(Al, Fe^{3+})Si_8O_{22}(OH)_2$
Asbestiform richterite	$Na(CaNa)Mg_5Si_8O_{22}(OH)_2$
Asbestiform fluoro-edenite	$NaCa_2Mg_5(Si_7Al)O_{22}F_2$

[1] Cation ratios from Leake and others (1997) and Gianfagna and Oberti (2001)

? Empty “A” site in the amphibole structure

Fibrous and nonfibrous erionite occur with other zeolite minerals in volcanic tuffs that were altered by low-temperature fluids, particularly saline lake waters (Sheppard, 1996).

Naturally Occurring Asbestos

Asbestos-bearing materials (some pipe wrappings and insulation, as examples) are frequently uncovered in older buildings and structures, causing health concerns for those exposed. As older structures are continually torn down or remodeled, contact with asbestos-bearing materials will likely be of concern for decades to come. The proper handling and disposal of these man-made asbestos materials is addressed by a number of federal regulations. Less straightforward is the regulation and management of “naturally occurring asbestos” (NOA), which has recently gained much attention from regulatory agencies, health agencies, and citizen groups. NOA is asbestos found in-place in its natural state; that is, asbestos minerals in a bedrock exposed by man’s excavations or by natural weathering.

NOA is of concern due to potential exposures to microscopic fibers that can be released airborne if asbestos-bearing rocks are disturbed by natural erosion or human activities (road building, urban excavations, agriculture, mining, crushing, and milling, as just a few examples). Examples of occupational and environmental exposures to asbestos are described in Nolan and others (2001) and Ross and Nolan (2003).

Recent attention towards NOA was spurred by the renewed recognition of high incidences of asbestos-related mortality and respiratory disease in vermiculite miners and residents of Libby, Montana; this disease has been attributed to fibrous amphibole particles within the vermiculite ore body once mined and milled near the town from 1923 to 1990 (Peipins and others, 2003). Meeker and others (2003) describe in detail the fibrous and asbestiform amphibole minerals intergrown with the Libby vermiculite deposit.

Large areas of exposed ultramafic bedrock in northern California, some now densely populated by housing and infrastructure, have become the focus of recent attention because they may contain chrysotile and tremolite-actinolite asbestos (Churchill and Hill, 2000; Clinkenbeard and others, 2002; Ross and Nolan, 2003; Swayze and others, 2004).

Local authorities have instituted ways to reduce exposure to naturally occurring asbestos. For example, the Fairfax County Health Department, Virginia, developed an asbestos exposure control plan that is mandated for use in construction projects that excavate "asbestos containing material" (ultramafic rock bodies) within the county (Dusek and Yetman, 2002).

Current federal asbestos regulations are provided in the Code of Federal Regulations (available online at http://www.gpoaccess.gov/cfr/). However, these asbestos regulations do not specifically address exposures to natural occurrences of asbestos.

APPLICATIONS OF ASBESTOS GEOLOGY

As will be documented in this paper, asbestos occurs *locally* in the following rock types:

- Metasomatized ultramafic rocks, such as dunite, peridotite, amphibolite, and pyroxenite, and especially their alteration equivalent, serpentinite, which have been altered by processes of regional or contact metamorphism.

- Metamorphosed mafic extrusive rocks, especially metabasalt (“greenstone”), and metamorphosed mafic intrusive rocks, especially metagabbro (“diabase”, “trap rock”), which have been subsequently sheared and silicified.
- Dolostones (dolomite, dolomitic marble) and dolomitic limestone that have been metamorphosed and metasomatized by contact or regional metamorphism.
- Iron formation that has been metamorphosed by thermal (contact) metamorphism.
- Alkalic intrusions and carbonatites that are internally metasomatized by magmatic fluids.

Other rock types appear unlikely to contain asbestos. The reported asbestos deposits and occurrences in the U.S. are hosted by one of the combinations of rock type and geologic setting listed above. It is important to emphasize that even in these rock types, asbestos occurrences are relatively rare and are confined to areas in which ideal asbestos-forming conditions were present (microfracturing, siliceous fluid flow, specific pressure and temperature conditions, and subsequent preservation).

By recognizing that asbestos is formed in particular rock types and geologic conditions, the presence or absence of asbestos in an industrial mineral deposit or bedrock terrain can be predicted within reasonable limits. Using the geology of asbestos as a guide, one can focus the costly and time-consuming efforts of asbestos evaluation, monitoring, regulation, and remediation towards those areas most likely to contain asbestos-bearing rock rather than devoting efforts to areas that have minimal NOA potential. Thus, regulatory agencies, health agencies, land managers, mining companies, and ultimately, the general public, benefit if the basic geology of asbestos is considered when asbestos policies are developed.

GEOLOGIC ENVIRONMENTS THAT HOST ASBESTOS

As with any mineral deposit, asbestos forms within particular geologic environments. All asbestos minerals contain magnesium, silica, and water as essential constituents, and some also contain iron and (or) calcium as major constituents (Table 1). Thus, the geologic terrains that host asbestos are enriched in these components. Most asbestos deposits form by the metasomatic replacement of magnesium-rich rocks. Asbestos-forming environments typically display shear and (or) show evidence that a significant influx of hydrothermal silica-rich fluids occurred at the site. The asbestos-forming processes can be driven by regional metamorphism, contact metamorphism, or magmatic hydrothermal systems. Thus, asbestos deposits, ranging in size from commercial-grade ore bodies to thin impure veinlets or low-grade occurrences, are typically hosted by magnesium-rich rocks (often also iron-rich) that have been metasomatized by a metamorphic or magmatic process.

The discussion that follows is a summary of the rock types and geologic settings that host significant asbestos occurrences within the Continental U.S. Similar geologic relationships occur worldwide. Prior to this paper, the author is aware of no single paper or report that summarizes all of the asbestos-bearing geologic environments in the Continental U.S. Detailed geologic and mineralogic descriptions are beyond the scope of this paper, but, the papers that are referenced herein provide considerable information on particular U.S. asbestos deposits and districts.

It should be noted that often the same geologic settings that form asbestiform amphiboles will also contain acicular and fibrous amphiboles. In fact, within and adjacent to an amphibole asbestos deposit a variety of amphibole particle forms are usually found, which range from prismatic to acicular to fibrous. See Meeker and others (2003) and Van Gosen, Lowers, and Sutley (2004) for examples.

Metamorphosed Ultramafic Rocks

The most well known and largest asbestos deposits in the U.S. and world-wide are those that have replaced or formed by alteration of an ultramafic rock (Ross and Nolan, 2003). Most commonly, the host ultramafic rock is a dunite, peridotite, amphibolite, pyroxenite, or their alteration equivalent, serpentinite. In the Continental U.S., asbestos-bearing exposures of ultramafic rocks are most abundant in the westernmost States—California (Wiebelt and Smith, 1959; Peterson, 1984; Churchill and Hill, 2000; Clinkenbeard and others, 2002; Ross and Nolan, 2003; Swayze and others, 2004), Oregon (Bright and Ramp, 1965), and Washington (Vhay, 1966)—and in the Eastern States (Fig. 1) from Alabama to Vermont (Larrabee, 1966, 1971; Van Gosen, 2005).

Large commercial-grade deposits of chrysotile asbestos hosted by altered ultramafic (serpentinite) rocks were mined in California until 2002 (Wiebelt and Smith, 1959; Ross and Nolan, 2003), and chrysotile hosted by metasomatized dunite was mined in north-central Vermont as recently as 1993 (Cady and others, 1963; Chidester and others, 1978; Van Baalen and others, 1999). In the Eastern U.S., large veins and pods of anthophyllite asbestos and tremolite-actinolite asbestos within altered ultramafic bodies were mined at relatively small scales in the past in Georgia, North Carolina, Virginia, Maryland, Connecticut, and Massachusetts (Van Gosen, 2005). The Hippy mine in Yancey County, North Carolina, stockpiled anthophyllite asbestos until 1978. Pennsylvania saw some small-scale mining of "amphibole asbestos" (unspecified type) in the early 1900s, extracted from small altered ultramafic rock bodies.

Ultramafic rocks, as their name implies, are enriched in mafic (ferromagnesian) minerals, such as olivine, amphiboles, and pyroxenes. This mineralogy makes the ultramafic rocks an ideal host for asbestos formation. In the simplest terms, metasomatism of ultramafic rocks that leads to asbestos formation is caused by an influx of silica-rich fluids into the rock under particular conditions of temperature and pressure. These fluids react with the ferromagnesian minerals in the rock, thereby providing all of the *chemical* ingredients (Mg, Fe, Ca, Si, H_2O) necessary to form chrysotile, anthophyllite, and (or) species of the tremolite to ferro-actinolite solid solution series (Leake and others, 1997). Metasomatism of ultramafic rocks typically forms serpentinite, a rock composed primarily of the serpentine group minerals antigorite, lizardite, and sometimes chrysotile (Faust and Fahey, 1962). The very presence of serpentinite in an outcrop indicates that the *chemical* conditions were suitable for asbestos mineral formation.

Fracturing, faulting, shearing, and associated microfracturing accompanied by relatively moderate fluid temperatures and pressures are thought to be other important factors in asbestos formation. Initially, the fracturing likely promotes the serpentinization process by providing conduits and permeability for hydrothermal fluid flow through the ultramafic body (Cady and others, 1963; Chidester and others, 1978). In chrysotile formation (asbestiform serpentine), and probably also in the asbestiform growth of amphiboles, microfractures in the ultramafic host rock likely play an important role. As described by Evans (2004, p. 479): “Chrysotile is most conspicuously developed in tectonically active environments, where associated lithotypes show marginal greenschist-facies parageneses and antigorite tends to make its first appearance. Chrysotile growth is favored in isotropic stress microenvironments of fluid-filled voids and pores (where it may ultimately crystallize pervasively), and in veins, generally after active hydration in the immediate surroundings has ceased." Refer to Evans (2004) for his detailed explanation of chrysotile growth, in which "lizardite and chrysotile behave as though they were a stress-antistress mineral pair".

Processes of regional metamorphism were the likely driving mechanism for the heat, pressure, and fluid flow that formed most of the serpentine, chrysotile, anthophyllite asbestos (Fig. 2), and tremolite-actinolite asbestos found within metamorphosed ultramafic rock bodies of the Western and Eastern U.S. The resultant asbestos deposits in ultramafic rocks vary widely in size, from large commercial-grade bodies (Ross and Nolan, 2003) down to thin veinlets (Rohl and others, 1977; Blake, 1982).

Narrow asbestos-bearing zones (inches to a few feet in width) are also formed by contact metamorphic reactions where felsic igneous masses have intruded into pre-existing ultramafic bodies. An example is described in the Addie district of North Carolina (Murdock and Hunter, 1946; Kulp and Brobst, 1954), in which the Day Book dunite deposit contains alteration zones composed of vermiculite (weathered phlogopite), fibrous tremolite and anthophyllite, and talc along serpentine-rich contacts between dunite masses and intruding pegmatites.

Thus, metamorphosed and (or) hydrothermally altered ultramafic rock types—dunite, peridotite, amphibolite, pyroxenite—and especially their altered counterparts—serpentinites—may merit some level of asbestos evaluation in those areas where they may be disturbed and potentially expose workers or the public to their dust. This type of approach has been instituted by the Fairfax County Health Department, Virginia, for projects that excavate ultramafic rock bodies (some with known asbestos deposits) within the county (Dusek and Yetman, 2002).

Metasomatized Mafic Rocks

In the Continental U.S., relatively small occurrences of asbestos have been reported within some mafic igneous rocks, including (1) metamorphosed extrusive rocks, especially metabasalt (sometimes called "greenstone"), which have been sheared and altered, and (2) some metagabbro intrusions (also called trap rock or diabase). A number of examples exist; a few are noted here.

Small amphibole asbestos and "serpentine asbestos" occurrences, often associated with copper deposits, are reported in metamorphosed mafic volcanic rocks (metabasalt) at several localities within the Catoctin Formation of north-central Virginia (Watson, 1907; Weed, 1911; Allen, 1963, 1967; Thiesmeyer, 1937). A similar copper prospect in metabasalt (Russel prospect), located in Pennsylvania, is reported to contain crocidolite (Geyer and others, 1976). Features of shear and siliceous alteration are described at these sites.

Minor occurrences of amphibole asbestos have been described at some trap rock (metagabbro or "diabase") quarries in the Eastern U.S. As examples, in New Jersey, crocidolite is reported in Cope's quarry (Germine, 1981; Germine and Puffer, 1981) and asbestiform actinolite in the Prospect Park quarry (Mason, 1960; Peters and Peters, 1978; Germine, 1981; Germine and Puffer, 1981). In southeastern Pennsylvania, Geyer and others (1976) report crocidolite in the Deyer quarry and asbestiform tremolite in the Teeter quarry. In northern Virginia, asbestiform tremolite-actinolite is reported in the Centreville (Fairfax) quarry (Medici, 1972; Bernstein, 1980) and "asbestoform amphibole" in the Arlington quarry (Dietrich, 1953). These amphibole asbestos occurrences are apparently minor in size and extent, limited to thin veins in sheared areas of the metagabbro exposed in the pits. Thus, these asbestos-bearing zones can be identified and avoided with careful planning of the mining operations.

Metamorphosed Dolostones

Chrysotile and asbestiform calcic and sodic-calcic amphiboles can form in dolostone and dolomitic limestone under some conditions of contact or regional metamorphism. The asbestos deposits that replace dolomitic rocks occur in a wide variety of styles, ranging from multiple commercial-grade veins of chrystotile to minor amounts of asbestiform amphibole found as an accessory mineral within a larger mineral deposit, such as a body of talc. Dolostone-hosted asbestos also occurs in variety of geologic settings, as is demonstrated below.

A chrysotile mining district with significant past production lies in Gila County, Arizona, north and northeast of Globe. From 1913 to 1966, about 75,000 tons of chrysotile asbestos was produced from more than 160 mines; production from an additional 60-70 occurrences in the region is unknown (Harris, 2004). Asbestos mining in this region ended in the early 1980s. The chrysotile deposits of the Globe region formed through contact metamorphism. Chrysotile veins formed in serpentinized contact zones where diabase intruded the Mescal Limestone (dolomitic limestone). The chrysotile occurs primarily as cross-fiber veins, with occasional slip-fiber examples. The asbestos is hosted by layers of serpentine, up to 2 ft thick, which replace the dolomitic limestone adjacent to the diabase. Single to multiple veins of chrysotile occur in each serpentine layer. The chrysotile veins vary from microscopic in size to a maximum of 14 inches thick, with most less than 2 inches thick (Wilson, 1928). Detailed descriptions of the chrysotile deposits of the Globe region are provided by Wilson (1928), Stewart (1955), Moore (1968), and Bromfield and Shride (1956).

Other examples of asbestos formed by contact metamorphism are found in the southern Death Valley region of California. These deposits are also the best examples in the U.S. of talc ores formed by contact metamorphism. The southern Death Valley deposits are talc-tremolite rocks that are geologically similar across the region, consistently associated with a carbonate horizon of the Crystal Spring Formation of Proterozoic age (Wright, 1968). In this interval, thick regionally persistent gabbroic sills intruded dolomite during the Mesoproterozoic, and formed laminated talc-tremolite-rich rock along the sill-dolomite contacts (Fig. 3). Metasomatic reactions during sill emplacement caused the massive replacement of dolomite by talc-tremolite-rich bodies, which are approximately 500 to 5,000 ft long and 10 to 100 ft thick. Relative proportions of talc versus tremolite vary across the deposits and either mineral can predominate within any particular deposit. Petrographic examinations of the ore show that most of the talc is platy, intergrown with tremolite that is primarily prismatic in shape; observations suggest that the intergrown talc and tremolite were contemporaneous. Examination of the talc-tremolite rock by scanning electron microscopy, accompanied by energy-dispersive spectrometry analyses, found scattered occurrences of asbestiform tremolite, asbestiform winchite, and asbestiform richterite, including bundles of fibers and loose fibers (Fig. 4) (see Van Gosen, Lowers, and Sutley, 2004; Van Gosen and others, 2004a, 2004b). In contrast, other talc deposits of the Death Valley region, which also replaced dolostones, but were created by hydrothermal fluids heated by deeply buried magmas, do not contain amphiboles (see Van Gosen and others, 2004b).

Fibrous varieties of talc, tremolite, and anthophyllite, formed by the regional metamorphism of dolomitic carbonates (now dolomitic marble), occur in the large tremolite-talc deposits of the Gouverneur talc mining district of upstate New York (Engel, 1962; Hull and others, 2002; Van Gosen, Meeker, and Brownfield, 2004; Webber and others, 2004). For more than 30 years, a debate has ensued as to whether the fibrous amphiboles in the Gouverneur talc ores meet the criteria of “asbestos”. The debate has centered on the complex and unusual "transitional fibers" that are a trademark of the Gouvernuer talc ores, and more specifically, whether these particles represent "asbestos". These "transitional fibers" are fibrous mineral particles composed partly of talc and partly of anthophyllite. See Van Gosen, Meeker, and Brownfield (2004) for a description of the Gouveneur talc deposits and a discussion of the controversy that has surrounded them.

Small occurrences of asbestiform amphiboles in Precambrian dolomitic marbles have been noted at several locations in New Jersey (Germine, 1981; Germine and Puffer, 1981; Van Gosen, 2005). As examples, Germine (1986) describes asbestiform and non-asbestiform (prismatic and acicular) tremolite-actinolite collected from two marble quarries in Franklin and Sparta, Sussex County, New Jersey.

Skarn deposits, specifically mineral deposits formed by the intrusion of felsic magmas into dolomitic carbonate rock, appear to be another favorable environment for the formation of amphibole asbestos or chrysotile. Tremolite or actinolite is often noted in the replacement bodies of skarn systems, in association with a variety of calc-silicate minerals. Thus, it would not seem surprising to discover amphibole asbestos within a metal-rich skarn deposit, garnet skarn, wollastonite skarn, or marble deposit that formed from an igneous intrusion into a dolomitic host rock. As an example, crocidolite and fibrous actinolite are minor accessory minerals in the iron-rich skarn at the former Iron Mountain iron mine, near Iron Mountain, southeastern Missouri (Allen and Fahey, 1956; Murphy and Ohle, 1968; Kisvarsanyi and Kisvarsanyi, 1989). “Asbestos” is reported to occur in the large copper ore bodies of the Bingham district, Utah, which have replaced highly metamorphosed, silicified limestone (dolomitic) that borders the intrusive felsic stock. The basic gangue mineralogy of the Bingham copper replacement ores (skarn deposits) includes garnet, wollastonite, diopside, tremolite, “asbestos”, and specularite (Hunt, 1924). Another example is the skarn deposit that was once mined at the Tilly Foster iron mine in southeastern New York State (Van Gosen, 2005). This iron skarn is reported to contain small amounts of vug-filling actinolite asbestos, chrysotile, and crocidolite (Januzzi, 1959, 1961). In the New Jersey-New York area, other skarn deposits that contain minor amounts of asbestos are listed in Van Gosen (2005).

Metamorphosed Iron Formations

Commercial deposits of crocidolite (asbestiform riebeckite) in metamorphosed banded iron formation (ironstone) were mined extensively in South Africa, Western Australia, and Bolivia (Virta and Mann, 1994; Miyano and Beukes, 1997; Ross and Virta, 2001; Virta, 2002). Amosite (asbestiform cummingtonite-grunerite) was mined from contact-metamorphosed layers of banded iron formation in South Africa. (The commercial term “amosite” is derived from “Asbestos Mines of South Africa”.) None of these asbestos mining districts are active today. Unfortunately, these crocodilite and amosite mines have left behind a harsh legacy of severe respiratory disease and mortality for a high proportion of their former employees (Gibbons, 2000; Dodson and Hammar, 2006).

Banded iron formation is well represented in the Precambrian craton of Minnesota, Wisconsin, and Michigan. None of the iron formation in this region, nor any other iron formation in the U.S., reportedly contains a commercial-grade deposit of crocidolite or amosite. However, the banded iron formation of the Mesabi Range of Minnesota (White, 1954), does have an asbestos controversy; it also provides an example of applying geologic information to asbestos issues.

The Precambrian-age Biwabik (Iron) Formation extends for roughly 120 miles in the Mesabi Range from Grand Rapids to near Babbitt, Minnesota. The Biwabik Formation has been an enormous source of "taconite", a commercial (and loosely applied geologic) term for the low grade iron ore that has been mined in this region (banded iron-formation composed of ferruginous chert and slate). The taconite ore from the Mesabi Range is mined, processed, and formed into taconite pellets, which have been used as an iron source by the U.S. steel industry since 1955 (Great Lakes Research Advisory Board, 1975).

In 1955, the Reserve Mining Company began commercial operation of the Silver Bay taconite processing plant on the shore of Lake Superior near Silver Bay, Minnesota. This plant produced millions of tons of iron ore pellets per year, with a high production of 10.8 million tons of pellets in 1966 (Great Lakes Research Advisory Board, 1975). The waste rock (tailings) at the plant site was disposed of as a slurry mixture that was piped into Lake Superior.

In the early 1970s, tests of the Duluth (MN) water supply, drawn from Lake Superior, indicated that the water contained asbestiform particles of cummingtonite-grunerite. These particles were attributed to the taconite tailings that were being piped into Lake Superior by Reserve Mining Company. Water studies by State and Federal agencies were accompanied by extensive litigation against Reserve Mining Company in the early 1970s, which climaxed with a U.S. District Court order that shut down the Silver Bay taconite processing facility in April 1974. The history of the "Reserve Mining Case" and water sample analyses are detailed in Great Lakes Research Advisory Board (1975) and discussed in Carter (1974). The Reserve Mining Case brought attention to the potential asbestos content of the taconite ores of the eastern Mesabi Range of Minnesota, which was the taconite material processed at Silver Bay.

Geologic and mineralogical studies of the banded iron formation of the Biwabik Formation in the Mesabi Range were conducted by Gunderson and Schwartz (1962), French (1968), and Morey and others (1972). These studies revealed that amphiboles within the taconite (mostly grunerite and lesser cummingtonite) were limited to the eastern Mesabi Range, coincident with the area where the Biwabik (Iron) Formation was thermally altered by the intrusion of the Duluth Gabbro Complex (thermal contact metamorphism with little fluid influence). French (1968) found that within several miles of the Duluth Gabbro Complex the moderately to highly (contact) metamorphosed taconite contains abundant grunerite in some layers. French (1968) described some of this grunerite as fibrous in habit. In contrast, he found that the unaltered (unmetamorphosed) taconite is devoid of amphibole of any type; the unmetamorphosed taconite extends from the western limit of the Mesabi Range northeastward to approximately the town of Aurora.

The asbestos issues surrounding taconite ores of the Mesabi Range remain controversial. Does the fibrous grunerite in the taconite ore bodies meet the morphological criteria of "asbestos"? Have taconite workers been harmed? While these issues remain, the earlier geologic studies can be used to help narrow the geographic extent of the debate. French (1968) showed that amphiboles, including fibrous grunerite, formed exclusively in the contact-metamorphosed taconite of the eastern Mesabi Range district. Therefore, asbestos studies and debate in the future can focus only on the taconite deposits of this area. This example demonstrates how geologic information can be used to define the geographic areas where asbestos *may* exist versus those areas where it is unlikely to exist.

Alkalic Intrusions and Carbonatites

Alkaline rocks and carbonatites are a particularly diverse group of igneous rocks that are widely distributed in the U.S. (see Woolley, 1987). None of the alkaline intrusions in the U.S. are known to contain commercial asbestos deposits (mined specifically for asbestos). However, several carbonatites in the U.S. and some alkalic intrusions do contain asbestiform amphiboles (sodic-calcic and calcic amphiboles) as accessory minerals.

A notable example of an asbestos-bearing alkaline intrusion is the Rainy Creek Complex near Libby, Montana, the host for a world-class vermiculite deposit that was mined from 1923 to 1990. The Libby (Rainy Creek or Zonolite) vermiculite deposit formed through supergene alteration of the Rainy Creek Complex, which is a large zoned pyroxenite pluton with a central biotite-rich pyroxenite core. A younger mass of syenite cuts the outer zones of the pluton and alkalic syenite dikes cut the biotitite core. A nearby small mass of nepheline syenite, and fenitization of the metasedimentary rocks surrounding the pluton, suggest that a carbonatitic mass occurs at depth (Boettcher, 1967).

Unusually high rates of asbestos-related respiratory disease and mortality have stricken former vermiculite miners and the residents of Libby, Montana, which has been attributed to amphibole mineral fibers intergrown with the Libby vermiculite deposit (Peipins and others, 2003). Fibrous to asbestiform amphiboles occur in hydrothermal veins and veinlets, and as the alteration products of pyroxenes, in the intrusive complex and vermiculite ore body (Boettcher, 1967; Meeker and others, 2003). A detailed sampling and analyses of amphibole-rich rock from the Libby (Rainy Creek) vermiculite deposit was performed by Meeker and others (2003). They found that: "The range of amphibole compositions, determined from electron probe microanalysis and X-ray diffraction analysis, indicates the presence of winchite, richterite, tremolite, and magnesioriebeckite." They show that nearly complete solid solution occurs in the Libby amphiboles between the ideal end-member compositions, as defined by Leake and others (1997). Also, the Libby amphibole particles display a continuum of morphologies, ranging from prismatic crystals to asbestiform fibers; most of the Libby amphiboles have a shape between prismatic and asbestiform. Meeker and others (2003) observed that Libby winchite, richterite, tremolite, and possibly magnesioriebeckite occur in fibrous or asbestiform habit.

A least one carbonatite in Colorado—the Gem Park Complex, which straddles part of the Custer and Fremont County boundary—also contains deposits of vermiculite and fibrous to asbestiform amphibole (Van Gosen and others, 2005). The Gem Park Complex consists mostly of pyroxenite and gabbro, cut by abundant carbonatite dikes and irregular masses with associated fenite (Parker and Sharp, 1970). This complex is further cut by minor dikes and bodies of lamprophyre, syenite porphyry, and nepheline syenite pegmatite. The entire intrusive complex is interpreted to be underlain by a large carbonatite body (Parker and Sharp, 1970; Armbrustmacher, 1984). The Gem Park Complex contains abundant amphibole fibers and some concentrations of asbestiform fibers, semiquantitatively determined (by energy-dispersive spectroscopy) to be winchite, richterite, and riebeckite (Van Gosen and others, 2005).

The Mountain Pass district lies in San Bernardino County, California, near the Nevada border in the southern Death Valley region (Woolley, 1987). In the district, the Sulphide Queen carbonatite contains a world-class-size reserve of rare-earth-bearing oxide minerals. This deposit was mined for use in rare earth commodities from 1954 until recently (Castor and Nason, 2004). A variety of minerals are reported in carbonatite in association with the rare-earth minerals, including crocidolite (asbestiform riebeckite) (Olson and others, 1954).

Crocidolite reportedly occurs within a mass of alkaline granite exposed on Beacon Pole Hill, near Cumberland, Rhode Island (Chester and Cairns, 1887).

An alkaline syenite dike that contains fluffy clumps of asbestiform amphibole crops out in the former Camp Albion mining district, Boulder County, Colorado (Fig. 5). The syenite dike contains an unusual assemblage of copper-bearing pyrite, galena, sphalerite, calcite, feldspar, quartz and pyroxene, as well as tufts of an amphibole with well-developed asbestiform habit (Wahlstrom, 1934). Results of x-ray diffraction, wavelength dispersive x-ray fluorescence spectrometry, and scanning electron microscopy accompanied by energy dispersive x-ray spectrometry (unpublished study by the author) suggest that this asbestiform amphibole is ferrian winchite.

The metasomatism and asbestos formation in each of the alkaline igneous rocks described above is thought to be caused by magmatic hydrothermal fluids, with no obvious relationship to regional or contact metamorphism.

As noted by these examples, fibrous to asbestiform amphibole are known to occur in some alkaline rocks in the U.S., especially in carbonatites. Perhaps the association between alkaline igneous rocks and asbestos has been under-reported or under-recognized in the U.S.

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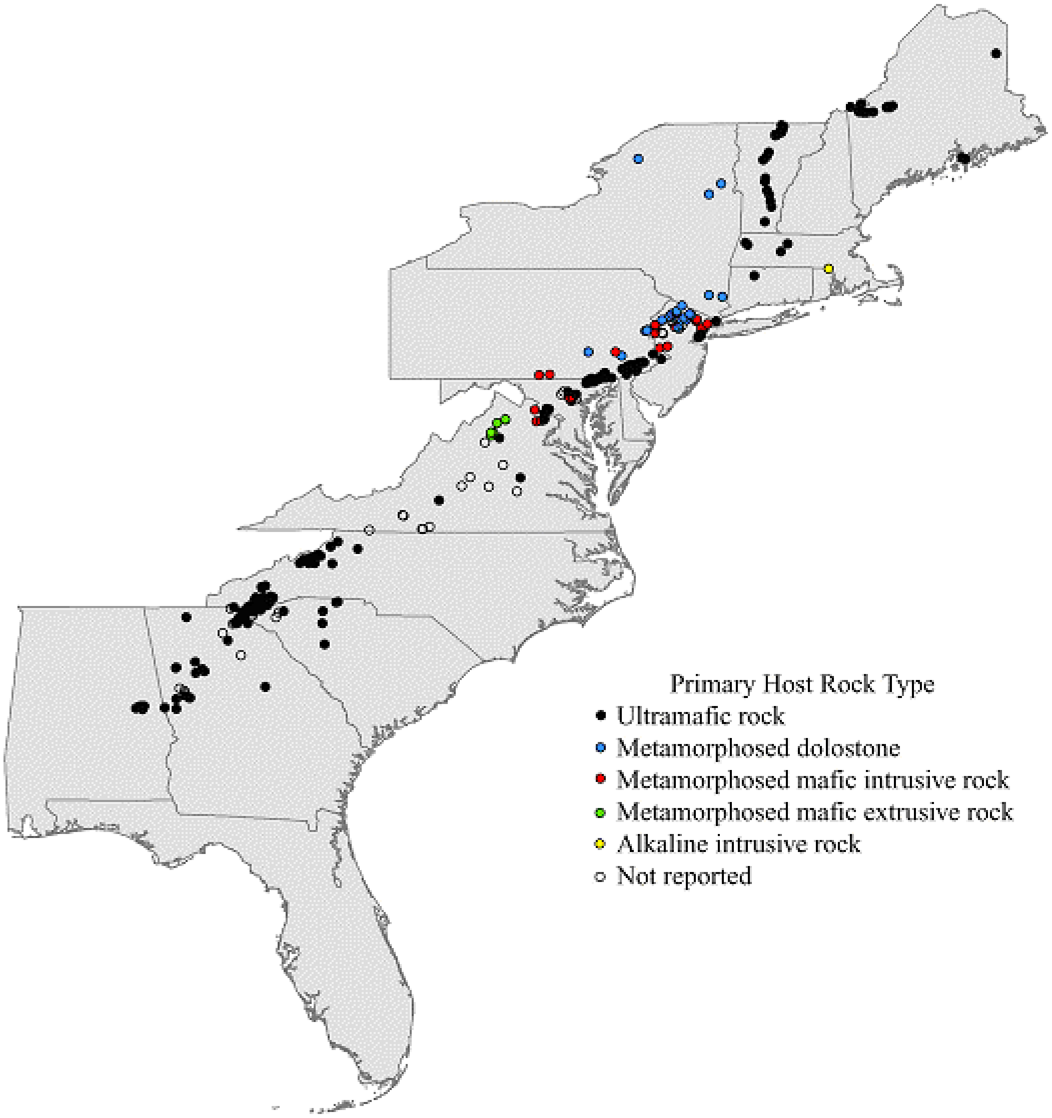

FIGURE 1 Index map of reported asbestos occurrences in the Eastern U.S., showing the primary rock type that hosts each occurrence. Adapted from Van Gosen (2005). A compilation of reported asbestos occurrences in the remainder of the Continental U.S. is currently in preparation and not yet complete.

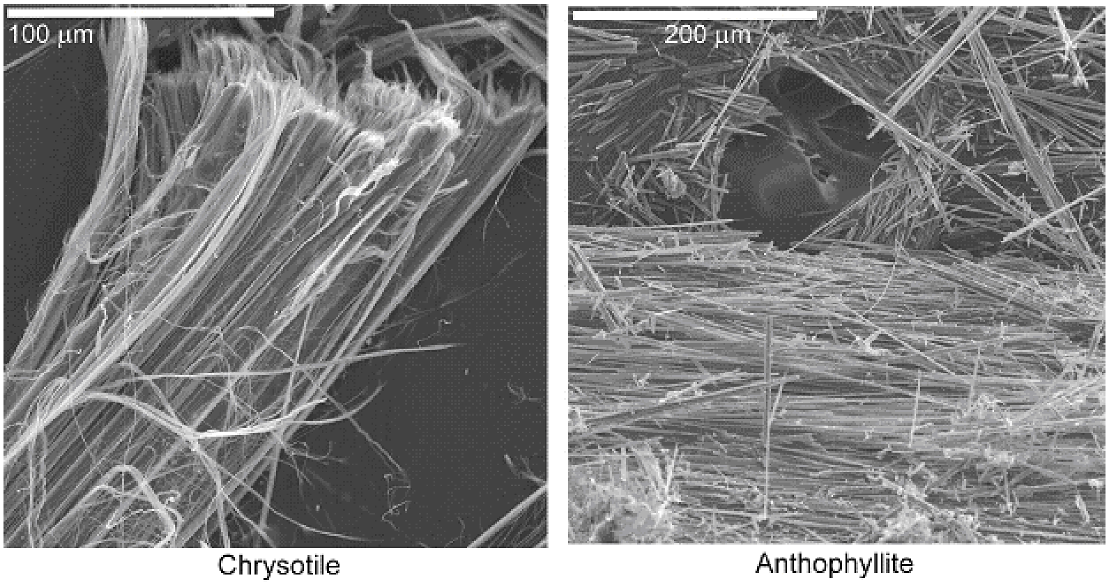

FIGURE 2 Scanning electron microscope (SEM) photomicrographs showing examples of chrysotile and anthophyllite asbestos, each once mined from veins within regionally metamorphosed ultramafic rock.

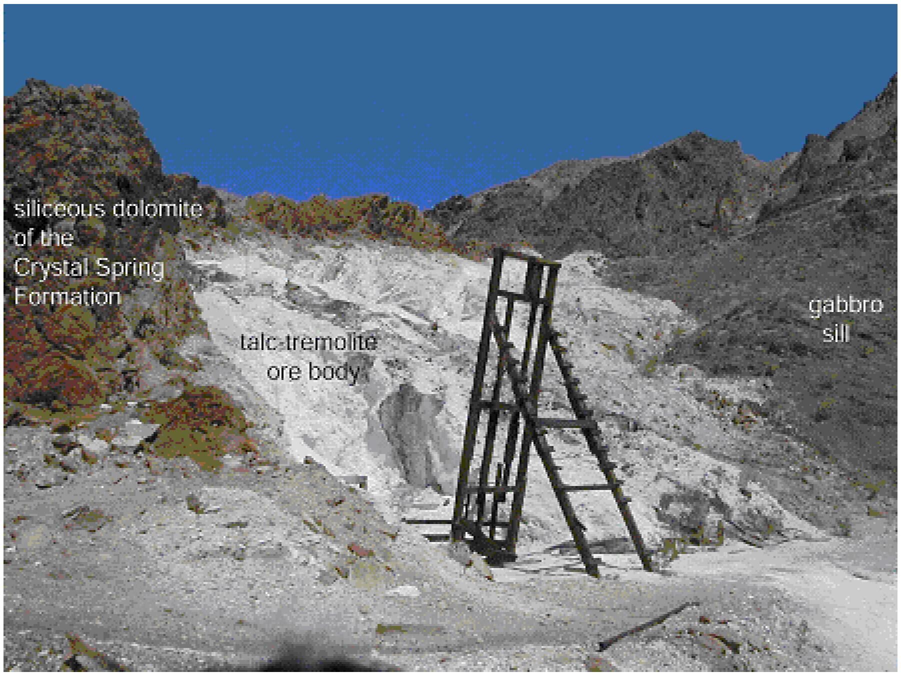

FIGURE 3 Site of the historic Pleasanton talc mine in Death Valley National Park, California, an example of the talc deposits of the southern Death Valley region (Wright, 1968; Van Gosen, Lowers, and Sutley, 2004; Van Gosen and others, 2004b). The talc-tremolite rock formed through metasomatic reactions caused by the intrusion of the gabbro sill into the siliceous dolomite.

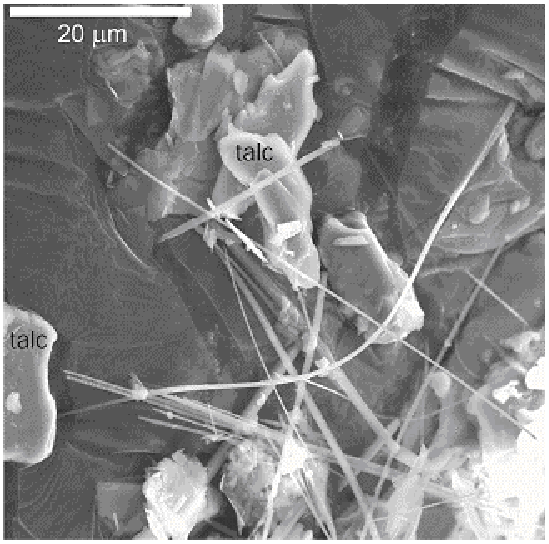

FIGURE 4 SEM photomicrograph of asbestiform sodic-calcic amphibole particles intermixed with platy talc in talc-tremolite ore from a southern Death Valley deposit of the type shown in Figure 3 (Van Gosen, Lowers, and Sutley, 2004; Van Gosen and others, 2004b).

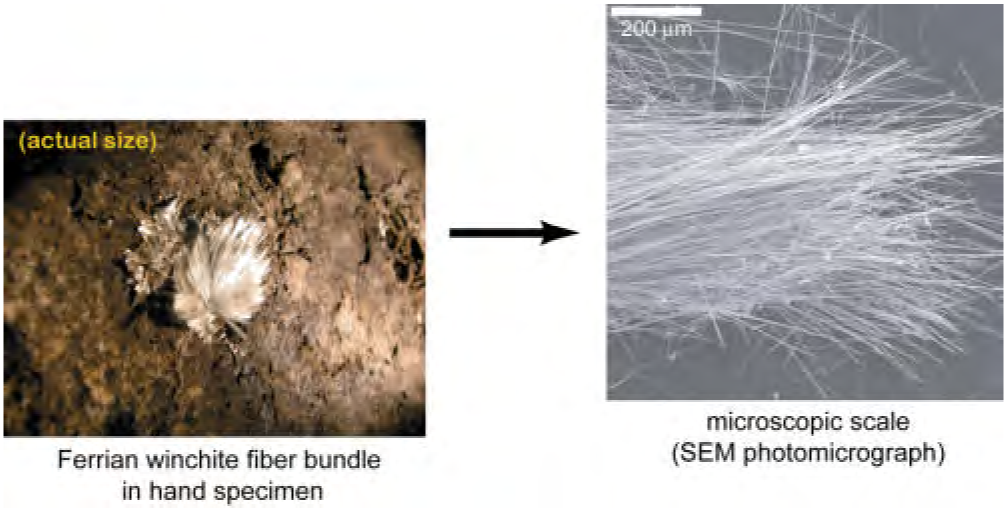

FIGURE 5 Example of the asbestiform ferrian winchite that occurs in a syenite dike in the historic Camp Albion mining district, Boulder County, Colorado (Wahlstrom, 1934)

Arkansas Mineral Commodity (AMC) Database – Update 2000

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ABSTRACT

This project was designed to extract and bring together Arkansas mineral commodity information from its many presently scattered sources. Basic information relating to Arkansas' mineral commodities is presently not readily available from one source to the Arkansas Geological Commission (AGC) staff members, much less the public. Having the information in one data set will make it much easier and faster to research any given request. The data set provides an overview of Arkansas' mineral commodities and lists data sources available for detailed examination. Presently, there are ~ 7,200 mineral commodity sites entered in this file.

Howard, J. Michael, 2006, Arkansas Mineral Commodity (AMC) Data Base – Update 2000, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

PROJECT TIME FRAME

An office and field project of this magnitude requires a serious analysis of time spent. Initially time in the office at the project startup was shared with other job duties, and amounted to 3 years. When the project finally reached the field checking phase in October of 2005, the AGC administration had to deem this project worthwhile and important to both agency personnel and the general citizenry of Arkansas to justify the cost and time involved with field work. In the spring of 2005, a grant was applied for from the US Geological Survey to pay for 48 weeks of field work to finish the project but was rejected, principally because the reviewers were looking for projects that were more "regional" in basis. After discussions with the State Geologist and AGC administration concerning the projected field expenses, the project was scheduled for one-two weeks per month with the goal of completion of a county per month. With 75 counties, this puts the project completion date in 2011, nearly 11 years after it was first conceived.

PROJECT GOALS

Several goals that were established at the beginning of the project include:

- To provide the public more readily available information concerning mineral commodities of Arkansas.
- To have this information easily available to AGC geologists so that their request response time is reduced.
- To test the accuracy of information in published literature and that presented on USGS 7.5-minute topographic maps, some of which are over 40 years old.
- To prepare the data digitally for future use with Arcview® maps and projects.

One additional goal was established immediately before the beginning of the field work. Several grants have been applied for through the USGS for digital mapping projects on a 1:100,000 scale by agency staff. It was proposed that the field work proceed ahead of the proposals in the selected areas so that when digitization takes place, the mineral commodity data will be already available as a digital layer for the base maps.

WHAT IS INCLUDED IN THE DATASHEET

The following information, if available, was considered useful in answering questions the AGC staff commonly receives, relative to mineral data, from our agency users and customers:

- **Location data**: County, General Land Office Survey (section, T. & R.), Latitude/Longitude
- **Site data**: Mine/Site name (also AKA), Operator, Contact, Address, Telephone Number, Status
- **Geologic data**: Rock Unit (formation/group)
- **Other data**: Data Sources, Date of data entry, Notes (includes a variety of site-specific information, like resource/production data, site data, potential use of resource, site appearance, et cetera)

DATA ORGANIZATION

It is built as an MSExcel® spreadsheet because Excel information is directly compatible with both MSAccess® and Arcview® software. The data is sorted in the spreadsheet first alphabetically by county, then alphabetically by commodity. MSExcel® was selected because it is the lowest common denominator for most computer users and may be readily sorted by many different topics, such as active status, geologic formation, or mineral commodity.

APPROACH

The database excludes all liquid and gas hydrocarbons because the Arkansas Oil and Gas Commission has that data and responsibility. All other mineral commodities are given: industrial, metallic, and coal/lignite. The data set includes both historical and current data, along with pertinent resource drillhole data. The project allows for continuous incorporation of new data, as it becomes available. For ease of data entry, the AMC project was divided into 3 Phases.

Phase I brought together data sets from many sources:

- Other state agencies (principally the Arkansas Department of Environmental Quality and the Arkansas Highway and Transportation Department)
- Published reports, such as USGS Bulletins (quartz, lead/zinc, etc.), USBM maps and reports (manganese, Bull. 645), AGC publications (crushed stone, clay, lignite, etc.)
- At least one comprehensive set of data has been furnished by private industry.

Phase I is now finished.

Phase II consisted of an examination of every 7.5-minute preliminary geology worksheet completed for the 1976 Geologic Map of Arkansas and every 7.5-minute USGS topographic map for the state. This was done to extract mineral resource data, like gravel pits, quarries, mines, etc. The original worksheets are on-file with the AGC and are available for staff examination. Supplemental to these worksheets are the COGEO geologic quadrangles completed by B. R. Haley and C. G. Stone for the Ouachita Mountains region, but never published, and the STATEMAP geologic maps for the Cretaceous rocks of southwest Arkansas and for north-central Arkansas. The principal information collected by the examination of the geologic maps is data concerning the geology and newer commodity sites noted during field mapping. Phase II is now complete.

For **Phase III**, it is necessary to field check all sites without complete data or accurate latitude/longitude, due to poor location data in published literature. This amounts to ~50 percent of the reported sites. New locations in the field, when encountered, are also being added during the fieldwork phase. This portion of the project started in October, 2005. Three counties were completed by the end of 2005.

DATA LIMITATIONS

The present compilation has not been completely field checked. Field checking is essential to provide ground truth and to add missing information to the data set. Maps with data points on 7.5-minute topographic map base allow for reasonably accurate placement of latitude/longitude values using Delorme's 3-D TopoQuads® software. Latitude/Longitude data were taken from this software, unless this information was provided by the original Data Source. All latitude/longitude data is given as decimal degrees so no conversion is necessary for plotting of data by mapmaking software. The locations given in some literature sources are given only to the section, so these must be field visited for an accurate latitude/longitude to be obtained. The current data is also limited by the age of the topographic map from which the data was extracted. Data from a 1961 vintage map concerning mineral commodity activity will not be as complete as data from a 1995 map. Major improvements include adding additional sites discovered during field checking and the elimination of false sites from existing topographic maps.

PROJECT COMPLETION DATE (?)

The project began Phase I in early July of 2001 and it was essentially completed early 2002. Phase II was finished during the Spring of 2003. Phase III was started in early Fall of 2004, piggybacked onto the National Geochemical Survey of Arkansas USGS grant work. Enough field work has now been done to estimate that the field checking portion will be finished by late 2011. However, it must kept in mind that this project will *never be completely* finished. It is ongoing. As new information and data is brought in by staff and interested citizens, it will be added to the data set. AGC geologists continue to add field data from their mapping projects into the database. The important thing is that, over some relatively short period of time, all mineral commodity information for Arkansas will finally be pulled together into a single working unit.

PRESENT/FUTURE USE OF PROJECT DATA

Other than a quick and ready reference source of basic mineral commodity data, the data base is expected to be used by the next generation of geologic mappers and map makers in the AGC. Once a quadrangle is digitally mapped, then additional types of maps with mineral commodity layers may be produced through the import of data from this spreadsheet. Latitude/Longitude is the common denominator so that locations may be pinpointed and additional information provided in clickable text boxes on additional digitized map layers. A recent trial County Geologic Map for Sevier County was published by the AGC. This map was built in Arcview® software and utilized the AMC county data as a layer for the commodities. Since the data is available in an easily searchable and sortable format in the spreadsheet, users may customize the data set for their particular needs.

Examples include:

- A major out-of-state quarry operator was interested in obtaining data concerning quarries sited along the Arkansas River. The data on crushed stone was extracted for 10 counties and forwarded to the company as an email attachment.

- An in-state quarry operator requested quarry information on 3 counties and later stated that I had saved him at least 3 months of library and field work!
- A Dallas, Texas stone retailer requested information on active dimension quarries in Arkansas. The data was extracted and forwarded by email attachment.
- A County Judge requested information concerning potential sources of gravel in his county since transportation costs had increased dramatically. All gravel pits, both active and abandoned were sent to him with the suggestion that a plot of that information on a county base map would show him where historic gravel producing areas are.
- A land owner requested information relative to past underground coal mine operations and his property. Data was recovered that indicated that his property was underlain by a major abandoned underground operation from the early 20th Century.

All of these requests were answered within a one-day turn around time. Now that's government service going in the right direction!

ACKNOWLEDGEMENTS

The author wishes to thank all who have published or filed accurate mineral commodity information in the normal course of their work in Arkansas. Also, the individual County Judges of Arkansas have been most responsive and helpful concerning this project and furnishing data for it. Individual property owners have been very cooperative during the field stage of the project, both in providing access to and oral history concerning sites. I wish to also thank those individuals who expressed an interest in the project during my first poster session to the Industrial Minerals Forum. They let me know right away that this was a most worthwhile effort. I also wish to thank my former supervisor, Benjamin F. Clardy, for imparting to me his interest in mineral deposits of Arkansas and the field training and map reading skills. Finally, I must also thank the several State Geologists of Arkansas – William V. Bush, Mac B. Woodward, and now Bekki White – for recognizing the value of this project to Arkansas and giving it their continued support.

The mineral resources of Virginia database: Wytheville 0.5° by 1° project area

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ABSTRACT

The Mineral Resources of Virginia Database (MRV) contains information about specific mineral occurrences, prospects, mines, quarries, and other mining and processing sites of base metals, industrial minerals, and energy resources in the Commonwealth of Virginia. During work in the Wytheville 0.5° by 1° project area, the range of attributes collected for sites has been expanded to include other types of digital data to increase the utility of the database for GIS applications, user interest, and to facilitate traditional publications that document the past, present, and potential future mineral resources of Virginia.

The Wytheville 0.5° by 1° project area is bounded to the north by the 37-degree parallel, to the south by the North Carolina and Tennessee State Lines, and to the east and west by the 81st and 82nd meridians, respectively. Many of the geologically controlled trends of these resources continue across the political boundaries with North Carolina and Tennessee.

Traditionally, a mineral resource database is integrated into geologic projects yielding bedrock geology, surficial geology, and hazard/resource maps as hardcopy and digital products. The incorporation of digital images, including historic photographs, aerial photography, and mine maps, adds significantly to the interest of database users and their understanding of the extent of the occurrence and mining methods and the stratigraphic or structural controls of resource deposition.

The value of the database extends well beyond the documentation of played-out mine sites and includes: archival records of historic mining methods and sites, the identification and characterization of mined-land/orphaned-mined-land sites, geospatial relationships of individual and related mineral resource commodities for depositional modeling and prospecting, environmental hazard distribution with respect to transportation and utility corridor planning and siting, and environmental and resource considerations with respect to land-use planning.

Hubbard, Jr. David, A., and Hostettler, Karen K., 2006, The mineral resources of Virginia Database: Wytheville 0.5° by 1° project area, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

The identification and characterization of mineral resources is a significant component of a state geologic survey's duties. In the Commonwealth of Virginia, a search for mineral fertilizers that could be used to revitalize the Old Dominion's farmed-out-soils was the concept that funded the formation of the Virginia Geologic Survey in 1835. By 1957, the identification and documentation of mineral resources was considered such an important duty that the Virginia Geologic Survey was renamed the Virginia Division of Mineral Resources. The Mineral Resources of Virginia Database (MRV) was developed, circa 1991, as an in-house data set of the mineral resources within the Commonwealth of Virginia. At the time, the available mineral resource databases that contained mineral resource information for Virginia were the U.S. Bureau of Mines' (USBM) MAS/MILS database, which was predisposed toward production information for mined sites, and the U.S. Geological Surveys' (USGS) MRDS database, consisting of geologic information about metallic and some industrial mineral mines and quarries, prospects, and occurrences. There were access problems with both the USBM and USGS databases, which prompted the development of an in-house database that could cater to and serve the needs of the Division.

The initial format of the MRV database was a set of hardcopy maps (7.5-minute USGS topographic maps) with plotted locations of mineral occurrences, prospects, mines, quarries, and other mining and processing sites of base and precious metals, industrial minerals, and energy resources in the Commonwealth of Virginia. Data on the map margin might have included site name, commodities, type of site (mine, prospect or occurrence), DMME/DMR repository number, and literature references. By the mid-1990s the map locations had been digitized and an electronic database started. In 2003, the lead author started working with the Microsoft Access-based MRV database in the Wytheville 0.5° by 1° project area and began to expand the data collected. Changes included additional specific data-fields, digital imagery, and incorporation of GPS technology.

The project area is located between 81st and 82nd meridians of longitude and the 37-degree parallel of latitude and the Virginia boundary with Tennessee and North Carolina (Figure 1). The principal counties covered in the project are Grayson, Smyth, Washington, and Wythe and fractions of Bland, Carroll, Russell, and Tazewell counties. The physiographic setting includes parts of the Appalachian Valley and Ridge, and Blue Ridge provinces, from the northwest to the southeast, respectively. The rock types include sedimentary, slightly metamorphosed sedimentary, slightly metamorphosed plutonic, and metamorphic (metasediments and metavolcanics) rocks. Most geologic map units in the area are oriented NE-SW and extend into the northern portions of North Carolina and Tennessee to the south of the project area.

MINERAL RESOURCES

Mineral resources of the Wytheville 0.5° by 1° project area have been utilized since the late eighteenth century and include aggregate, barite, clay (brick, ceramics, and other structural clay products), coal, dimension stone (dolostone, granite, limestone, quartzite), gas and oil, gold, gypsum, iron, lead, lime, manganese, marble (agricultural lime and monument stone), salt, saltpeter, shale, travertine-marl (agricultural lime), and zinc. Perhaps the most well known exploitation of a mineral resource in the project area, occurs at Saltville, where the salt has been mined since the late 1700s. Extraction was by solution mining (Figure 2a) from the evaporite sequence in the Mccrady Shale. Salt mining was discontinued in 1969, but in 2000, salt production was resumed. Iron mining was of major significance in the area and included at least fifteen iron furnaces, which operated between 1794 and 1914. The known blast furnaces include: Bell & Kincannon's Furnace, 1810-1870; Beverly Furnace, 1880-1893; Cave Hill Furnace, 1882-1891; Grey Eagle Furnace, 1863-1893; Irondale Furnace, 1881-1893 (Figure2b); Little Wythe Furnace, 1810-1849; Marion Furnace, 1860-1864; Paulina Furnace, 1828-1858; Pine Hope Furnace, 1800-1845; Raven Cliff Furnace, 1876-1892; Speedwell Furnace No. 1, 1794-1851; Speedwell Furnace No. 2, 1873-1893; White's Furnace, 1800-1839; White Rock Furnace, 1875-1914; Wythe Iron Company Furnace, 1873-1892. The majority of iron ores exploited in the area were replacement ores deposited within and adjacent to the stratigraphic position of the Cambrian-aged Shady Dolomite and simultaneously associated with the dissolution of this carbonate unit. These limonite, goethite, and hematite ores have variously been termed: valley ore, mountain ore, and limestone limonites (Watson, 1907; Stose, and others, 1919; Miller, 1944). Additional mined iron deposits include iron carbonate (siderite), magnetite, sulfides, and gossen ores. Many of the replacement iron ore sites were also rich in manganese and were subsequently re-mined for manganese, especially in the Glade Mountain District, in the late 1800s, World War I, World War II, and Korean War eras (Stose, and others, 1919; Miller, 1944). Although the area is immediately adjacent to Austinville, where lead-zinc mining began circa 1750, lead-zinc mine sites within the project area are of minor significance and include the Rye Valley mine (1890s), Calhoun prospect, Keesling prospect, Livesay prospect, Martin prospect, McCarter prospect, Mount Ephraim prospect, Riggles prospect, Scott prospect, Taylor prospect, and Van Hoy prospect (Currier, 1935).

The only other commercial metallic resource that was worked in the area is gold. No significant production of gold has been reported in the area, but workings include: Walt Williams mine, Baker Branch prospect, Dixon prospect, Gold Hill prospect, Kinzer prospect, Marion Miller prospect, and Osborne prospect.

Clay resources were historically exploited for utilitarian uses and are of widespread distribution, so they commonly were only of local interest. The two most prevalent uses were for brick and ceramics. The earliest brick manufacturing was at or near individual house sites. Area historic commercial brick manufacturers include the Virginia Vitrified Brick and Paving Company at Chilhowie (1890s) and the Marion Brick Company (1920s-1940s) (Figure 2c). Currently, General Shale operates a plant near Atkins. Early ceramics consisted of earthenware, a porous and low temperature ceramic that required a glaze to seal it, and after 1840, stoneware, a higher temperature ceramic in which the clay is vitrified and produces a non-porous product. An initiative to capture knowledge of the area potters is currently underway and being led by the William King Art Center in Abingdon. They are co-funding both archaeological and historic studies (Espenshade, 2002; The Ottery Group, 2004; Maust-Blosser, 2005) and working with local ceramic researchers. There were at least 52 potters who worked with earthenware and/or stoneware in the project area (Moore, J.R., 1983; Espenshade, 2002) (Figure 2d).

Dimension stone use dates to the late eighteenth century. Many of the quarries are small and local to the building site and thus are rarely seen and documented. The most commonly utilized materials were limestone and dolostone. Quartzite was used in the construction of most iron furnaces. In the 1930s, Italian stone workers were brought into Grayson County to work the Stripped Rock granite, which was used for bridge and culvert construction along the Blue Ridge Parkway in the Roanoke area in the late 1930s and early 1940s. In the late 1800s, monument stone was worked in the Mt. Carmel area near Marion, from a deposit of cave onyx (marble) (Figure 2e, 2f). The only other known use of area marble, a traditional metamorphic marble, was as an agricultural ground lime. Other lime products include a travertine-marl aglime that was dug, screened, and spread on area fields in the 1940s, and traditional lime. Area lime kilns range from the most primitive of kilns to a couple of brick, silo-type, kilns (Figures 3a, b, c) and have used both limestone and dolostone. Extensive quarrying of dolostone for a chemical stone for the Olin-Matheson Company occurred at the Henry quarries, Porterfield quarry, and the Worthy quarry in Smyth County, as well as a series of small quarries near Mt. Carmel. Limestone and dolostone have been quarried extensively through the Interstate 81 corridor in Wythe, Smyth, and Washington county project area for crushed stone (Figure 4). Elsewhere in the area, granite, quartzite, and sandstone have been quarried, in addition to limestone and dolostone, for use as crushed-stone aggregate. Sand and gravel locally were dug and used for road-base material by Virginia Department of Transportation (VDOT). Silica sand is mined on Sand Mountain near Wytheville, in Wythe County, and was mined along Brushy Mountain in Smyth County from the Erwin Formation sandstones.

Barite was first prospected in the area in Grayson County circa 1850 in pre-Cambrian-aged metamorphic rocks (Edmundson, 1938). Barite was mined in Smyth (1875 to 1906) and Russell Counties as residual ores concentrated upon dissolution of the carbonate host-rock of the Ordovician-aged Beekmantown Formation (partial equivalent of Knox Group) (Watson, 1907; Edmundson, 1938). Mines and prospects include: H.P. Copenhaver mine, Cornett-Hull mines, Counts mine, Eller mine, Faris mine, Henderlite mine, Honaker mine, Hubbard mine, McDonald mine, Miles-Gardner mines, Myers-L. Copenhaver mines, Orr mine, Shanklin mine, Stump mine, Groseclose prospect, J.C. Groseclose prospect, Cox prospect, Martin prospect, Moore prospect, Phipps prospect, Poole prospect, Porter prospect, Rudy prospect, F. Vaught prospect, and S. Vaught prospect.

Gypsum occurs along a 20-mile belt of Mccrady Shale from Plasterco to 3 miles west of Chatham Hill in Smyth and Washington counties and was mined from circa 1815 to 2000. Mines and workings include the Buchanan mine, Barnes mine, Locust Cove Mine, Pierson Plaster bank, and Taylor’s plaster bank. Early use was as a land plaster and for *plaster of paris*, and later for wallboard.

Shale is used locally for fill and farm roads and for brick manufacture. General Shale manufactures brick in the Atkins-Marion area.

Perhaps the most poorly known mineral resource industry of the area, was niter or saltpeter. Although cave nitrates were utilized prior to the Civil War, the project area includes parts of the Confederate Nitre Bureau’s Nitre Districts 1 and 2. Only six area saltpeter caves are known to have been mined for nitrates (Figure 5) for manufacture of black powder (gunpowder).

Fuel or energy resources that have been worked in the area include oil and gas and coal, all of which are trivial in production. Most area oil and gas wells are capped, however some of the old solution salt wells are presently used for gas storage. The reactivation of salt mining, in 2000, was as a partnership initiated to create new underground storage capacity for natural gas. The area coals are part of the Valley coal fields and are Mississippian in age, locally deformed, and range from medium volatile bituminous to semi-anthracite (Brown and others, 1952; Gwin and Henderson, 1984).

Three coals are locally of minable-thickness, two of which are correlated with the Merrimac and Langhorne coals. Area coal mines include Boyd's mine, Vandever Crabtree mine, Conn Simms mine, Davidson mine, and Howdyshell Hollow mine.

MRV DATABASE

The initial format of the Mineral Resources of Virginia Database was a set of 7.5-minute topographic maps, on which mines, quarries, prospects, mineral occurrences, and some processing sites were plotted and accompanied by symbols identifying each site as an active or abandoned mine or quarry, shaft, prospect or occurrence. Each map was divided into ninths using the two-and-a-half degree tick-marks of latitude and longitude with site numbers keyed to their respective ninths. Along the map border, site information included the site number, name, commodities, type of site (mine, prospect or occurrence), DMME/DMR repository number, and a literature reference.

During the mid-1990s, map locations were digitized and the site information on the map margin was entered into a newly designed Microsoft-Access database. Some of the modifications made to the database before 2003, included fields for the geologic formation name, the site reporter, date of visit, and comment field. A screen capture image of the data entry screen shows the data fields available in 2003 (Figure 6).

With the commencement of the Wytheville 0.5° by 1° project area initiative, additional types of data were collected and recorded and another stage in the evolution of the database began. One significant change was the addition of digital imagery for each site. A picture can convey a vast amount of information about a mine site and mining methodology. At least one digital site image was collected for each site as were historic images, which were digitized. For very large sites, a segment of a low-altitude aerial photograph was digitized. Additional data fields were added for site imagery, the mine district, feature dimensions, accessory minerals, deposit characterization (strata unit or subunit, surficial unit, hydrothermal deposit, etc.), strike and dip, site lead (initial information source), reference citing (expanded beyond agency reference), ID number, DMME ID or sub-agency ID number, date site opened, latitude and longitude in decimal degrees, elevation, GPS qualifier (accuracy key for type of GPS data or other type of coordinate calculation method), published illustration (figure, diagram, or map), production data, production era, Orphaned Lands classification, LA abrasion (500 cycles) data, absorption data, specific gravity, and mineral resource classification (construction material, industrial rock or mineral, metallic, energy resource). A screen capture image of the data entry screen shows the data fields available in 2006 (Figure 7).

The site image is linked to each site report so that it appears on the screen view of a site report, while other imagery is linked to display when the "other image" button is double clicked. A site publication report form is under development to capture a site's information in a standardized format for publication.

MRV DATABASE UTILITY

The traditional use of the MRV Database has been for in-house research and reviewing mineral resource sites for information requests, and other targeted research, including commodity studies, mineral resource information for geologic map and report development, and site inventory for the Orphaned Lands Program. Mineral resource information is important in the development of bedrock geology, surficial geology, and geologic hazard/resource maps and summarizing the significance and history of mineral resource use. Commodity and accessory mineral information can be queried and coupled with GIS applications to use in depositional modeling and prospecting. Mineral resource sites also are important with respect to hazards associated with mined and processing sites. Database inquires can be coupled with GIS applications to screen land-use proposals, including transportation and utility corridor planning and siting.

An initiative under development is a screening classification for the Orphaned Mine Lands (*those lands disturbed by surface mining for minerals other than coal that have not been reclaimed*) Program, whereby sites would be screened for hazards as they are evaluated for the MRV database. Such a classification would identify hazards, thus targeting them for follow-up prioritization and reclamation, while unnecessary field visits to the low priority sites would be minimized.

DISCUSSION AND SUMMARY

As a relatively young, yet important, database, the MRV project has morphed from an extremely primitive map-based dataset into a utilitarian database within its 15-year history. The addition of photographic imagery and imagery of figures, sketches, and maps has enhanced and enriched the story that many a mineral resource site record can convey. The timing of such an evolution in the MRV database is fortuitous. As with other governmental geologic surveys, we have perceived the need to shift the audience focus of our reports beyond our peer group of professional colleagues, to related industry, the public, and government as we compete within government for a shrinking share of the taxpayer dollars.

The public's perception of the importance of mineral resources in their homes, their transportation corridors, and the physical utility conveyances, is out of cycle with mineral resource product demand. It seems that there is an direct proportionality between the public's grasp of their dependence on mineral resources to their lack of tolerance for the industries that harvest and process those resources.

In the rural area that this project area spans, the communications conveyed during the active field work of locating and documenting mineral resource exploitation and processing sites is an important link in the community awareness of mineral resources exploitation, jobs, and how the particular mineral resources were and are utilized in society. A significant interest in old imagery of mine sites, equipment, and processing is expressed by young and elderly landowners of old mineral resource sites and many venture questions or offer anecdotal stories of what they heard about the mining era. Many individuals question why the Commonwealth of Virginia is interested in a particular old site. Sometimes a spark of interest, if the site may yet have a bit of value to coax from the ground, is conveyed by the expressions of longtime-landowners during a conversation. But many newer landowners are fearful that the inventory is the first scene in their worst nightmare. To all, the answer is that the state is completing an inventory of mine, prospect, and mineral occurrences for a statewide database. Our understanding of the mineral resources that were found in the past, along with the knowledge of what and where we presently are mining will contribute to our understanding of how best to utilize our mineral resources in the future. Most mineral resource exploitation ends when the remaining resource is no longer economically viable, either by depleting the resource, falling commodity prices, or by land-use constraints. New or renewed mining requires a significant amount of investigation, proving of the resources, and site permitting.

Aside from the opportunity to learn about historic mining operations, MRV inventories also serve the public as the mechanism whereby mined and processing site hazards are brought into review for the Orphaned Mined Land Program and prioritized for reclamation.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the information provided by and discussions with colleagues Palmer Sweet (retired), Jim Lovett, Michael Upchurch, Bill Whitlock, Gerry Wilkes, Billy Lassetter, and Ed Erb in understanding the history of the project and ideas on where the project may and should lead. Harry Haynes, manager of the Museum of the Middle Appalachians, in Saltville, VA, provided imagery and information about solution mining of salt in the vicinity of Saltville.

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FIGURE 1 Location map of the project area in southwest Virginia, USA.

FIGURE 2a Mathieson Alkali Works Salt Wells, circa 1900, near Saltville, image courtesy of the Museum of the Middle Appalachians.

FIGURE 2b The Irondale Furnace was active from 1881-1893, along Francis Mill Creek in Wythe County, VA.

FIGURE 2c Old image of Marion Brick Company beehive kilns, along Staley Creek in Smyth County, VA (Byrd and Williams, 2005).

FIGURE 2d Stoneware crock made in late 1800s by area potter John B. Magee in Washington County, VA (Maust-Blosser, 2005).

FIGURE 2e and f (e): Peter Mock's cave onyx gravestone in a Washington County, VA cemetery. The edge view (f) is looking at the distinctive calcite crystallization perpendicular to the onyx layers.

FIGURE 3a Primitive lime kiln, where rock is removed and replaced in quarried area with fuel and burned. After removal of lime, only a small quarry with traces of calcined lime-rock remain, seen under yellow GPS case. Waste partially calcined rock is visible on the mound in the left foreground.

FIGURE 3b Traditional lime kiln.

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FIGURE 3c A brick, silo-type, lime kiln.

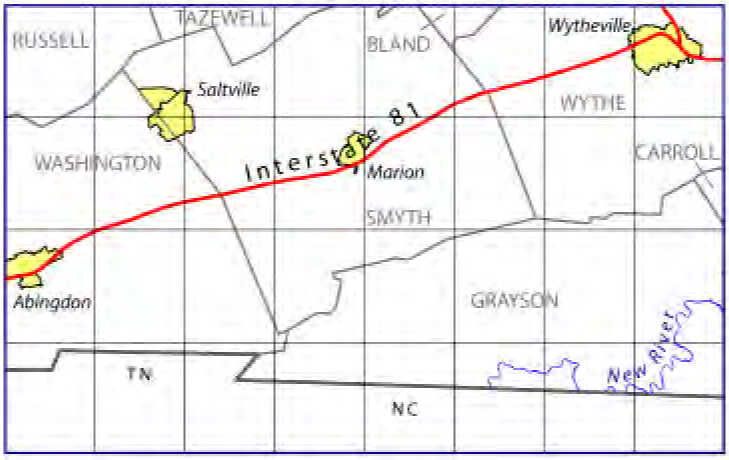
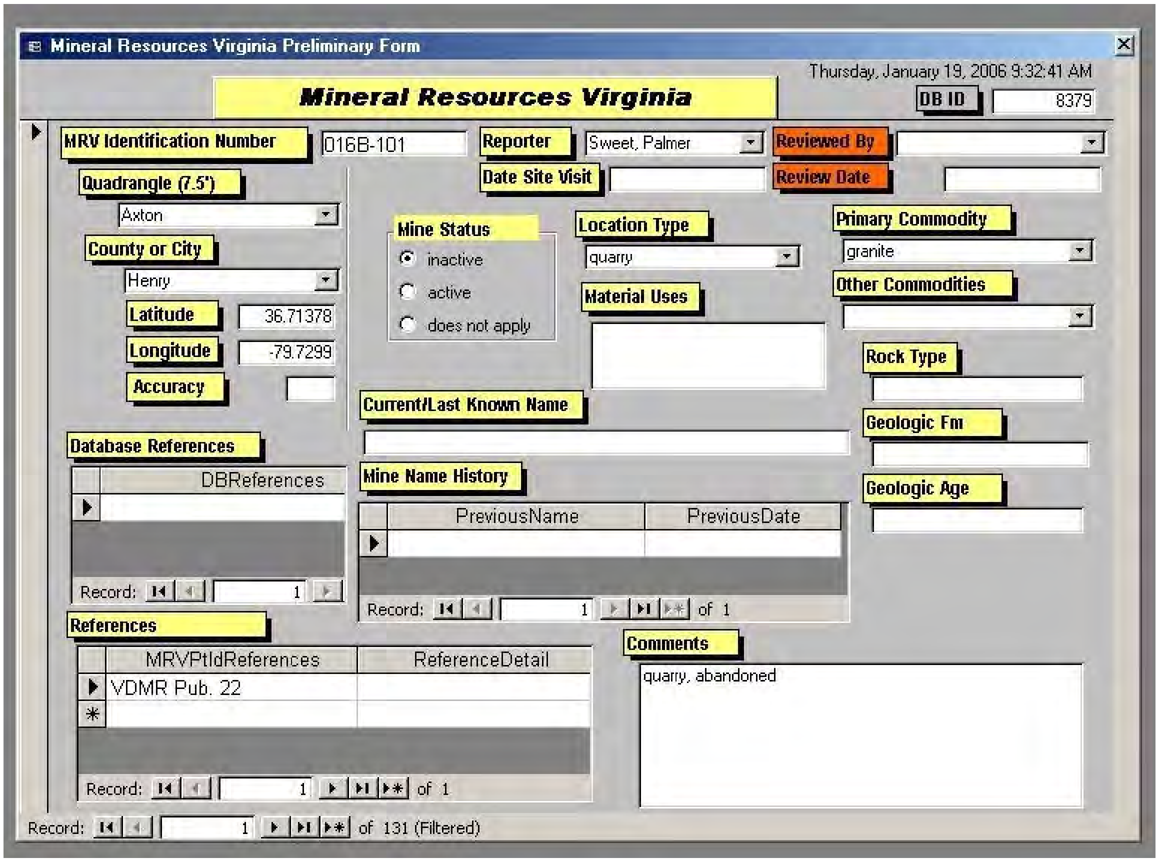


FIGURE 4 MRV project area depicting I-81 corridor.

FIGURE 5 Wooden rail system used in Civil War era to haul nitrate-rich sediments through a project area saltpeter cave.



Mineral Resources Virginia

Thursday, January 19, 2006 9:32:41 AM

DB ID: 8379

MRV Identification Number: 016B-101

Reporter: Sweet, Palmer

Reviewed By:

Date Site Visit:

Review Date:

Quadrangle (7.5'): Axton

County or City: Henry

Latitude: 36.71378

Longitude: -79.7299

Accuracy:

Mine Status: ● inactive ○ active ○ does not apply

Location Type: quarry

Material Uses:

Primary Commodity: granite

Other Commodities:

Rock Type:

Geologic Fm:

Geologic Age:

Current/Last Known Name:

Database References

DBReferences

Record: 1

Mine Name History

PreviousName	PreviousDate

Record: 1 of 1

References

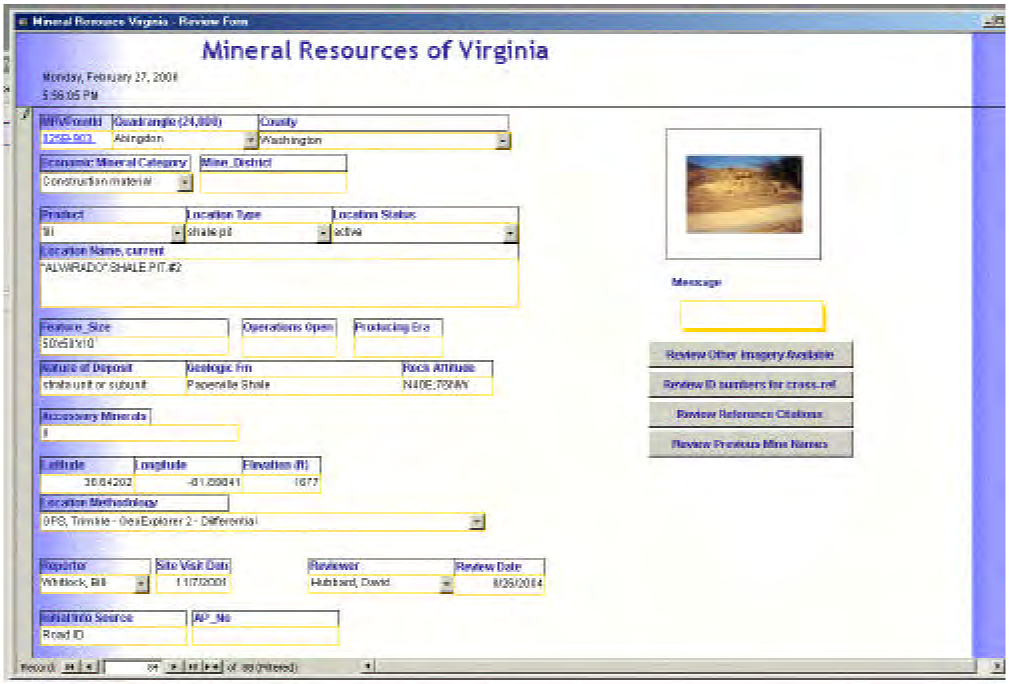
MRVPtIdReferences	ReferenceDetail
VDMR Pub. 22	

Record: 1 of 1

Comments: quarry, abandoned

Record: 1 of 131 (Filtered)

FIGURE 6 MRV Database screen for data entry in 2003.



Mineral Resources of Virginia

Quadrangle (24,000): Abingdon

County: Washington

Economic Mineral Category: Construction material

Mine_District:

Location Type: shale pit

Location Status: active

Location Name, current: "ALVARADO" SHALE PIT #2

Feature_Size: 50x50'x10'

Operations Open:

Producing Era:

Nature of Deposit: strata unit or subunit

Geologic Fm: Paperville Shale

Elevation (ft): 1677

Location Methodology: GPS, Trimble - GeoExplorer 2 - Differential

Reporter: Whitlock, Bill

Reviewer: Hubbard, David

Initial Info Source: Road ID

AP_No:

FIGURE 7 A screen captured image of the data entry screen showing some of the data fields available in the 2006 MRV database iteration.

Session Ten

Very white commercial grade muscovite mica from a new sedimentary source, central Georgia, USA

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ABSTRACT

A variety of grades of very white muscovite mica have been in production for the past five+ years from sedimentary clays and sands in Central Georgia. The mica is naturally concentrated near the base of lens-shaped commercial grade sedimentary kaolin deposits, and also disseminated in associated quartz sands and in old kaolin processing waste materials. The same weathering and bacterial alteration processes which have transformed the Cretaceous and Early Tertiary Georgia kaolins from dark organic deltaic muds to white pigment-grade industrial clays have also removed discoloring iron from the associated mica, resulting in an unusually white grade of natural muscovite.

Further, this same chemical alteration has removed some potassium from the muscovite atomic structure, resulting in an easily delaminated residual mica which can be cleaved to uncommonly fine, high bulking, high-aspect-ratio flake shaped products. The peculiar alteration history of these sedimentary micas enables production of some of the whitest, finest particle size, and thinnest aspect ratio mica products on the world market today.

Raw mica feed is obtained from kaolin and sand processing by-product waste material, and also from beneath the useful base of abandoned kaolin mines. The resulting wet processed ultrafine and filler grade muscovite mica products find ready markets for paint, plastics, cosmetics, mold release, thermal and electrical insulation, epoxy, polymer, and dry wall joint cement applications. Current muscovite product production and sales from the Georgia Industrial Minerals, Inc. operation in Washington County is more than 35,000 short tons per year.

Pickering, Sam M., Jr., and Avant, David M., Jr., 2006, Very white commercial grade muscovite mica from a new sedimentary source, central Georgia, USA, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

Traditionally, muscovite mica has been produced from hard-rock igneous sources; principally from granite pegmatites, alaskites, schists, etc. In the U.S. such micas are mined from hard-rock sources in North Carolina, Arizona, Georgia, New Mexico, South Carolina, and South Dakota (Hedrick, 1999). Imports have come from similar sources in India, Canada, Finland, Argentina, and Japan (Tanner, 1994), (Clark, 1983). Although it has long been well known that some of the better grades of mica often come from the softer and more easily mined upper saprolite weathering zone of the hard-rock sources, to our knowledge commercial muscovite micas have never before been produced from sedimentary sources. The advantages of development of high quality wet ground sedimentary micas have proven to be considerable.

SOURCES OF SEDIMENTARY MUSCOVITE MICAS

In 1995 production of mica products from sedimentary sources began at Georgia Industrial Minerals, Inc. operations near the small central Georgia coastal plain town of Deepstep, in Washington County. This area is the world center of very white sedimentary kaolin production for paper, paint, plastic, adhesive, and ceramic applications (Hurst and Pickering, 1997).

Mica has long been regarded as a detrimental impurity in the kaolins, as it has a ruinous effect on slurry viscosity and causes scratches and flaws in paper coating (Pickering and Avant, 2000). The kaolin industry goes to great pains to remove all possible mica from their products, discharging it as a useless material to waste impoundments. Mica associated with the kaolins is depleted in potassium, a key factor for production of superior grade products.

Georgia Industrial Minerals obtains their crude muscovite mica from the following three different ore sources:

- From micaceous high viscosity kaolin which has been left as waste at the bottoms of worked-out kaolin mines. Muscovite has been naturally concentrated at the base of the lens-shaped sedimentary kaolin deposits during their formation. It probably settled there as part of the clastic fining-upward process of kaolin deposition in the Late Cretaceous to Early Tertiary, and may also have crystallized in place by authigenic overgrowth of micron-size detrital sericite/illite. Typically, the waste clays left in the bottoms of many worked-out mines contains about 50 percent bad viscosity kaolin, 30 percent quartz sand/silt, and 20 percent +200 mesh muscovite mica. Mica from the bottoms of clay mines tends to be finer in crude particle size, whiter and brighter, lower in potassium, higher in natural aspect ratio, and much more easily cleavable by delamination than the associated sand micas. Mica from the younger fine particle size hard kaolins often contains troublesome amounts of dark graphite and biotite, while mica from the older coarse kaolins typically contains much less.

- From white waste sand overburden that is being removed from the nearby active kaolin mines and from the sand sequences below the micaceous clays. The sands average about 75 percent quartz sand, 20 percent kaolin clay, and 2 to 5 percent muscovite mica. This sand mica is distinctly coarser in particle size, thicker and lower in natural aspect ratio, darker in color, higher in potassium, and considerably tougher and more difficult to delaminate than micas from the more highly weathered micaceous clays from worked-out kaolin mines.

- From by-product "useless" materials dredged from degritting waste disposal impoundment ponds that hold the coarse non-clay "grit residue" minerals separated during the kaolin refining process. Mineral content of these impounds varies with the distance from the waste discharge point. Coarse quartz sand settles first nearest the discharge point, thin flakes of muscovite mica settle somewhat farther out depending on their particle size and aspect ratio, and kaolin agglomerates lost during the degritting process settle farthest down the impound length toward the dam. Thus, if there has been only a single discharge point throughout the life of the waste impoundment, the dredge can be placed to produce almost any desired mineral percentage and concentration. A productive impound may yield from 5 to 20 percent mica that is intermediate in quality between the clay and sand micas. Dredging waste minerals from these impounds is a valuable service to the big kaolin companies, as they are costly to build, take up much otherwise valuable land, and always seem to fill with waste sooner than expected.

MICA MINERALOGY AND OPTIMUM CHEMISTRY

Chemistry

Normative ideal muscovite mica ($K_2O{\bullet}3Al_2O_3{\bullet}6SiO_2{\bullet}2H_2O,F$) contains some 45.2 percent SiO_2, 38.5 percent Al_2O_3, 11.8 percent K_2O, and 4.5 percent formula water (Dana and Ford, 1949). Hard rock muscovite, which is usually produced from a weathered saprolite zone, may contain 9 to 10 percent K_2O, while sedimentary muscovites from the Georgia kaolin district have benefited from K_2O content that may be from 4 or 8 percent.

X-Ray Analysis

X-ray diffraction can distinguish between low and high K_2O content micas by the relative intensity of the 10 angstrom peak at approximately the 9^o 2-theta position (Elser, Elliott, Wampler and Hames, 2001), and (Bailey, 1984). Generally, the lower the 10 angstrom X-ray peak, the less K_2O is present.

As has been indicated, typical sedimentary micas associated with commercial kaolin deposits in central Georgia are considerably depleted in potassium and iron compared with the well known hard rock muscovite micas.

Product Aspect Ratio

Further, the less K_2O is present in well-delaminated sedimentary mica products; the lower the loose bulk density, the finer the ultimate particle size, and the higher the particle thickness-to-width aspect ratio (and bulk density) becomes. In situ bacteria may well have consumed potassium along the mica cleavage planes as an essential growth nutrient.

Weathering and bacterial alteration have been thus been natural keys to enable development of a wide variety of high aspect ratio white mica products from these sedimentary sources. This has greatly reduced the energy needed to delaminate the crude muscovite to ultra-fine high aspect ratio thin, flat cleaved mica platelets.

The optimum chemical content for delamination to <10 micron median particle size very high aspect ratio sedimentary mica products seems to be 3 to 6 percent K_2O. Coarser filler grade joint cement mica product may range from 6 to 9 percent K_2O.

Product Brightness and Color

Similarly, weathering alteration and the action of anaerobic iron-reducing bacteria have significantly enhanced mica brightness and whiteness by having solubilized and removed discoloring iron oxides (hematite and goethite).

This iron oxide removal has enabled development of fine mica products in the green filter (547 *nm.*) brightness range of GE 80 to GE 86, in comparison with typical hard rock micas in the GE 60's to low GE 70's. Along with high brightness, the sedimentary micas are silver-white in color as opposed to the tan to gray color of typical hard rock micas. Hunter "L" grayness color values of fine sedimentary micas are in the 90 to 92+ range.

SEDIMENTARY MICA PROCESSING

In order to take advantage of the special quality features of the white sedimentary micas associated with kaolin mining, certain new industrial processing techniques have been developed and patented. The general procedure by which the crude material is processed is to blunge the ore to a water slurry, and wet sieve through a 5/16th inch screen to remove the coarsest silica sand. Commercial size quartz sand, mica, and kaolin clay are then separated by further wet screening and hydraulic classification.

Georgia Industrial Minerals (G.I.M.) has patents on: 1. Cleavage delamination and commercial sale of mica from sedimentary sources, and 2. A proprietary non-chemical process for separating mica from kaolin clay and other minerals. There are no chemicals used in the process, so mica products have very clean naturally charged particle surfaces (Avant, 1999). The following is a simplified flow scheme of G.I.M.'s basic wet processing methods:

GA. INDUSTRIAL MINERALS' MICA PROCESS SYSTEM

Blunge ore, using no
dispersant chemical
ß
Cyclone & screen
to separate coarse sand
ß

Proprietary technology
to separate mica slurry
from the other minerals
ß
Centrifuge, delaminate, and
repeat the cycle as needed
for the mica product
particle sizes intended
ß
Dewater, dry, and air classify
for further separation into
product particle size grades
ß
Package mica and ship, or
ship mica in bulk form.

Georgia Industrial Minerals has recently completed a considerable expansion of their mica production capacity. They are now capable of making approximately 52,000 tons per year of refined wet ground filler and ultrafine grades of white mica products. The products range in median particle size from 200 mesh (74 microns) to well under 10 microns (Avant, 1999).

WHITE MICA SPECIFICATIONS AND MARKETS

As has been mentioned, Georgia Industrial Minerals produces both the coarser filler grades, and also ultrafine grades of wet ground white mica products, for use in a wide range of industrial market applications (see Table 1).

Filler Grades

These coarser types of mica products (see Figure 1) are principally sold as a white mineral component of wallboard joint cement for interior home and office construction. They are used to fill and smooth the joints between gypsum plaster wallboard.

The flat mica flakes are essential to give board joints a very smooth finish, to provide reinforcing stiffness to avoid sagging before the joint cement sets up, and to give dry strength to resist age-cracking. A further advantage is that the mica acts as a relatively inexpensive opaque white mineral extender to minimize the amount of much more costly polymer adhesive needed in joint cement formulation.

Other coarse filler grade sedimentary mica market applications include use in paints and coatings, adhesives, caulks, dustings, dry lubricants, and plastics.

Ultrafine Grades

Wet ground ultrafine mica grades (see Figure 2) undergo multiple cycles of intensive cleavage delamination processing to reduce particle size and thickness; thereby greatly increasing aspect ratio.

TABLE 1 GEORGIA INDUSTRIAL MINERALS’ WHITE MICA PRODUCT APPLICATIONS

Market Category	Specific Application	SG-70	SG-90	CD-800	CD-1600	CD-2200	CD-3200	CD-325	OPTI brite	OPTI fine	OPTI sheen
Paint-Coatings	Cementious	X						X			
“ “	Industrial Primers		X			X	X				
“ “	Decorative	X					X				
“ “	Marine					X	X				
“ “	Roof	X									
“ “	Stucco	X									
“ “	Texture	X	X				X	X			
“ “	Trade sales		X								
“ “	Interior		X				X				
“ “	Forest (tree paint)					X	X				
“ “	Traffic	X	X				X				
“ “	Metal				X	X					
“ “	Automotive								X	X	
“ “	Pool		X			X	X				
“ “	Foundry	X	X				X				
“ “	Refractory	X	X				X				
“ “	Paper						X		X	X	X
Construction	Adhesives	X					X				
“ “	Asphalt products	X					X				
“ “	Caulking	X	X				X				
“ “	Epoxy flooring							X			
“ “	Grout	X					X				
“ “	Joint compound	X									
“ “	Roof coatings	X									
“ “	Sealants	X					X				
“ “	Spackling	X					X				
“ “	Fireproofing	X						X			
“ “	Roofing membranes	X									
“ “	Concrete patch	X									
Rubber	Dusting	X	X								
“ “	Mold release					X	X				X
“ “	Silicone dispersants					X	X				
“ “	Slab dips	X				X	X				
“ “	Wire & cable								X	X	
Plastics	Engineering plastics	X					X	X			X
“ “	RIM					X	X				
Automotive	Engineering plastics	X					X	X			
“ “	Asphalt products	X									
“ “	Gaskets							X			
“ “	Polish compounds	X	X								
“ “	Underbody coatings					X					
“ “	Paint			X	X						
“ “	Fenders					X					
“ “	Facia					X					
Miscellaneous	Cosmetics								X	X	X
	Lubricants										
	Pipe joint compounds	X		X		X					
	Refractory						X				

One of the major advantages of sedimentary muscovite use is that the mica has been naturally leached of just enough K_2O to greatly enhance ease and perfection of delamination cleavage to make far thinner, finer crystalline flakes. The intense scrubbing action during delamination also removes the traces of soft kaolinized zones along fresh mica cleavage plane surfaces.

SUMMARY AND CONCLUSIONS

The result of Georgia Industrial Minerals' development of sedimentary muscovite is a new range of specialty mica products of various particle sizes that have an exceptionally high aspect ratio (ratio of particle diameter to thickness) and particle surface chemical cleanliness (Avant, 1999). Particle size and shape are measured by Malvern laser diffraction Mastersizer, after ultrasonic mechanical dispersion.

Ultrafine grade mica is used as a white functional filler in paint and plastic formulation; as a pearlescent base for paints, plastics, and cosmetics; as a release compound for rubber and other molded products; as a vapor and water resistant coating on paper; as thermal and electrical insulation in plastics and epoxies, etc. Potential new marketing applications include extensive use in lightweight, tough automotive interior and exterior plastic panels, and as a substrate in pearlescent/colored and flake types of automotive paints.

Ultrafine delaminated grades of Georgia white sedimentary mica normally bring much higher prices than the coarser filler grades, and are frequently sold in the range of $400 to $1,500 per short ton f.o.b. the Deepstep plant.

For the future, these sedimentary micas offer the opportunity to make increasingly fine high aspect ratio white products down into the nanoparticle size range (less than 0.1 microns thick) to enable development of highly engineered composites for automotive, aviation, plastic, and aerospace applications.

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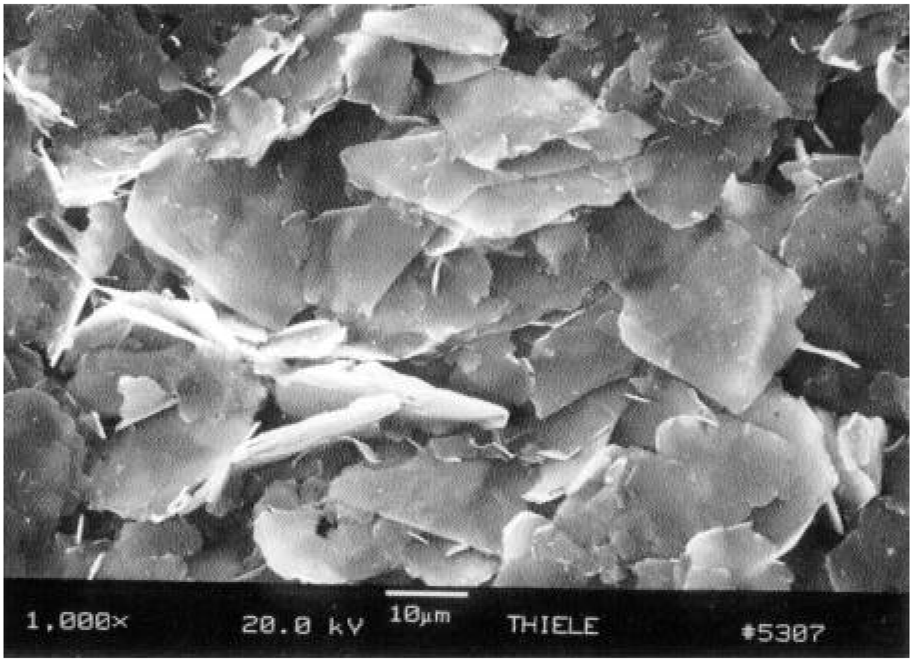

FIGURE 1. 1,000x magnification scanning electron micrograph of Georgia Industrial Minerals' Filler Grade delaminated muscovite mica product. Image by Thiele Kaolin Co. Research Department. Note 10 micron bar for scale.

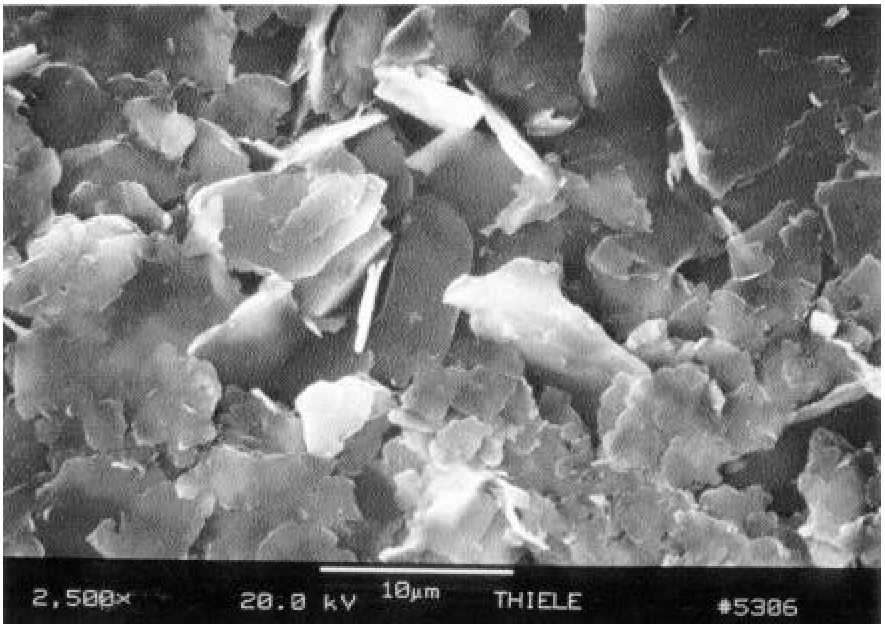

FIGURE 2 2,500x magnification scanning electron micrograph of Georgia Industrial Minerals' OPTIfine delaminated muscovite mica product. Image by Thiele Kaolin Co. Research Dep't. Note the 10 micron bar scale.

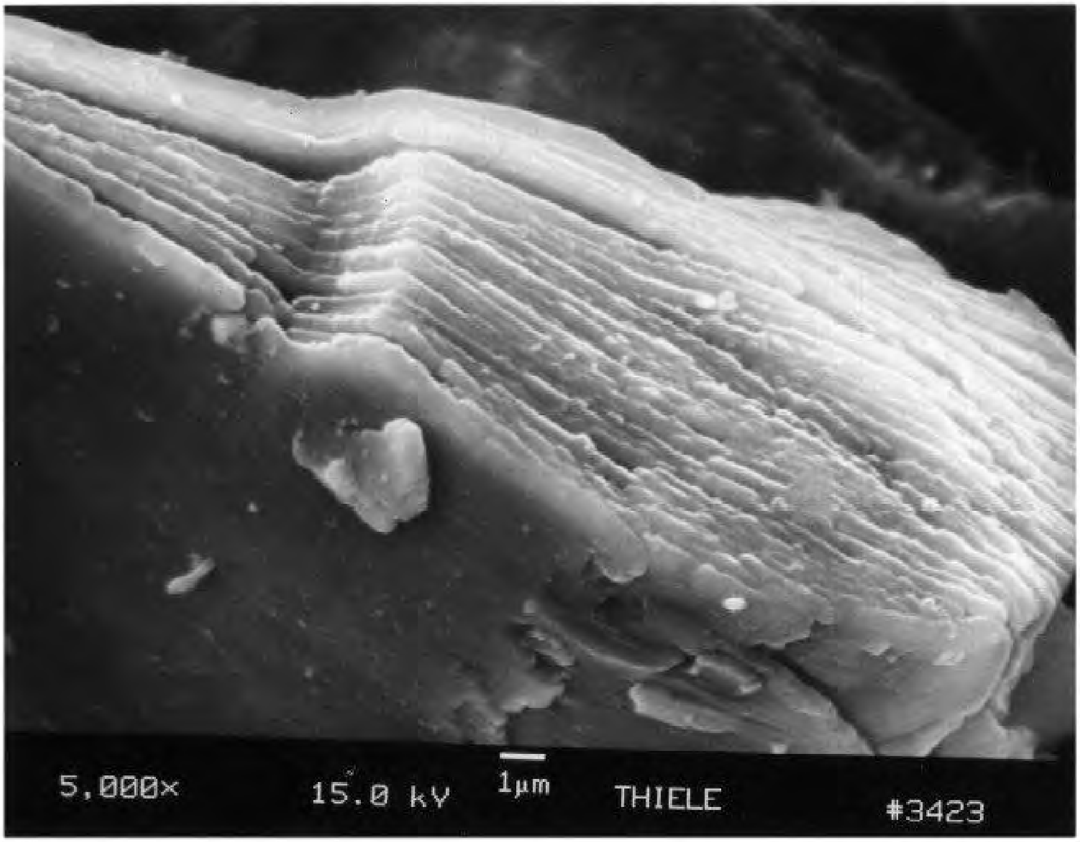

FIGURE 3 5,000x magnification scanning electron micrograph of Georgia Industrial Minerals' crude mica crystal before any industrial processing or delamination. Note the 1 micron bar scale, and how the cleavage planes have been opened on the right edge. This is thought to be due to weathering and microbial removal of K_2O, which has greatly eased the delamination process. Image courtesy of Thiele Kaolin Co.

Geology of the Old Hickory heavy mineral sand deposit, Dinwiddie and Sussex counties, Virginia

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ABSTRACT

Old Hickory is a heavy mineral sand deposit located 60 km south of Richmond, Virginia, USA. It has been an active mine since 1997, operated by Iluka Resources, Inc. The deposit is one of several known large occurrences of heavy mineral sand along the "Fall Zone" from southern Virginia to central North Carolina. These deposits were formed by marine processes, probably at the intersection of shorelines and major paleorivers, during multiple transgressive/regressive cycles throughout Tertiary time.

The pre-mining resource was estimated at 75 million tons averaging 9% heavy mineral. The average heavy mineral assemblage comprises 63% ilmenite, 19% zircon and 2.5% rutile plus leucoxene. The remaining non-valuable heavy minerals are predominantly staurolite, kyanite and sillimanite. The host sediment is a dominantly a clayey sand, which contains an average of 33% material finer than 75 microns, mainly clay. The original sediment was dominantly feldspar quartz sand and quartz sand. The clay currently disseminated in the deposit is thought to have been derived by weathering of feldspar and infiltration through the pile in descending meteoric water. Much of the sediment is massive from bioturbation, but locally planar cross-bedding, trough cross-bedding, planar laminations, and dewatering structures are preserved. Most fossils have been obliterated, but ophiomorpha and scolithus burrows have been identified. The bulk of the heavy mineral appears to have been deposited in foreshore and backshore (dune) facies, although some of the basal material may have been fluvial. Bouldery units serve as horizon markers and were probably deposited by debris flows related to storms or earthquake activity.

Unusual for heavy mineral deposits, Old Hickory experienced widespread faulting, which spanned pre- to post-mineral deposition. Most faults appear to be high-angle with reverse sense of shear. Ridges were uplifted, which commonly have high-grade heavy mineral along their flanks and in intervening swales. Paleochannels have been identified cutting across stratigraphy, which commonly have high-grade heavy mineral with elevated zircon content. The deposit can be separated into two parts: a topographically higher western, older part and a lower younger eastern part. The eastern part commonly has higher titanium values than the western part, and, in the eastern part, rutile and zircon values increase to the east and in cross-cutting paleochannels.

(continued)

The Old Hickory deposit formed where a paleoriver(s) met the sea along a prominent topographic break, which may have marked the point of maximum transgression from Cretaceous through Tertiary time. The deposit formed through multiple transgressive/regressive events in the same area with reworking and redeposition of heavy mineral in foreshore and backshore environments.

Newton, M. Claiborne, III, and Romeo, Andrew J., 2006, Geology of the Old Hickory heavy mineral sand deposit, Dinwiddie and Sussex counties, Virginia, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

INTRODUCTION

The Old Hickory heavy mineral sand deposit is located in Dinwiddie and Sussex Counties, southeastern Virginia. Heavy mineralization was discovered here and described in publication by C.R. Berquist, Jr. (Berquist, 1987). The deposit has been mined by Iluka Resources, Inc., since 1997, and is currently producing about 350,000 tons per year of ilmenite, zircon, rutile and leucoxene. Rutile and leucoxene are blended back into the ilmenite product which is primarily sold in the TiO_2 pigment market. Zircon is sold separately, primarily to the ceramics industry.

The Old Hickory deposit is one of several locations of heavy mineral concentration lying along the "Fall Zone" from central Virginia to central North Carolina (Figure 1). This zone roughly marks the western edge of Cenozoic coastal plain sediment overlap on Paleozoic and Precambrian piedmont crystalline basement rocks. The Fall Zone is so named because it is a topographic break causing rapids in rivers, and north of Old Hickory it is marked by a scarp of several meters relief at around 80-90 meters elevation, which is at least as old as 5-10 million years BP (Howard, et al., 1993). The maximum height of the westernmost (oldest) heavy mineral sand at Old Hickory is 90 meters and the basement underlying it is at 80 meters elevation and progressively slopes off the east, suggesting that the Old Hickory deposit formed on top of the Fall Zone scarp.

The segment of the Fall Zone from central North Carolina north through central Virginia is a promontory with Piedmont basement rocks in contact with Miocene-Pliocene coastal plain sediments (Figure 1). Cretaceous to Oligocene sediments are absent along this segment of the Fall Zone, yet they are thick to the south where the Fall Zone bends westward forming an embayment in southern North Carolina, South Carolina and Georgia. It is likely that in southern Virginia and northern North Carolina, these ages of coastal plain sediments were successively eroded and reworked by younger transgressive/regressive events. All major known heavy mineral deposits along the Fall Zone occur on this promontory. The Fall Zone deposits are unique among southeast U.S. heavy mineral deposits in that they have high clay fines content, averaging around 35%, and they contain exceptionally high-grade heavy mineral, commonly averaging 6-10% heavy mineral.

STRATIGRAPHY AND PETROLOGY

Host sediment in the Old Hickory deposit consists mainly of angular to sub rounded medium to fine quartz and iron-stained kaolinitic clay. Sands within the heavy mineral-enriched zones are well sorted to very well sorted, with rare grains greater than 2mm. The deposit consists predominantly of paleobeach sands with less abundant dune facies and possible fluvial facies. Two major periods of heavy mineral deposition are recognized, informally called the older and younger units, and are delineated in Figure 2. The older deposit has an elevation range of 42-90 meters and the younger deposit ranges from 53-73 meters. Terraces are locally well-developed at roughly 70 and 55 meters elevation. Figure 3 shows five proportionally spaced vertical cross-sections of heavy mineral content in the central part of the deposit. Noting that the sections have vertical exaggeration of 20 times horizontal, the sections show that basement scarps and terraces are punctuated by peaks and valleys which, in three dimensions, are linear ridges and swales. On excavation, ridges commonly reveal themselves to be elongate domes or horsts of basement rocks and sediments uplifted along reverse faults. This irregular basement presents a grade-control challenge for miners and mine geologists, discussed in an earlier publication (Romeo, 2005).

Older Deposit

The bulk of the older deposit is a clayey sand with 10-30 wt % heavy mineral. In pockets, heavy mineral grades can get quite high (up to 80%). These pockets are often located adjacent to the flanks of buried ridges of saprolitic bedrock.

The sand is dominantly clayey quartz sand and locally white kaolinitic pseudomorphs after feldspar are common. Much of the sand originally may have been feldspathic quartz sand, although the higher grade heavy-mineral facies may have been mainly quartz sand. Clay fines content, which is material less than 75 microns in size, commonly comprises 15-40% of the clayey sand. Locally there are intercalated coarse pebble-rich zones or fine clay-rich zones in which may primarily be sedimentary clays. Zones of angular cobbles to boulders occur as discontinuous lenses intercalated with heavy mineral sand and represent debris flows from storm or earthquake activity. These zones appear to occur at particular horizons and have been used as stratigraphic markers. The base of the deposit, on top of saprolite, commonly contains abundant rounded quartz pebbles and cobbles. Locally, pebble-rich cross-bedded heavy mineral sand beneath a weakly developed unconformity surface is present at the base of the sand sequence and may be relict fluvial deposits.

Although the upper part of the deposit is massive (structureless) due to bioturbation, in deeper parts, relict planar laminations and thin bedding, planar cross-bedding and soft sediment deformation features are preserved. Fossil evidence is rare within the ore zones in the Old Hickory deposit, but the trace fossils scolithus and ophiomorpha have been identified. Ophiomorpha, thought to be fossilized burrows of the ghost shrimp callianassa, have been found just below some of the high-grade heavy mineral zones. These shrimp live very near the swash zone of an active beach face. The planar laminations and thin bedding are probably foreshore swash sedimentary structures and the bulk of the sediment of the older deposit appears to have been deposited in foreshore to upper shoreface environments.

Clay content is generally high in the first 2-3 meters below surface. The clay is sticky and plastic and the subsoil is reticulately mottled with strong plinthite development (Daniels, personal communication, 2000). Soils developed on the older deposit have been identified as Paleudults (Daniels, personal communication, 2006), old high-level clay soils with particularly deep accumulations (>2 m) of fine clay. Colors in the heavy mineral sand commonly change from dark red (highly oxidized) at the surface downward through yellow-brown to gray (unoxidized) at the base. Commonly at the base of the weathering profile is a zone < 1 meter thick of indurated Fe-oxide cemented sand termed "laterite" in the industry. This is better developed in the older deposit than the younger deposit.

In general, most of the clay disseminated in sand is considered to be secondary and post-depositionally introduced as supergene enrichment from weathering of feldspar and infiltration of clay-laden meteoric water. The clay in the top 3 meters may have come from millions of years of precipitation of clay derived from overlying material, much of which was probably feldspar bearing sand. This upper clay continues to be dispersed throughout the lower parts of the deposit by the same process. Indicative of this process are clay-lined seams that have been observed cutting down through the sediment.

The deposit is displaying an intact weathering profile which, based on the extremely mature soil development, may be inherited from Early Pliocene weathering and may be correlative with similar surfaces identified to the north by Howard, et al. (1993) as having formed 3-5 million years ago. As will be discussed in the geochemistry section, vertical variation in Ti and Fe content may also be attributable to the section being a weathering profile. The area of the older deposit has been mapped as Miocene sand and gravel by Mixon, et al. (1989) and suggested to be a fluvial to marginal-marine facies of the Middle Miocene Choptank Formation or the Upper Miocene Eastover Formation. The possible age range of deposition therefore would be approximately 5-10 million years BP and early Pliocene weathering and soil development in the 3-5 million year BP range is plausible.

Younger Deposit

The younger deposit is composed of two facies. The bulk of it has planar laminations and thin bedding and appears to be primarily a paleobeach facies. The east side of the northern half of the deposit has well-developed festoon cross-bedding and appears to be primarily a back-barrier dune facies. Bioturbation in the upper portion of the entire deposit has obliterated sedimentary structure and more of the unit may be dune facies than is presently recognized.

The younger deposit most commonly adjoins the older deposit at an elevation around 70 meters (230 feet). Below this level, a buried scarp is commonly well-developed and may largely have been erosional, cut back into the older deposit by wave action. However, locally this scarp was accentuated by tectonic uplift along reverse faults that occurred after the younger deposit was laid down (see Figure 5). The younger deposit is up to 11 meters (35 feet) thick and was deposited on the scarp and adjacent to it to the east to a base level of about 55 meters (180 feet) above sea level. The younger deposit overlies the older deposit east of the scarp and the two are separated by a barren zone of coarse yellow-white feldspathic quartz sand which thickens toward, and contains abundant pebbles near, the scarp zone. This unit may in part be fluvial/deltaic and it is considered to be the upper portion of the Miocene regressive sequence of which the older deposit is part. Overlying the coarse sand is up to a half meter of barren pinkish gray gummy clay. The upper contact of the clay zone is sharp beneath heavy mineral sand of the younger deposit and locally soft sediment deformation features such as ball and pillow and flame structures have been noted below the contact. This clay zone is interpreted to be a lagoonal mud deposited during transgressive drowning of channels, and it marks the base of the Pliocene transgressive/regressive sequence of which the younger deposit is part.

The basal few meters of the younger heavy mineral deposit on top of the clay bed consists of well-developed planar laminated to thin bedded heavy mineral-rich fine sand. The well-stratified sand commonly has low-angle cross-bedding with foresets dipping either east or west, climbing ripples and reactivation surfaces, suggesting swash stratification (see Figure 4). The planar beds generally dip ≤ 5° to the east (seaward). Overlying the planar beds near the scarp zone is a thick zone of cross-stratified heavy mineral-rich sand with foresets dipping 25° east (seaward). The general environment appears to have been foreshore with rare high energy events. Large-scale trough cross-bedding is also locally preserved near the scarp's southern part, suggesting local dune formation. Festoon cross-bedding is common on the far east side of the northern half of the deposit, and this is predominantly a back-barrier dune sequence deposited on top of the beach sequence during continued regression.

Like the older deposit, the younger deposit consists mainly of clayey quartz sand with 10-40 wt% slimes and 5-40 wt% heavy mineral. It also has a high concentration of clay in the upper two meters. Locally, a weathering profile is well-developed with red-yellow-gray downward color zoning, but plinthite in the subsoil is only weakly to moderately developed, suggesting a less mature weathering profile than in the older deposit. Laterite at the base of the weathering profile is only weakly developed. Vertical chemical zonation is also weaker compared to the older deposit. Also in contrast to the older deposit, the younger deposit displays a marked lateral geochemical and mineralogical zonation, discussed in the geochemistry section. This unit has been mapped as Pliocene sand and gravel by Mixon, et al. (1989) and suggested to be a marginal-marine equivalent to the Yorktown Formation (Berquist, personal communication, 1998; Carpenter and Carpenter, 1991), a regionally extensive Early to Late Pliocene (3.4-5.3 million years old) marine transgressive-regressive sequence (Bailey, 1987). The weathering probably dates from about 3 million years ago. The younger deposit was probably a regressive sequence formed after a circa 5 Ma transgression. The area experienced post-regression subaerial exposure and prolonged weathering.

Several lines of evidence suggest that the older deposit was partially eroded and resedimented to form the younger deposit. The scarp zone with its top at about 70 meters elevation has an irregular trace with concave eastward embayments extending west into the older deposit. These embayment features probably mark stream/tidal channels that cut back into the headland. Thick heavy mineral accumulations locally are found at the mouth of these embayments. These areas also have higher zircon fractions of heavy mineral (see Figure 6) and represent channels in which zircon concentrated, perhaps due to its slightly higher specific gravity relative to other heavy minerals. Poorly sorted alluvial deposits with abundant pebbles and cobbles in a matrix with high clay content are locally common adjacent to the embayments and scarps and are intercalated with and cut out part of the older deposit. These conglomeratic deposits contain clasts of indurated highly oxidized heavy mineral sand (plinthites), probably eroded from an existing deposit. As will be discussed in the geochemistry section, bulk and zonational geochemical and mineralogical differences between the younger and older deposits also support that the older one was reworked to form the younger one.

FAULTS AND FOLDS

In the first year of mining, unexpected offsets and folding of mineralized sediment and basement were observed, and NW-trending faults displacing saprolitic basement over top of heavy mineral sand in the older deposit were identified. Those faults strike NW and WNW, dip moderately steeply both SW and NE, and have oblique striations that plunge moderately to steeply NW on SW-dipping faults (Berquist and Bailey, 1999). The dominant sense of shear is sinistral oblique reverse with a maximum separation of 6 meters (20 feet).

In the third year of mining, a portion of the scarp zone was exposed which revealed that the "scarp" in that area was the nose and upright limb of an overturned anticline in the hanging wall of an east vergent thrust fault (Figures 5A and 5B) striking N15W. Sediments of the younger eastern deposit were cut by the thrust fault and overridden by basement metavolcanic rocks. Movement on these faults would not have been enough to produce the scarp, which has vertical relief of 18 meters (60 feet). The scarp was probably produced by wave cutting but was locally accentuated by uplift along reverse faults.

Many of the faults appear to bound linear basement uplifts. These uplifted areas commonly have thin to no cover of heavy mineral sediment and may have been eroded in Pliocene time, with alluvial heavy mineral being deposited in adjacent structural depressions and carried downstream to be resedimented in the younger deposit.

Additional N-S striking faults have been identified in the southern and northern parts of the deposit, and they generally have steep dips either east or west with reverse sense of shear. Individual faults can not be traced for any great distance and appear to be associated with discrete linear domes or horsts. The faults at Old Hickory are consistent with a WNW-ESE compressive stress field which has been suggested to have characterized the Mid-Atlantic region throughout Cenozoic-Recent time (Wentworth and Mergner-Keefer, 1983). Several Cenozoic high-angle reverse fault systems have been identified in the eastern United States displacing Coastal Plain sediments and Piedmont basement rocks (Prowell, 1988). It is possible that faulting along the edge of the Coastal Plain in Virginia and North Carolina occurred at various times and places during the Cenozoic era and that zones of fault-generated topographic ridges and troughs acting as coastal barriers and traps may have helped to localize heavy mineral deposits such as Old Hickory.

MINERALOGY AND GEOCHEMISTRY

The pre-mining resource at Old Hickory was estimated at 75 million tons averaging 9% heavy mineral. The average heavy mineral assemblage comprises 63% ilmenite, 19% zircon and 2.5% rutile plus leucoxene. The remaining non-valuable heavy minerals are predominantly staurolite, kyanite and sillimanite.

The heavy mineral suite is dominated by fine, black, rounded to well rounded, equant ilmenite grains, comprising 50 to 70% of the suite. The grain surface is usually pitted to some degree. Zircon comprises 12 to 30% of the suite as rounded to well rounded white to pink, frosted very fine grains. The remainder of the valuable heavy mineral suite is composed of 2-4% very fine grained, rounded, red to black rutile grains and well-rounded butterscotch to silver-colored leucoxene (very altered ilmenite) grains. Grains of sillimanite and kyanite occur as relatively coarse, tabular, white to translucent grains, averaging about 6% of the heavy mineral suite. Staurolite occurs as brown-orange coarse, angular grains averaging about 10% of heavy mineral. Other accesory minerals include tourmaline, limonite, goethite, magnetite, and spinel. Heavy minerals, most noticeably zircon, commonly have iron-staining on the outside of the grains, due to precipitation of Fe-oxide from groundwater.

Ilmenite and TiO_2 Content

Titanium content of ilmenite shows marked zonation patterns that differ in the older and younger deposits. In the older deposit, there commonly is a vertical zonation with moderate TiO_2 content in the top three meters of the profile and low TiO_2 content at the bottom of the profile. In the younger deposit there is locally a weak vertical zonation of TiO_2, but there is a marked lateral zonation with moderate TiO_2 values close to the scarp zone increasing to high TiO_2 values to the east.

Variations in TiO_2 content of ilmenite are due to the relative proportions of altered (weathered) ilmenite to fresher ilmenite. The vertical zonation patterns in the older deposit are related to weathering and the section probably represents a paleoweathering profile relict from early Pliocene time when subtropical (hot and wet) conditions existed and the deposit was situated in a well-drained area such as a back-barrier/dune setting. Intense weathering at the top of the profile would have released Fe from ilmenite, relatively increasing Ti and altered ilmenite contents, and adding Fe to percolating meteoric water which may have filtered through the lower part of the deposit, depositing Fe on sand grains. Periods of exposure above the water table would be necessary for Fe to be fixed in dominantly an Fe^{3+} oxidation state.

The deposit east of the scarp zone is younger than the older deposit and may in large part represent reworking and resedimentation of the older deposit. The bulk of the eroded material would have been derived from the upper portions of the older weathering profile, thereby generally containing relatively abundant altered ilmenite and leucoxene. The lateral zonation of TiO_2 in ilmenite in the younger deposit from moderate to high values west to east is probably related to density sorting of altered versus fresher ilmenite as lighter grains (more altered) moved farther out seaward from the beach.

Zircon

Zircon from Old Hickory is of premium quality on the world market. A primary reason is its low average U and Th contents, which average a little over 200 ppm U plus Th. Age dating of zircon was performed by C. Naeser of the U.S. Geological Survey. He identified three populations of zircons with U-Pb dates of 357 ± 34Ma, 230 ± 30Ma and 156 ± 18Ma, with the error quoted being ± 2 standard deviations (Naeser, personal communication, 2005). He identified a likely source for the 231 Ma group as the Piedmont of Virginia and North Carolina. The 357 Ma group matches ages found in the Blue Ridge Mountains of North Carolina and Virginia. No local (mid-Atlantic) source was identified for the 156 Ma population (Naeser, personal communication, 2005). Naeser (personal communication, 2005) indicates that the Old Hickory zircons have unusually low U contents and lack U zoning which is common in other zircons. Of interest also are the strong rounding and frosting ubiquitous in Old Hickory zircons which suggest extreme abrasion (Naeser, personal communication, 2005).

Figure 6 is a map of the distribution of zircon as a percentage of heavy mineral. Evident are two cross-cutting zones of higher zircon. Within these zones, E-W trending paleochannels have been identified in the mining pits. These channels have high-grade heavy mineral and the heavy mineral has higher than average content of zircon. It is interpreted that zircon is preferentially upgraded in channels because it is heavier than altered ilmenite, rutile and other heavy minerals in the suite. Possible paleochannel locations are shown in Figure 6. The increase on the central east side of the deposit may be due to dispersion by longshore drift from the channel point sources. Heavy mineral in these channels was probably largely derived by erosion of the older deposit.

ROLE OF RIVERS IN DEPOSIT FORMATION

In general, the major sources of sediment today on Atlantic shorefaces and continental shelf are rivers (fluvial deltas) and tidal channels (ebb-tidal deltas). The fluvial deltas derive their sediment from the source area the streams erode. Short rivers that head only in the coastal plain mainly derive their sediment from reworking older coastal plain sediments. Longer rivers that head in the Piedmont and Appalachian Mountains carry a less mature assemblage including abundant feldspar and may contain abundant heavy minerals, the assemblage and geochemical characteristics of which reflect the nature of the eroding source rocks in the drainage basin. The ebb-tidal deltas derive their sediment from reworking mainly Pleistocene barrier ridges and normally contain little heavy mineral except where earlier heavy mineral concentrations are being reworked.

The larger longer rivers carry copious sediment and create large deltas. During regression these deltaic deposits may be exposed and reworked in beach and back-barrier settings. During transgression the deltas may be abandoned and submerged, leaving lobes of sediment with positive relief on the sea floor. These piles of sediments are reworked by storm waves and currents and may be the major source of sediment in the construction of barrier islands and in the longshore drift stream. Heavy mineral concentration is commonly seen downdrift of these delta lobes. Once entrained in the littoral environment heavy mineral suites will mature in both textural and mineralogical senses. In these settings, there may also be admixture with exotic sediment brought in by longshore drift. A mixture of heavy mineral grains of varying textural maturity might be expected.

Thorium and other radioactive elements in detrital minerals such as monazite, zircon and feldspar are concentrated in deposits of streams whose upper reaches are in basement rocks. Iron oxide and hydroxide coatings on detrital grains also scavenge thorium and uranium and clays in floodplain deposits scavenge potassium. Thus, present drainages and sometimes paleodrainages are highlighted by radiometric anomalies. This tool can be used to interpret the courses of paleodrainages, which may no longer be associated with a stream.

Figure 7 shows the present Appomattox, James and Rivanna rivers with SE-trending segments that fall in a roughly straight line. These segments are probably remnants of a SE-flowing river, herein called the paleoRivanna River, which was pirated by the younger east-west trending Appomattox and James rivers. Sections of interfluve with NW-SE thorium anomalies connect the residual SE-trending stream segments and are labeled as "Pirated paleoRivanna River". Figure 7 shows the interpreted trace of the paleoRivanna River south to the Old Hickory deposit. It is worthwhile to note that the paleoRivanna would have drained anorthositic granulite-facies metamorphic terranes in both the Roseland and Goochland areas, possible sources for ilmenite and rutile.

There is an interesting juxtaposition of levels of maturity of Old Hickory sediment. Intercalated sediment is compositionally immature with abundant kaolinite-altered but still recognizable feldspar pseudomorphs. The heavy mineral suite is texturally mature, being well rounded and frosted from abrasion. Yet, it also is compositionally immature. The suite is ilmenite-dominated with a high percentage of compositionally immature ilmenite, with TiO_2 contents down to 53 wt%. In deposits formed at locations such as Florida, at the down-drift ends of extensive longshore transport tracts, rutile, zircon and leucoxene contents and average TiO_2 content in ilmenite are significantly higher while ilmenite contents are significantly lower than at Old Hickory.

Just east of the Old Hickory deposit, on and east of the toe of the Fall Zone scarp, topography has a shield shape with a semi-annular stream pattern around the northeast and southeast sides. This geometry suggests a relict alluvial fan or delta lobe.

The association with identifiable paleoriver drainages, relict fluvial geomorphic features and intercalated feldspar and gravel-bearing facies of fluvial affinity suggest a large component of fluvially-derived sediment at Old Hickory. A plausible explanation is that rivers were continuously active at the deposit site for the millions of years that the shoreline ranged across an east-west distance of only 3 kilometers. Heavy mineral from older deposits was reworked over and over again while being admixed with sediment of fluvial and longshore transport derivation. The heavy mineral may have been reworked from coastal plain deposits as old as Cretaceous.

When compared to other heavy mineral deposits along strike in the Fall Zone in North Carolina, the Old Hickory deposit has about three times higher average zircon content, even though the other deposits are of equal or larger size and grade. This suggests differences in the source area of sediments and supports individual fluvial point sources for the deposits. Although heavy mineral may have come from sediment as old as Cretaceous, the lack of homogeneity of heavy mineral suites along this segment of the Fall Zone argues against a large longshore drift component or extensive bulldozing of older sediment during transgression. Cretaceous heavy mineral deposition may also have been controlled by proximity to rivers and local heavy mineral sources.

SUMMARY

The Old Hickory heavy mineral sand deposit was formed during Miocene to Pliocene transgressive-regressive cycles along multiple strand lines established near the maximum elevation of inundation, during probable subtropical climatic conditions. The Old Hickory deposit contains two main units, termed the older and younger deposits. The older deposit, of probable Miocene age, rests directly on an irregular surface of saprolitic crystalline basement rocks. It has a well-developed weathering profile with a strongly weathered and leached top and a weakly weathered and supergene-enriched base. The upper portion has high slime content and moderate TiO_2 content in ilmenite. The lower portion has moderately low slime content and low TiO_2 content in ilmenite. This weathering profile is probably relict from Early Pliocene time, when regression left the older deposit in a high well-drained coastal setting in a wet hot climate.

The younger deposit lies east of a prominent scarp zone and is probably Pliocene in age. It has a less well-developed weathering profile, of probable Late Pliocene origin. Also in contrast to the older deposit, it has moderate to high TiO_2 content in ilmenite. The deposit has a well-developed lateral zonation of altered ilmenite contents from moderate near the scarp zone to high on the east side. Zircon, rutile and leucoxene also increase to the east in the younger deposit. The increase in leucoxene and TiO_2 content in ilmenite in the younger deposit deposit suggests that the ilmenite was already weathered prior to deposition. The younger deposit is suggested to have been mainly derived by erosion and reworking of the upper portion of the older deposit.

Protoliths of both the older and younger deposits were probably quartz sands and feldspathic quartz sands. The sands gained appreciable secondary clay derived from weathering of feldspar and infiltration by clay-laden meteoric water. Primary sedimentary structures are preserved below bioturbation levels and planar laminations and thin bedding are common, suggesting much of the sediment was deposited in foreshore environments. Cross-stratification is also common and the northeast part of the younger deposit has abundant festoon cross-bedding, suggesting back-barrier dune formation.

Movement on reverse faults raised linear ridges of heavy mineral-capped basement, which were eroded in Pliocene time contributing to the younger deposit. Faulting appears to have taken place at various times during deposition of the ore bodies. Relief on scarps is due to a combination of wave-cutting and tectonic uplift. Structural ridges and troughs may have acted as coastal barriers and traps, localizing heavy mineral deposition.

The high degree of rounding of hard heavy minerals such as zircon, rutile and ilmenite indicates the great amount of transport, reworking, and winnowing that the grains underwent. The greater angularity of quartz and staurolite may be related to lower relative hardnesses with greater tendency to fracture. Despite the textural maturity of the heavy mineral suite, the deposit is compositionally immature as sediments contained a large component of feldspar and the heavy mineral assemblage is dominated by ilmenite of relatively low TiO_2 content.

The prolonged reworking of heavy mineral and lack of Cretaceous through Oligocene age sediments along this segment of the Fall Zone suggests that sediments perhaps as old as Cretaceous were reworked by younger transgressive/regressive episodes, upgrading heavy mineral by marine processes. However, protoliths of feldspathic quartz sands, gravel zones and fluvial facies, recognition of paleochannels, and geomorphology of a relict alluvial fan or delta lobe east of Old Hickory suggest the influence of a river at the site throughout its depositional history. The compositional immaturity of the heavy mineral suite and the variation of assemblage among deposits along strike on the Virginia/North Carolina segment of the Fall Zone, suggests that individual heavy mineral deposit sites were related to the location of paleorivers, perhaps from Cretaceous through Tertiary time.

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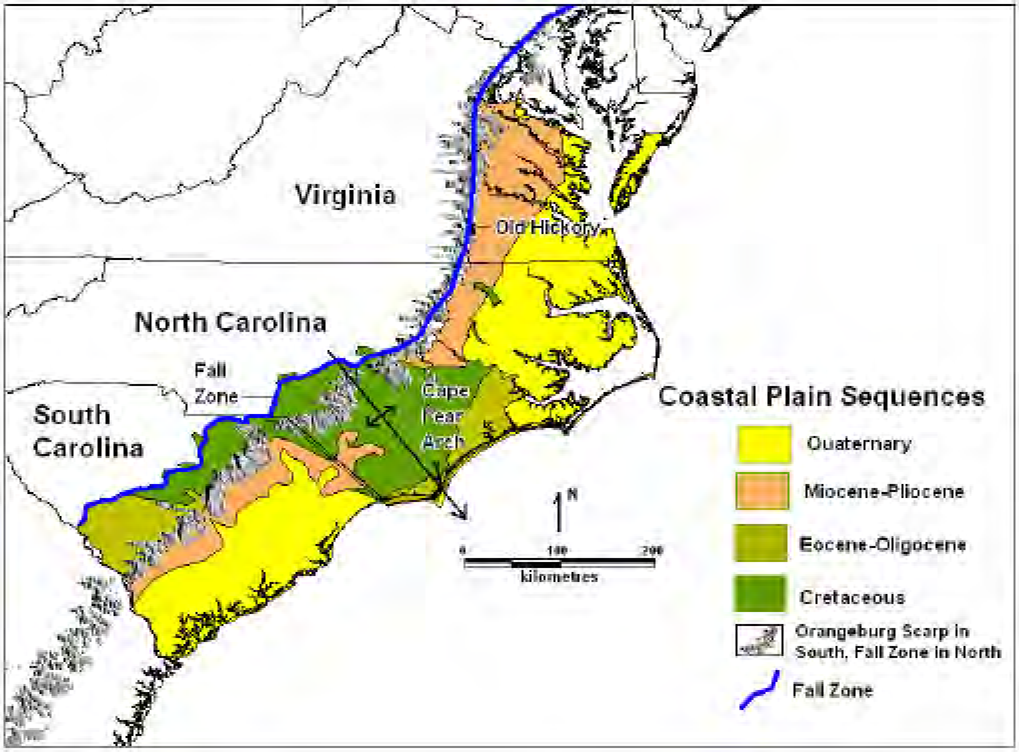

FIGURE 1 Location of Old Hickory Deposit and Fall Zone

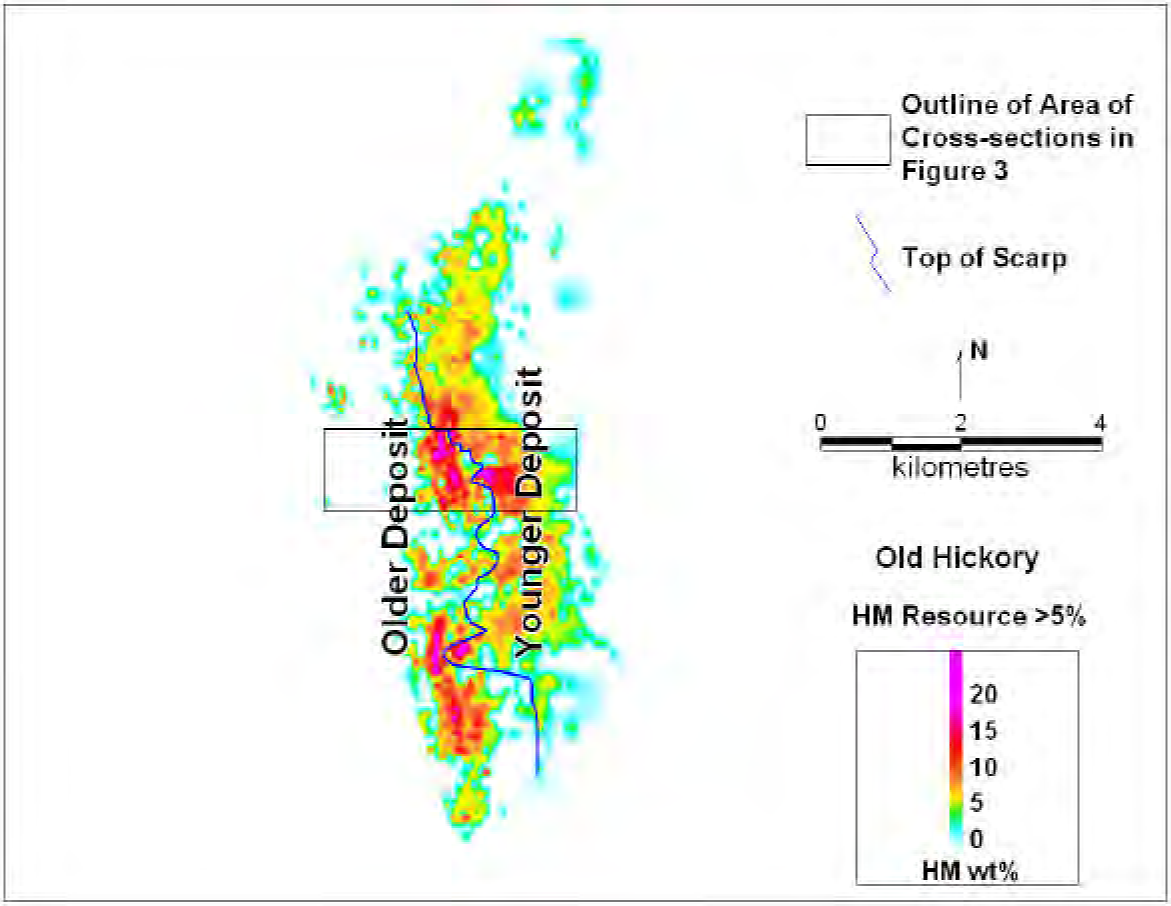

FIGURE 2 Map of Heavy Mineral Resource, Scarp and Older and Younger Deposits

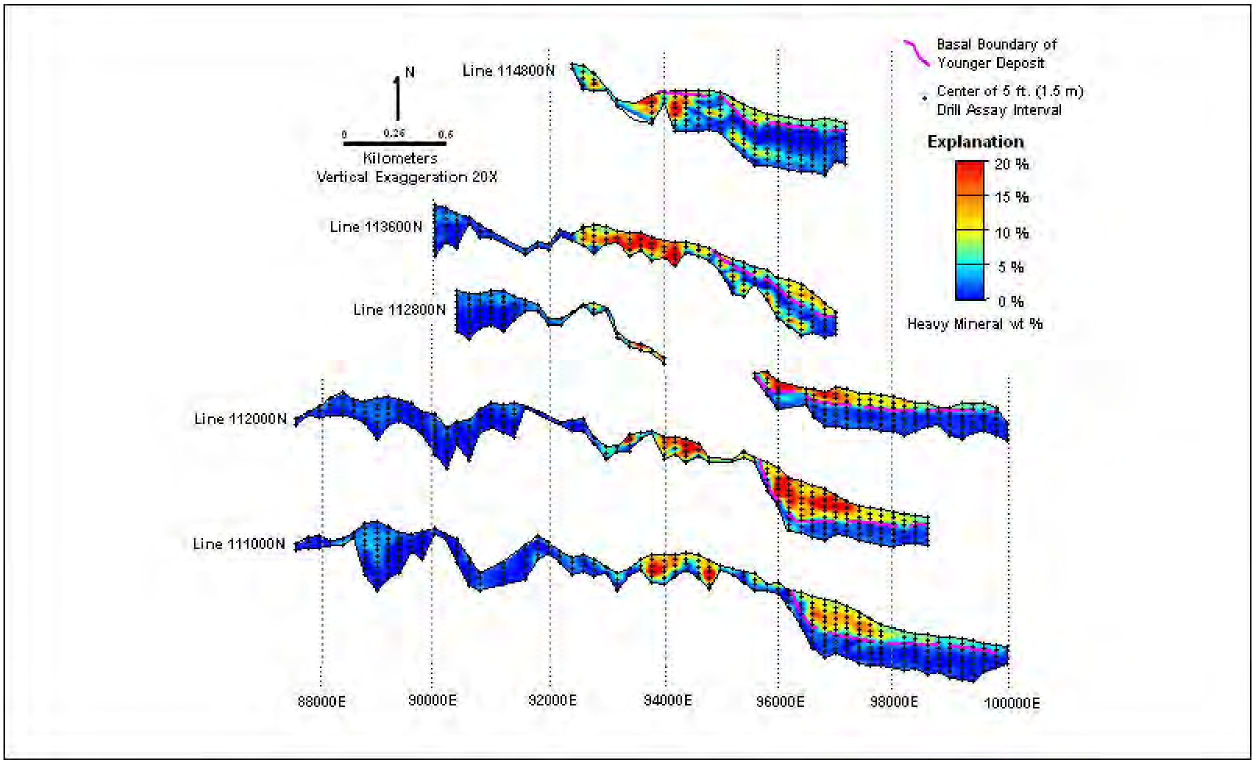

FIGURE 3 Heavy Mineral Variation, Stacked Cross-sections From Central Area

FIGURE 4 Planar Stratification, HM Grade = 20-25%, Younger Deposit

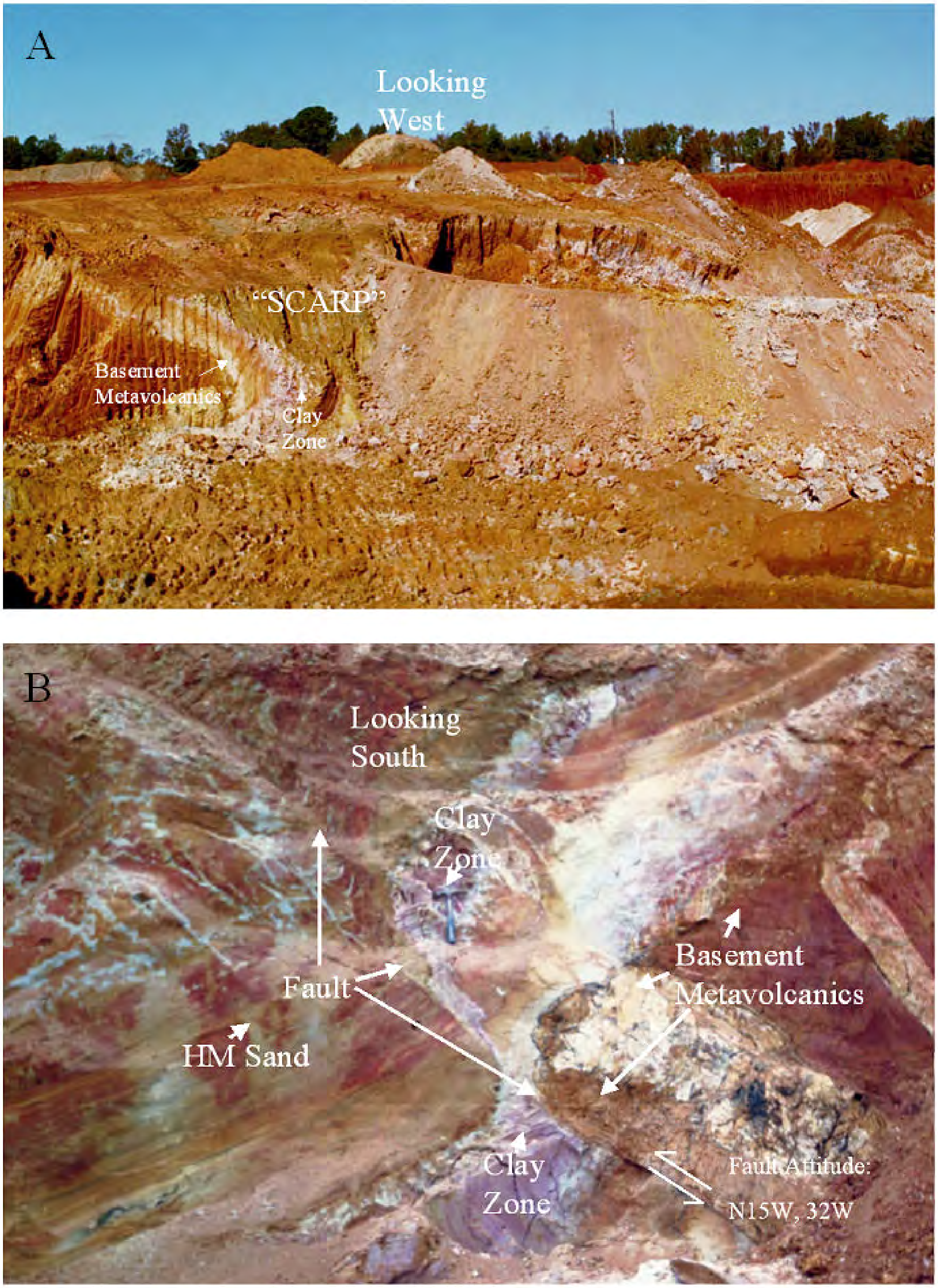

FIGURE 5A Nose of Recumbent Anticline, Drag Fold in Hanging Wall of Thrust Fault Shown in Figure 5B (Hammer in Center for Scale)

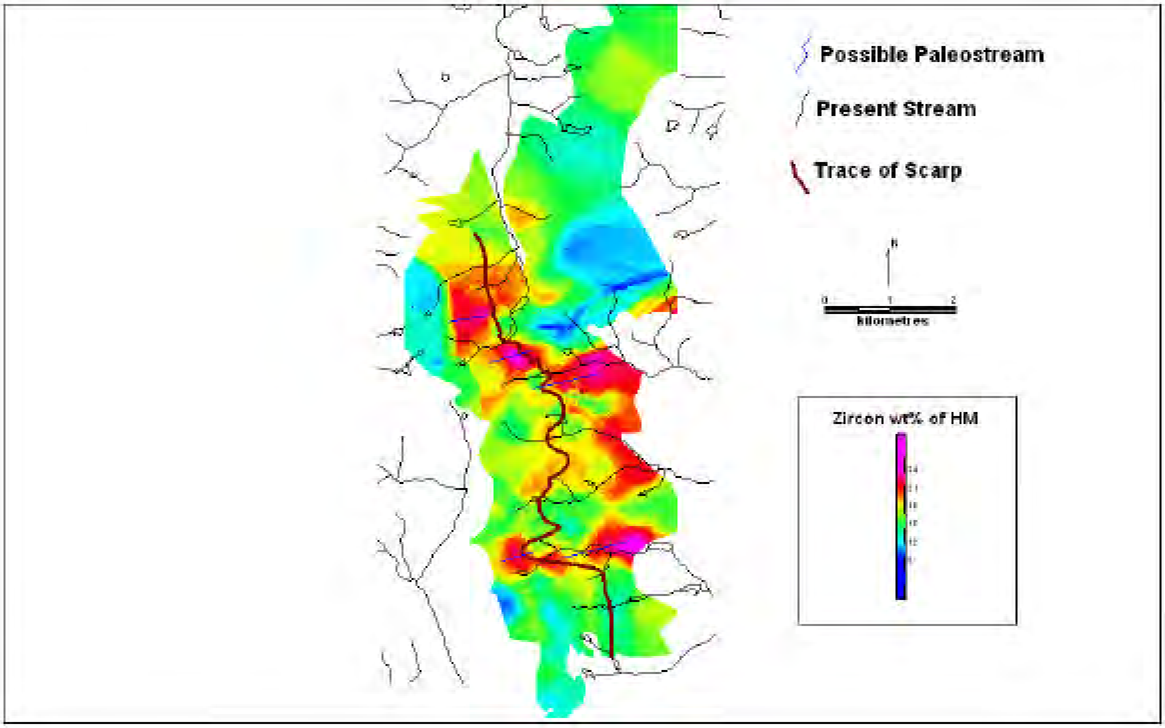

FIGURE 6 Map of Zircon as a Percentage of Heavy Mineral

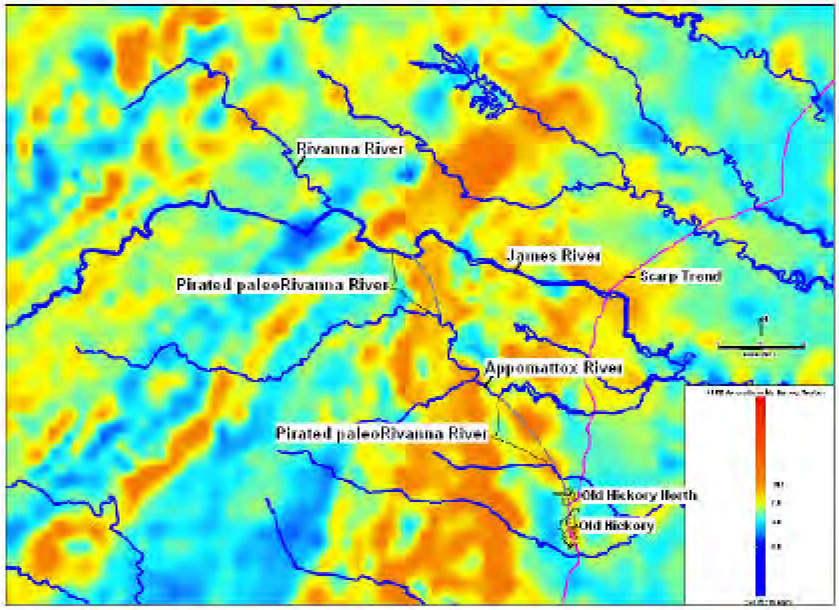

FIGURE 7 Thorium Anomaly Map and Suggested Trace of PaleoRivanna River

What's been (and what will be) strategic—My metal or your paint?

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ABSTRACT

Concerns about future availability of industrial minerals sometimes have included special attention to essential raw materials that are deemed "strategic minerals." The regional setting of this Forum offers a platform for discussion of the history of the concept of strategic and critical minerals as applied to industrial minerals—and rocks. In a discussion about 25 years ago, one writer observed that it was not clear that the cobalt in the jet engine was any more strategic than the aggregate in the runway.

In the past few years, we have seen the concept of strategic minerals change in several ways. However, one constant is the need for a comprehensive storehouse of accurate and timely minerals information. This information is essential if we are to understand our mineral position from a business or public policy perspective, whether the scope of our concerns is regional, corporate, national, or global.

Examples of past investigations of resources of strategic minerals in North Carolina and in nearby States set the stage for thinking about future industrial mineral production possibilities in a strategic context.

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INTRODUCTION

Have there been, are there, or will there be strategic industrial minerals? The answer is certainly yes, but the simple answer glosses over the complexity of the question. A clear understanding of why the question is complex lies in (1) the background and definitions of strategic minerals or materials; (2) the classification(s) of mineral production into categories like fuels, industrial minerals, and metals; and (3) the body of historical information that we trust will be collected, disseminated, and archived on mineral production, trade, and use. Ideally, we would find that there are definitions of strategic minerals and industrial minerals that enable us to see which mineral commodities fall into both categories (Figure 1). In reality, a review of several sources of such definitions shows that this is not the case.

Following an examination of these three topics, our presentation will review historical production of mineral resources in this region and comment on whether titanium offers the possibility of being a strategic industrial mineral in this area's future.

THINKING ABOUT STRATEGIC? MINERALS AND NATIONAL SECURITY

The concept of strategic minerals was a result of the evolution of the role of mineral resources in national security, a history that is intertwined with that of the Federal Government's role in minerals information. In 1833, George Featherstonhaugh, an English-born geologist, wrote to Secretary of War Lewis Cass explaining the value of a geological map to the Nation's industry and prosperity. He noted that such efforts in the United Kingdom, Germany, and France were "amongst the most remarkable monuments which have ever been produced in Europe," and he recommended that the resulting product done for the United States might be "advantageously diffused" among the cadets at the Military Academy at West Point (Featherstonhaugh, 1833). The next 100 years saw the founding of the U.S. Geological Survey in 1879 and the U.S. Bureau of Mines (USBM) in 1910 and the transfer of the USGS mining statistics division and the USBM from the Interior Department to the Commerce Department under Secretary Herbert Hoover in 1925. (The North Carolina Geological Survey had already been established in 1823!)

Problems in the lack of domestic production were brought into focus in World War I with manganese, potash, tin, tungsten, and other minerals. This is when "Minerals that were essential to the war effort but could not be produced in adequate amounts from domestic sources became known as **strategic minerals**." (Cameron, 1986, p. 254). In his 1931 book, "World Minerals and World Politics," Charles Kenneth Leith, a professor of structural and economic geology at Wisconsin who had served as minerals adviser to the U.S. peace delegation after World War I, wrote about the vital dependence of nations on minerals that was demonstrated during wartime. He saw minerals as a cause for war and also as a deterrent, given the increasing level of interdependence in the global mineral industry during the 1920s. He stressed the need in a later paper (1933) for the dissemination among nations of more definite knowledge about the world's mineral industry. Leith and geologist Josiah Edward Spurr and the War Shipping Board made decisions that saved shipping and helped U.S. Department of the Interior (DOI) efforts to encourage domestic production. Bernard Baruch, South Carolina financier and Chairman of the War Industries Board, made decisions that encouraged imports, which reflected industrial needs rather than mining concerns (Eckes, 1979, p. 17–25).

In 1934, the USBM was transferred back to the Interior Department and the annual Federal mineral statistics publication was titled “Minerals Yearbook.” Elmer Pehrson, Chief of the USBM’s Economics and Statistics Branch, provided comparative analyses of the mineral supply positions of the Allies and the Axis in World War II, and addressed the meaning of the terms **strategic**, **critical**, and **essential**, which came into use in the period preceding World War II, replacing the “deficient” and “war minerals” terms of World War I. He pointed out the adverse effect that declining mineral self-sufficiency had on national military power and the need to look beyond stockpiles to maintain national security (Pehrson, 1942; 1944; 1945).

Alan Bateman, professor of geology at Yale, wrote after World War II in “Economic Geology” (1946) and “Mining Engineering” (1949) about the contributions of geologists in the Foreign Economic Administration and other Government agencies, which ensured that the war machine was adequately and continuously supplied. Nevertheless, the costly efforts to develop domestic supplies under the Strategic and Critical Materials Stock Piling Act of 1939 were, like those in World War I, mostly unsuccessful (Cameron, 1986, p. 255). Still, the experience of World War II led to the Strategic and Critical Materials Stock Piling Act of 1946, signifying recognition of the problem, although equivocal on the solution.

A perusal of a 1947 textbook from the U.S. Military Academy, “Raw Materials in War and Peace,” featuring a foreword by C.K. Leith and extensive graphical presentations from Elmer Pehrson on mineral reserves and raw material self-sufficiency, would seem to indicate that Mr. Featherstonhaugh’s advice of 114 years earlier had been heeded (Department of Social Sciences, U.S. Military Academy, 1947). Some of the same minerals information, in more detail, graced the pages of transcripts of hearings held on the Nation’s mineral resource position before Senator George Malone’s National Resources Economic Subcommittee of the Committee on Public Lands in May 1947 and on accessibility of strategic and critical materials to the United States in time of war and for our expanding economy before Senator Malone’s Minerals, Materials, and Fuels Subcommittee of the Committee on Interior and Insular Affairs in July 1953.

Another seminal study was completed in 1948; a doctoral dissertation at School of Mineral Industries of The Pennsylvania State College titled “The Domestic Mining Industry of the United States in World War II—A Critical Study of the Economic Mobilization of the Mineral Base of National Power” examined the successes and failures at solving domestic mining problems in World War II and was followed by numerous other contributions to the Nation’s mineral position by its author, John D. Morgan, Jr. (1948).

Pehrson was back again in 1962, speaking from his position at the Henry Krumb School of Mines at Columbia, observing that the fundamental importance of mineral supply was being overlooked or sidelined by those who advocated wilderness preservation, free trade, government control, and global “do goodism.” In fact, when a Domestic Policy Review of Nonfuel Minerals was conducted in 1978–79, national security was not the focus, as the review came at a time when restrictions on access to domestic public lands were of heightened concern.

The rising commodity prices and the oil embargo of the early 1970s that had provided impetus for the mineral policy review set the stage for the passage of the Strategic and Critical Materials Stock Piling Revision Act of 1979, which reaffirmed the need for stockpiling, conservation, and development of domestic resources (Cameron, 1986, p. 256). That year also marked the publication of Alfred Eckes’ comprehensive study of how mineral resources considerations have influenced U.S. foreign relations since World War I, “The United States and the Global Struggle for Minerals.” Eckes’ book was followed in 1980 by the opening salvos of the Resource(s) War, a June 1980 forum in Pittsburgh on “The Resource War in 3–D—Dependency, Diplomacy, Defense” and a December 1980 press conference at the American Geological Institute (AGI) where a resource war against the United States was charged. Both events drew upon a 1980 white paper, “The Resource War and the U.S. Business Community—The Case for a Council on Economics and National Security,” by the Washington, DC-based council of the same name. The AGI said that the white paper correctly pointed out that the Soviet Union was conducting a resource war against the United States in order to deny access to strategic and critical materials indispensable to the U.S. economy and defense. News and trade magazines featured cover articles on security of national mineral supplies, the NOVA series on PBS television proclaimed “The Cobalt Blues,” studies by the Office of Technology Assessment and the Congressional Budget Office voiced concern about increasing import dependence, and Government agencies and academia directed new research towards such mineral resources as chromium, cobalt, and manganese.

The end of the resource war was not as well defined as the start. Joel Clark and Frank Field presented an alternative view in the Massachusetts Institute of Technology’s “Technology Review” in 1985, stating that concerns about future availability of critical minerals was needless and that stockpiling, trade agreements, alternative resources, and new materials could solve many material supply problems and that supply disruptions themselves have the beneficial effects of stimulating conservation and recycling. Penn State Professor William Vogely, a former Interior Department official, expressed his view that the resource war was a media event and that it had served its purpose of increasing public awareness about the use of minerals.

Some new public and private sector efforts on mineral-resources data bases and publication series on minerals information were started during this period, including a series of global mineral-resource reports done by the U.S. Bureau of Mines and the U.S. Geological Survey in cooperation with agencies from five other countries in the International Strategic Minerals Inventory. “The Death of Mining” was proclaimed on a cover of Business Week in 1983. Discussion of the mineral security concern continued as the Washington, D.C. AIME Mineral Economics Subsection titled its 1985 annual symposium, “The National Security Implications of a Declining Minerals Industry.”

Kesler (1994, p. 8) observed that the emergence of Japan as a dominant manufacturing power without having significant domestic mineral production has demonstrated that economic success can be achieved without secure mineral supplies by taking advantage of greater market transparency and materials like plastics, polymers, ceramics, and composites that offer a competitive alternative to some conventional materials. These are cited as two reasons that weaken the concept of strategic minerals, but recent conflicts are evidence that the security of supply concept still has some merit. However, Japan relies on more than market transparency and substitution; it maintains an industrial stockpile and, through exploration and investment partially funded by Japanese organizations, develops agreements that give Japanese firms the right to take a share of any mineral supply resulting from successful exploration.

In his 1986 book, “Trouble in the Third Kingdom,” Simon Strauss, a former mining industry executive, covered the elements commonly considered in addressing the problems that import dependence poses for national security, including stimulating domestic production; increases in recycling, conservation, and substitution; and the use of stockpiles. His conclusion, that import dependence problems are ignored until some unexpected event forces attention, is consistent with our experience in the past century.

But is ensuring supply security all there is to minerals and national security? USGS geologist David Menzie (1997) documented a broader set of national security, economic, and environmental issues where mineral resources may motivate, complicate, or ameliorate national security and foreign policy. Among these issues are (1) the creation of stable societies through economic development, (2) the initiation of disputes related to environmental effects of mineral production and use, (3) social disruption owing to major changes in mineral markets, (4) the development of trade disputes as a result of increased competition for raw materials needed to support rapid economic growth, (5) temporary disruptions of supplies of strategic materials owing to regional political instability, and (6) the exacerbation of existing regional disputes and conflicts.

THINKING ABOUT STRATEGIC? DEFINITION OF TERMS

Strategy originates from the Greek word strategia, meaning “generalship.” Military strategy often refers to the deployment of an army ahead of a battle, and the campaign plan for that battle. Strategy in the context of business or government is similar if “army” is replaced with “resources,” providing the twin elements of a campaign plan and resource allocation. Strategy is usually understood to refer to higher level, longer term choices rather than short-term, smaller decisions, which are often described as tactical.

Supply security for essential materials was and continues to be a reason for labeling a material “strategic.” The historical experience of the 20th century shows how “strategic minerals” replaced the “deficient” and “war mineral” terms of World War I and that a legal definition was created in the 1939 and 1946 stockpile acts. The phrase defined in the later law was “strategic and critical materials.” The number of materials that fell under that definition increased from 9 in 1940 to 65 in 1945 (Eckes, 1979, p. 130). In 1982, the Federal Emergency Management Agency (FEMA) reported to Congress that 61 items were strategic and critical, or 93 items when several grades or forms were considered (Cammarota, 1984, p. 30). The Defense National Stockpile Center listed 69 stockpile commodities on January 31, 2006, of which 64 were minerals. However, only three of these (beryllium metal, mica, and quartz crystal) were to be retained.

The AGI Dictionary of Geological Terms (1962) and Lowenstein and Shao (1981) define critical [materials] and strategic [materials] separately. A Commerce Department colleague on the staff of the 1978–79 Presidential Review of Nonfuel Minerals Policy summarized the two-definition concept by saying, “Critical means you need it; strategic means you don’t have it!” (William Kaestner, U.S. Department of Commerce, oral commun., 1978). Contrast those views with Evans (1993, p. 10) who states, “A material needed for military purposes is considered strategic and a material is termed critical if future events involving its supply from abroad threaten to inflict serious harm on a nation’s economy.”

The 1947 U.S. Military Academy textbook offers an explanation for the issue of separate and joint definitions of strategic and critical. Calling the 1922 creation of the Army and Navy Munitions Board (ANMB) a major step forward during “the national relapse into military weakness,” the authors explain how the ANMB wrote definitions that classified the seriousness of specific shortages:

Strategic materials are those essential to national defense, for the supply of which in war dependence must be placed in whole, or in substantial part, from sources outside the continental limits of the U. S.; and *for which strict conservation and distribution control measures will be necessary*.

Critical materials are those essential to national defense, the procurement problems of which in war would be less difficult than those of strategic materials either because they have a lesser degree of essentiality or are obtainable in more adequate quantities from domestic sources; and *for which some degree of conservation and distribution control will be necessary*. (Department of Social Sciences, U.S. Military Academy, 1947, p. 86–87).

In 1944, during the latter part of World War II, the impracticability of differentiating between strategic and critical became apparent and a new definition, recognizing "that physical stockpiling represents only one of the several media for assuring adequate supplies of strategic and critical materials," was approved. "Strategic and critical materials are those materials required for essential uses in a war emergency, the procurement of which in adequate quantity, quality, and time is sufficiently uncertain for any reason to require prior provision for the supply thereof." This was accompanied by "corollary definitions" for three groups of strategic and critical materials (Department of Social Sciences, U.S. Military Academy, 1947, p. 131–132).

In the early 1980s, a cooperative data-collection effort of earth-science and mineral-resource agencies in six countries (the International Strategic Minerals Inventory working group, ISMI) sought to make publicly available nonproprietary data and characteristics of major deposits of strategic mineral commodities for use of policy analysts. ISMI struggled to find a mutually acceptable definition of "strategic." A single list of strategic minerals could not be prepared because a mineral that was strategic to one country might not be strategic to another. The group concluded, "The term 'strategic minerals' is imprecise. It generally refers to mineral ore or derivative products that come largely or entirely from foreign sources, that are difficult to replace, and that are important to a nation's economy, in particular to its defense industry. Usually, the term implies a nation's perception of vulnerability to supply disruptions, and of a need to safeguard its industries from the repercussions of a loss of supplies" (DeYoung and others, 1984, p. 1). ISMI also struggled with maintaining the "Strategic Minerals" part of its label when the earth's carrying capacity and industrial ecology replaced supply security as a major concern in the late 1990s, but decided against replacing "strategic" with "sustainable." Instead, ISMI morphed from the International Strategic Minerals Inventory to the International Strategic Mineral Issues working group (Werner and others, 1998).

Whether or not one believes that supply security remains a fundamental reason for classifying a material as strategic, the term may be applicable for several other reasons. So how do industrial minerals fit under this label?

INDUSTRIAL MINERALS? AND OTHER MINERALS USED BY INDUSTRY

Defining industrial minerals should be much easier, shouldn't it? It's what attracted participants to this Forum. In the introduction to the second edition of AIME's "Industrial Minerals and Rocks," editor Samuel Dolbear writes, "In no other publication is there available so complete a collection of data on the so-called industrial minerals—a term which has now largely replaced 'nonmetallic minerals' in technical usage" (Dolbear, 1949). In 1968, the USBM staff defined industrial minerals as "Rocks and minerals not produced as sources of the metals but excluding mineral fuels" (Thrush, 1968, p. 577).

Bates (1969, p. 3) also followed this exclusive approach when he divided all minerals into four categories and stated that industrial minerals are the substances that don't fall into the other three—metals and metallic ores, mineral fuels, and groundwater. (He also indicates a preference for "industrial minerals and rocks" over "nonmetallics".) Evans (1993, p. 3) defines industrial minerals to include rocks, but not gemstones. Bates (1975) recognizes that even an acceptable simple and straightforward definition can impart incongruous components to classification, such as including industrial diamond and corundum, but excluding precious varieties of the same minerals, gem diamond and sapphire—so they're included.

In the editor's introduction to Bates (1969), reference is made to the "so-called Paley Commission" having issued its five-volume report, "Resources for Freedom," in 1952, with emphasis on strategic nonmetallics only appearing in three chapters in volume II. (Some consideration of nonmetallic uses of mineral commodities like magnesium and titanium were made in chapters grouped in metals sections of the report.) One senses that industrial minerals had a "we get no respect" feeling.

Actually, industrial minerals were often the poster children for strategic materials and stockpiling. Eckes (1979, p. 131) quotes from an unpublished 1945 paper by William Y. "Wild Bill" Elliott, a Harvard government professor, expert on economic warfare, and later teacher of Henry Kissinger, which explained that only the Federal Government could be expected to maintain stockpiles. Elliott relied totally on nonmetallics when he wrote, "No private corporation could afford to make the costly investment in materials like quartz crystals, industrial diamonds, strategic grades of mica, and graphite which were absolutely essential if we were to be relatively well protected against the loss of sources of these supplies."

Asbestos, bauxite, beryl, chromite ores, fluorspar, graphite, iodine, mica, quartz crystal, rutile, sapphire and ruby, talc, and titanium minerals were among the stockpiled mineral commodities in 1982 (Morgan, 1984, p. 76–79). The Government was also using more ink each year as the bars on the charts used to track U.S. reliance on foreign sources of mineral commodities got longer and more numerous with each passing year (Figure 2). These charts and most of the books and reports referred to in this story have tapped a common source for the basic data used in their trend and cross-sectional analyses—the Federal Government's collection and publication of minerals information.

MINERALS INFORMATION? INDUSTRIAL, STRATEGIC, AND MORE

2004 was the 200th anniversary of a major event in the development of the United States, Lewis and Clark's expedition of discovery to the Pacific Northwest—President Jefferson specifically charged the explorers with observing "mineral production of every kind…" as they charted the new Territory. In George Featherstonhaugh's 1833 letter expounding on the virtues of expending public funds to expand the Nation's knowledge of its mineral resources, he wrote, "It is difficult to form an estimate of the great disadvantages any country lays under, precluded from a correct knowledge of its own mineral resources; and this remark may be especially applied to the United States, a country so extensive, so rich in useful minerals, and yet without any systematic survey, by the aid of which the geological features of the great mineral districts of the Union would be delineated."

In 1866, the position of Commissioner of Mining Statistics was established under the U.S. Department of the Treasury to report on the status of mining in the Western States and Territories. The Commissioner's reports, which included "estimates" of precious metal production, resulted from one of the early attempts by Congress to establish a national bureau of mining. The Treasury Department reports were discontinued at a time when monetary crises surrounding the gold standard were facing the Nation. In her history of the USGS, Mary Rabbitt (1979) wrote that “even those who had hoped that knowledge and corporate responsibility would accomplish the conservation of mineral resources were beginning to think of Government action.”

Some of those thoughts were expressed by Harvard Professor Josiah Dwight Whitney in the early 1850s. As recounted by Rabbitt, Whitney stated that:

> . . . the collection of mining statistics had long been recognized by the principal governments of Europe as an essential part of their watchful care over the public interest. It would be impossible to obtain statistics in the United States that were as accurate as the Prussian and French results, for American tradition would not countenance the constant inspection of mining localities that would be necessary. Nonetheless, something should and could be done. It must be done by experts, and the best way, he thought, would be to follow the system that he had used in collecting his statistics for *The Metallic Wealth of the United States*. . . .

The year 1882 marked the start of what is now the well-known USGS Minerals Yearbook series. The reports in those volumes were organized by mineral commodity and presented the results of a national canvass of mineral producers. The activity and people were transferred from the USGS to the USBM in 1925 at the same time that the USBM, which had been established in DOI in 1910 with mine safety responsibilities, was moved to the Commerce Department under Secretary Herbert Hoover. By the time that the USBM (and minerals information) was moved back to DOI in 1934, the need for such information had expanded from minerals needs for national economic development to minerals for the Nation’s security in a world at war. The USBM responded to changing minerals information needs by adding capability (and a new Yearbook volume) for State reports in the 1952 Minerals Yearbook and another volume for international reports (country chapters) in 1963. The USBM’s energy minerals statistics responsibilities were moved to the Department of Energy in the 1970s.

In September 1995, Congress announced the closure of the Bureau of Mines. Certain functions of Bureau were transferred to other Government agencies, most notably mining health and safety research to DOE (and later to NIOSH) and minerals information activities to the USGS. This transfer took effect on January 21, 1996, when 168 Bureau employees (154 in Washington, DC and 14 in Denver) became USGS employees. One week later, the Washington employees moved to the USGS National Center in Reston, Virginia.

QUANTITIES AND VALUES OF MINERAL PRODUCTION? THE CASE OF NORTH CAROLINA

North Carolina’s 2005 production of nonfuel minerals was valued at $846 million, ranking 23d among U.S. States (U.S. Geological Survey, 2006, p. 11). In recent years, crushed stone has accounted for about two-thirds of the State’s annual mineral production value, with phosphate rock, construction sand and gravel, industrial sand and gravel, and feldspar together accounting for another quarter of the State total.

As part of the USGS mineral-resource assessment of 1:250,000-scale map quadrangles in the 1980s, a study of cumulative nonfuel production of the Charlotte, NC–SC, quadrangle based on historical USGS and USBM production records, with some additional data from State publications and the Bureau of the Mint, was conducted. Regrouping the constant dollar value of cumulative production of mineral commodities from 1900 through 1978 (the authors followed the unit-regional value analysis standards that placed asbestos and mica under construction materials), construction aggregates and common clay accounted for 68 percent of the total, other industrial minerals (feldspar, mica, kyanite, kaolin and specialty clays, industrial sand, vermiculite, barite, talc, etc.) for almost 20 percent, metals about 10 percent, and precious metals just over 2 percent (DeYoung and Lee, 1989, p. 153). As noted earlier, the diversity of definitions and classifications can result in major differences in such summary statistics. The Charlotte quadrangle study area includes the Kings Mountain Belt, and lithium production was classified as a metal. Moving that value (over 8 percent of the cumulative total) to industrial minerals increases that group's share to about 28 percent and drops metals to about 1.4 percent.

Of the long list of minerals that constitute this region's (the Charlotte area and adjacent areas of North Carolina and South Carolina) mineral-production history, have any been classified as strategic and critical? The greater part of the production (construction aggregates), by value, has not, but there are a few examples, including mica, that have. Records of a Federal program to stimulate exploration for and production of defense-related minerals show that North Carolina's mica resources accounted for a significant part of this program's activities.

From 1950 to 1958, the Defense Minerals Administration and the Defense Minerals Exploration Administration administered this Federal program, which offered financial assistance to private industry on a joint participation basis through contracts to explore deposits of specified minerals. In 1958, this function was transferred to the USGS Office of Minerals Exploration. (There were no requests for Congressional Appropriations for new contract funds after fiscal year 1974, Congress discontinued funding authority in 1979, and the Regulations for Obtaining Federal Assistance in Financing Explorations for Mineral Reserves, Excluding Organic Fuels, in the United States, its Territories and possessions (30 CFR part 400) was removed from the Code of Federal Regulations in 1992.)

There are over 5000 file records (called "dockets") of applications for assistance by this program, 671 (13 percent) of which were for properties in North Carolina. Of the North Carolina total, 93 percent (624 records) were for mica alone or for mica and some other mineral(s). Contrast this with neighboring States, Virginia with 32 dockets (4 for mica, 23 for metals) and South Carolina with 10 dockets (3 for mica). In addition to mica, applications in North Carolina included occurrences of beryl, corundum, kyanite, monazite, quartz crystal, and talc.

An early edition of the topographic map for the Charlotte quadrangle features a location of a mine in York County, South Carolina, that was producing a product included in the list of strategic and critical materials covered in FEMA's biannual reports to Congress on the National Defense Stockpile inventory—quinine! It's suspected that a "kyanite" mine located on the topographic feature known as Henry's Knob was misinterpreted as "quinine" (Jacob E. Gair, U.S. Geological Survey, November 2, 1981, oral commun.).

If mica was a leading (by some measures) strategic mineral of the past for this region, which of the many mineral resources in this region holds promise of being held in that regard in the future?

TITANIUM? A NEW ROW ON THE COMMONWEALTH'S TABLE

Titanium accounted for about 0.2 percent of the value of cumulative production of nonfuel minerals covered by the Charlotte quadrangle assessment. From 1942 to 1952, titanium dioxide (TiO_2) concentrates used in the manufacture of pigments were produced from saprolitic overburden of the Yadkin River Valley (Richlands Cove) deposit, a high-grade lode deposit of granular ilmenite in the Blue Ridge belt (Broadhurst, 1955, p. 26; Barksdale, 1956, p. 211; DeYoung and Lee, 1989, p. 158).

In 1954, the writers of the "Malone Report" introduced their analysis of titanium by describing it as "a modern metal for a growing progressive America" and declared it "a must for modern fighting planes" (U.S. Senate, Committee on Interior and Insular Affairs, 1954, p. 195). The report goes on to say "Titanium is just beginning to find itself in a competitive world hungry for new ideas and developments in structural designs in the air and on the sea—and the making of daily use equipment for Mr. and Mrs. America will create a new industry." (U.S. Senate, Committee on Interior and Insular Affairs, 1954, p. 195).

The Malone Report's inclusion of titanium as a strategic material seems to be focused on its metal and alloy uses, not only for aircraft (today's uses include the F–22 Raptor), but also in ships and ground vehicles (for example, armor plate). However, one of the first defense uses was in World War I as titanium tetrachloride for smokescreens. In World War II, production and distribution of titanium minerals and TiO_2 pigment was regulated because of its use in paints and coatings for naval vessels and aircraft (Figure 3). Domestic consumption of TiO_2 pigment is driven by paint, paper, and plastics consumption. These materials are pervasive and increased consumption for these purposes is linked to national economic growth. Titanium metal consumption is cyclical, a result of changes in requirements for military and commercial aerospace industries. Double-digit increases and decreases are common. For example, there were dramatic falls in use after the cancellation of the supersonic transport and the end of the Vietnam conflict in the 1970s, the breakup of the Soviet Union in the 1990s, and the terrorist attacks of September 11, 2001. Domestic production of TiO_2 pigment exceeds domestic consumption. Although the United States is a net exporter of TiO_2 pigment, the Nation has a 63-percent net import reliance for the titanium minerals used as a feedstock. Domestic resources could be developed to meet increases in demand.

Titanium is more abundant in the earth's crust than many other elements—there is more titanium in the crust than there is copper, lead, nickel, tin, and zinc combined (McDivitt and Manners, 1974, p. 120,121). Brooks (1976, p. 149) notes in a discussion of cutoff-grade limits in the resource base that former USGS Director Vincent McKelvey had pointed out to him that the titanium content of beach placers mined in Florida is somewhat below the clarke of titanium. (Magnesium from seawater is another example of a material being produced from a source below its average crustal abundance.)

When the USBM and the USGS investigated North Carolina monazite placer deposits for the U.S. Atomic Energy Commission in 1952 and 1953, they reported "reserves" of titanium minerals of small tonnages and low mineral content in the Appalachian and Piedmont regions of the State (Peterson, 1966, p. 33–35). Coastal plain sands and gravels received brief mention under the "Other Deposits" heading as having been extensively prospected but having no commercial concentrations. Over 20 years later, researchers had delineated 19 deposits in the upper Coastal Plain of North Carolina and Virginia, almost 380 million metric tons (Mt) of sand containing almost 23 Mt of heavy minerals, including ilmenite, zircon, and rutile (Carpenter and Carpenter, 1991, p. 1657). The band of heavy mineral sands deposits, which formed during a major Pliocene transgressive-regressive event, extends south from Virginia into North Carolina. Some researchers have suggested that the Pliocene transgression was related to climatic warming and substantial melting of the East Antarctic ice sheet (Carpenter and Carpenter, 1991, p. 1667, 1669). Current mining operations are in Dinwiddie and Sussex Counties, Virginia. Several companies have conducted exploration and acquired mining rights for similar deposits in Greensville County, Virginia, and for locations in eastern North Carolina (Figure 4). These areas may write another chapter (or add another production bar) to the history of U.S. titanium mine production, depending upon the zircon content of the resources in these areas (a key factor in determining economic viability) and upon new technologies that may result in expanded uses.

Since its commercialization, the use of titanium metal has been limited by cost. A host of new technologies are under development to replace the traditional Kroll process with a process that would lower the cost of titanium metal. These new technologies are being funded by the private and public sectors. The USGS is participating in the U.S. Army's Titanium Extraction Mining and Process Engineering Research Project to identify non-traditional mineral sources of titanium that could be used as a feed material to produce titanium metal.

OUTLOOK

Will eastern North Carolina be the venue for another chapter in the history of titanium mining in the United States? If so, will the product be considered strategic? Will it be classified as a metal or an industrial mineral? For those involved in such enterprises, investors, land owners, miners, distributors, and those who reap the benefits provided by using the end products, the answers to questions about the "strategic" or "industrial mineral" labels are of no consequence. The often quoted example of Prof L.C. Graton's 1930 article pronouncing little chance of finding new copper regions and the subsequent history (Strauss, 1982) provides a stimulant for continued "re-searching" for (as well as research on) industrial mineral resources.

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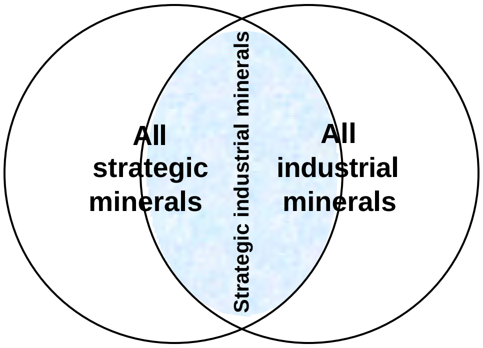

FIGURE 1 Strategic industrial minerals; a subset of all strategic and all industrial minerals.

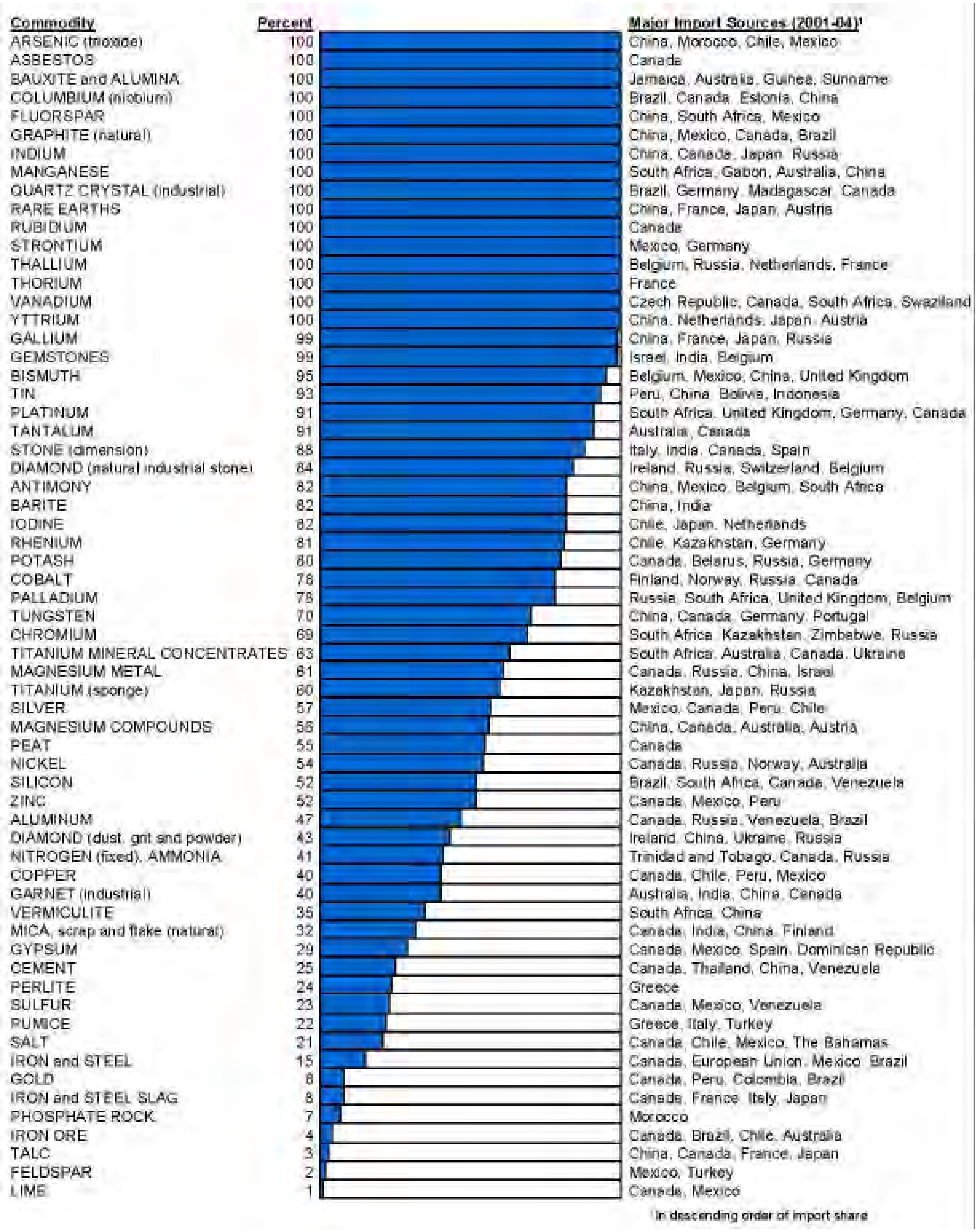

FIGURE 2 2005 U.S. net import reliance for selected nonfuel mineral materials. Most reports on U.S. strategic minerals cite USGS/USBM data on import reliance; import reliance data are published annually in the USGS Mineral Commodity Summaries.

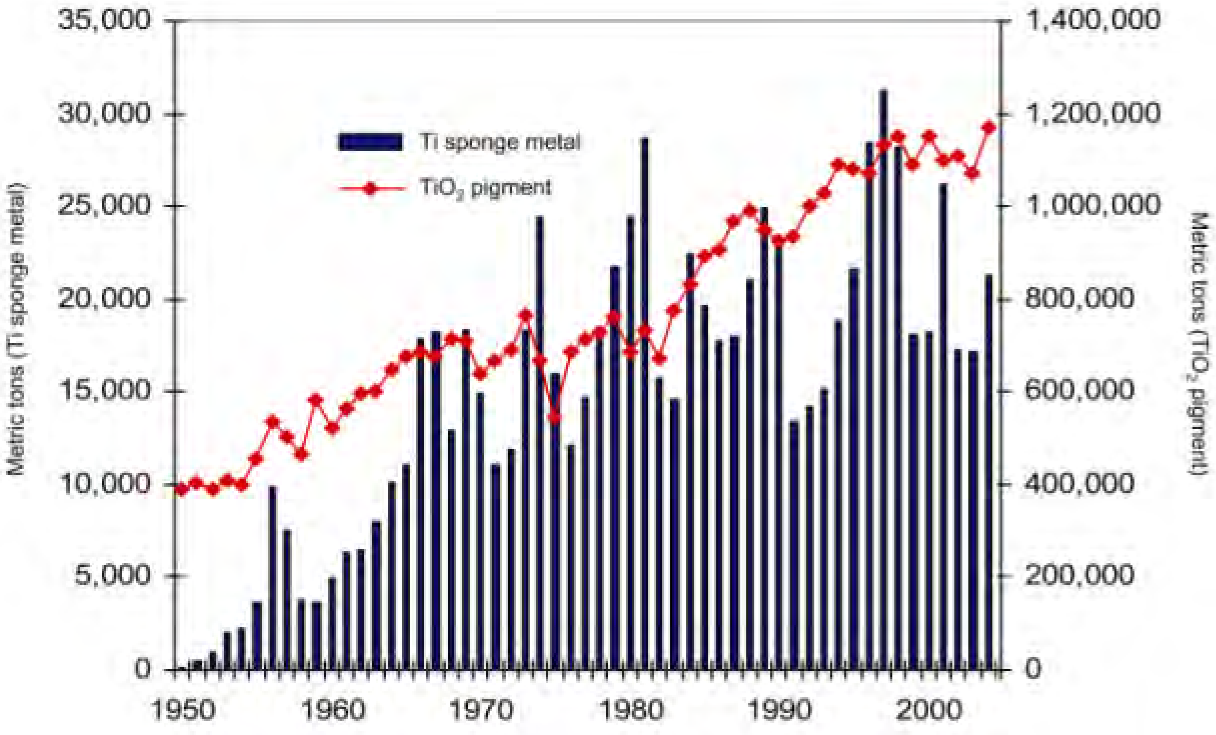

FIGURE 3 Titanium metal and TiO_2 pigment consumption in the United States.

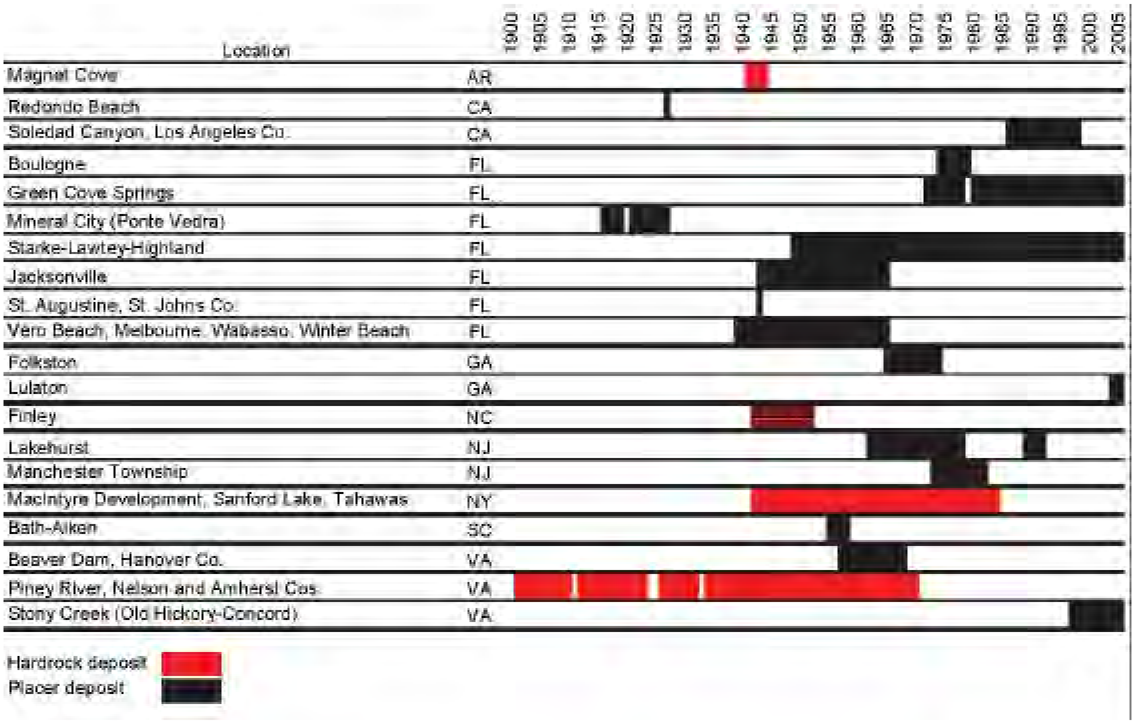

FIGURE 4 Sources of titanium minerals mined in the United States, 1900–2005.

Gypsum from flue gas desulphurization –
One opportunity for use in North Carolina

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ABSTRACT

A recent trend in the gypsum wallboard industry is to utilize gypsum produced by $S0_2$ scrubbers on Coal Fired Power Plants. Clean air legislation will soon make it mandatory for most of the coal fired plants in the United States to capture their sulfur emissions. One option for beneficial use of the waste material from the scrubbing process is to convert it to gypsum. Once manufactured, the gypsum can be used in cement, fertilizer or gypsum board. In early 2008, Progress Energy will produce and deliver gypsum to a BPB gypsum board facility. The BPB Board Plant will be located adjacent to Progress Energy's (PE) Roxboro Plant in Roxboro, North Carolina.

Critical elements contributing to the partnership were:

- The location of the gypsum relative to BPB's market needs.
- PE's decision to generate wallboard quality gypsum.
- PE's ability to produce large quantities of gypsum allowing the construction of a modern high speed plant.
- BPB's long-term need for gypsum supply and PE's long-term need for a gypsum buyer.

This paper reviews the pathways taken by BPB and PE to reach a long-term agreement. The flue gas desulphurization (FGD/scrubbing) process, gypsum manufacturing technologies selected, general past and future industry trends, clean air legislation drivers and other types of synthetic gypsum will be discussed.

- Click here for the presentation (~4.3 MB) – MS PowerPoint format only – paper follows below.

College, John and Farrow, Ginny, 2006, Gypsum from flue gas desulphurization – One opportunity for use in North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

BPB BACKGROUND

BPB was incorporated as a private company in 1917. In 1932 the company was launched on the UK stock market. For the most part BPB operated solely in the UK until 1952 when it expanded into France with the purchase of Placoplatre. In 1954 BPB purchased Westroc limited in Canada. This was the extent of the companies' major expansions until the late 1980's. From 1986 to 1990 BPB expanded by purchasing IECME & VIC in Italy, Rigips in Germany and Iberyeso and Placosa in Spain. By 2000 BPB had expanded into all of Western and Eastern Europe, South America, South Africa, and the Far East. In 2000 BPB made a major move into the US market with the purchase of Celotex USA. In 2002 BPB increased its North American presence with the purchase of James Hardie Gypsum.

Today the BPB group operates 140 plants, serves markets in 50 countries and has over 13,000 employees. It is the world leader in the production of gypsum board and plasters. One in every 5 gypsum boards produced comes from a BPB plant. The total gypsum board production for BPB is 15,494 million sq. ft. /year (1,440 million sq. meters/year).

In North America BPB has a 16% market share of the gypsum board production. BPB-NA operates 13 gypsum board plants, 6 finishing product plants and three ceiling tile facilities.

Since the late 1980's BPB has grown tremendously as a company. BPB has stated growth plans for both North America and the world. Much of the previous growth has been through acquisition. Recently BPB has focused on growth through the construction of new plants in specifically targeted market areas. BPB has announced the construction of two new plants in North America and is building 7 new plants in other parts of the world.

In December 2005 BPB was purchased by Saint-Gobain a world leader in production of materials for the construction industry. BPB is now a subsidiary of Saint Gobain that operates over 1,200 companies in 50 countries and has over 200,000 employees.

GYPSUM MARKET INFORMATION

Today approximately 38,000,000 tons of gypsum is consumed each year. The major markets utilizing gypsum are:

Gypsum Board	32,000,000 tons/year
Cement	3,300,000 tons/year
Fertilizer	1,100,000 tons/year
Plasters	500,000 tons/year

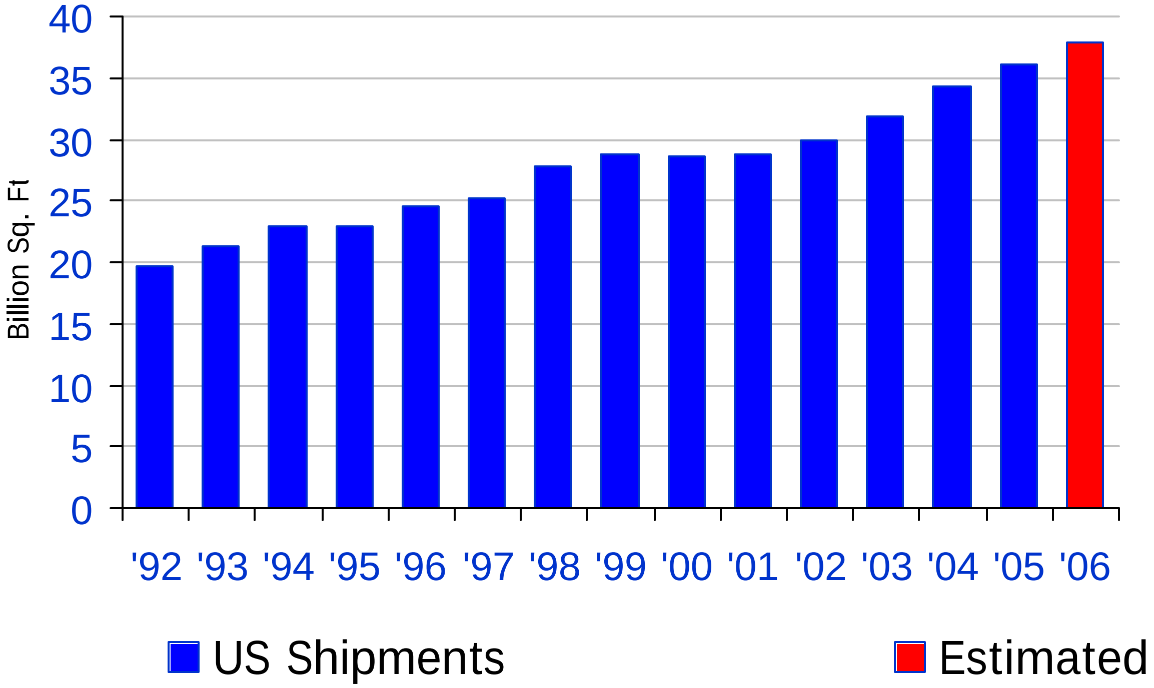
Gypsum is also used as a mineral filler, binder, and food additive. By far the major use of gypsum is in gypsum board (sometimes called drywall or wallboard). For many years the only source of gypsum for the board industry was natural rock. Board plants were built close to the natural deposits or in locations where the gypsum could be easily shipped. Major gypsum deposits are located in Nova Scotia and the Baja of

Mexico. At one time and continuing to today these deposits supported a tremendous amount of the industry. Ships transport the rock to plants located on the eastern seaboard, Gulf of Mexico and the west coast where it is processed and made into gypsum board.

There are many gypsum deposits in the United States. Unfortunately most of these deposits are not located near population centers. Major deposits can be found in Wyoming, Oklahoma, Arkansas, Colorado, and New Mexico. Shipping gypsum or gypsum products from these areas does not make economic sense. Gypsum products are made and sold usually within a radius of 250 miles of the board plant.

A large gypsum deposit in Fort Dodge, Iowa has allowed the supply of gypsum board to the Chicago area market for many years. Four competing companies have plants at this site. Unfortunately gypsum deposits have finite lifetimes and these plants are now looking for other sources of supply to extend their mine life. Similarly, Ohio at one time had gypsum deposits that now have been completely depleted.

The gypsum board market has been growing steadily for many years. Demand for these products is at its highest level and new products and uses will ensure continued growth. The chart below shows the market growth.



There are over 100 gypsum board plants in operation today. Most of these plants are running at full capacity. Many new board plants are needed to meet the needs of a growing industry.

Coincidental to this market growth has been a requirement by the US EPA for coal fired power plants to reduce $S0_2$ emissions. In many cases $S0_2$ capture is achieved by wet scrubbing. By adding an oxidation step to the scrubbing process, gypsum can be manufactured. Over the years this gypsum has been given many different terms. It has been call DSG (Delsulfogypsum), synthetic gypsum, or FGD gypsum (flue gas desulphurization).

By 2009 power companies will have the capability of producing over 40,000,000 tons of FGD gypsum per year. This will increase to 60,000,000 by 2015. The power companies' production of gypsum will far exceed the current market needs of 32,000,000 tons/year. The type of gypsum used will still be determined by the location of the board plant. Many older board plants continue to use gypsum from mines. Some have been converted to FGD gypsum. The key to the conversion is the availability of FGD gypsum in the area of the existing plant. All of the newer operating board plants and 7 of 8 planned expansions and plants under construction will use FGD gypsum. Many of the new board plants are over the fence operations. This is the ideal situation as there is no gypsum transportation cost and in many cases are very close to the gypsum board market.

FGD *vs.* NATURAL GYPSUM

The cost to manufacture gypsum through the FGD process is very competitive with surface mining costs. The benefit to the power company is avoided landfill costs. Placement of gypsum in a landfill could cost between $3 and $20 depending on location and landfill requirements.

There are over 100 gypsum board plants in operation today, most running at full capacity. Many new plants are needed to meet the needs of a growing industry.

The benefit to the gypsum company comes mostly from location. Unlike gypsum mines, power plants are located near the population centers. Gypsum board manufacturers and power companies have formed symbiotic alliances for the use of FGD gypsum. The power company avoids landfill costs while the board company avoids transportation costs. Other benefits to the board company include consistent product quality, consistent particle size, less grinding required, generally higher purities, and low salt content.

The major disadvantage to using FGD gypsum is its high moisture content. Before its use gypsum must have all of its free water removed. The cost of this evaporation is directly related to the gas costs used for drying.

The basic properties of FGD gypsum is as follows:

Free Moisture	< 10%
Average Particle Size	50-150 Microns
Gypsum Purity	95-100%
Calcium Sulfite Content	< 0.5%
Calcium Carbonate Content	< 5%
Flyash content	< 1%
$C1^-$	< 100 mg/kg
Na^+	< 100 mg/kg
Mg^{++}	< 100 mg/kg
K	< 100 mg/kg
Total Dissolved Salts	< 600 mg/kg

Currently 6.5-8.5 million tons of the total gypsum supply is from FGD. By 2009 approximately 12-14 million tons will be FGD gypsum.

BPB has announced the construction of two of the new board plants. One plant will be located in Moundsville, West Virginia. This plant will be using FGD gypsum from AEP's Mitchell power station. The second plant will be located in Roxboro, North

Carolina and will we use FGD gypsum from Progress Energy's Roxboro and Mayo Plants.

WHY ROXSBORO? BPB PERSPECTIVE

BPB expanded into the United States *via* the acquisition of Celotex-USA and James Hardie Gypsum. A total of eight gypsum board plants were purchased. The locations of these plants were:

Seattle, Washington,
Cody, Wyoming,
Las Vegas, Nevada,
Nashville, Arkansas,
Fort Dodge, Iowa,
Carrollton, Kentucky,
Port Clinton, Ohio, and
Jacksonville, Florida.

The plant in Port Clinton was subsequently shut down due to the fact that the quarry purities had dropped off considerably and the plant was fairly old.

It was BPB's full intent to become a major player in the United States market. Purchasing existing plants with established markets was part of the strategy. Developing new markets and building new plants was the second part of the strategy.

Looking at the geographical locations of the plants BPB purchased and BPB's needs in other growing markets it can be seen that there are major holes. The construction market in North and South Carolina is growing tremendously. BPB does not have a facility capable of supplying this market and three new supply sources were available. Progress Energy, Duke and Santee Cooper Power Companies all announced that they would be adding $S0_2$ scrubbing systems.

All three offered good plant locations, less than 250 miles to prime markets, sufficient quantity of gypsum, the possibility of over the fence operations, rail and water availability.

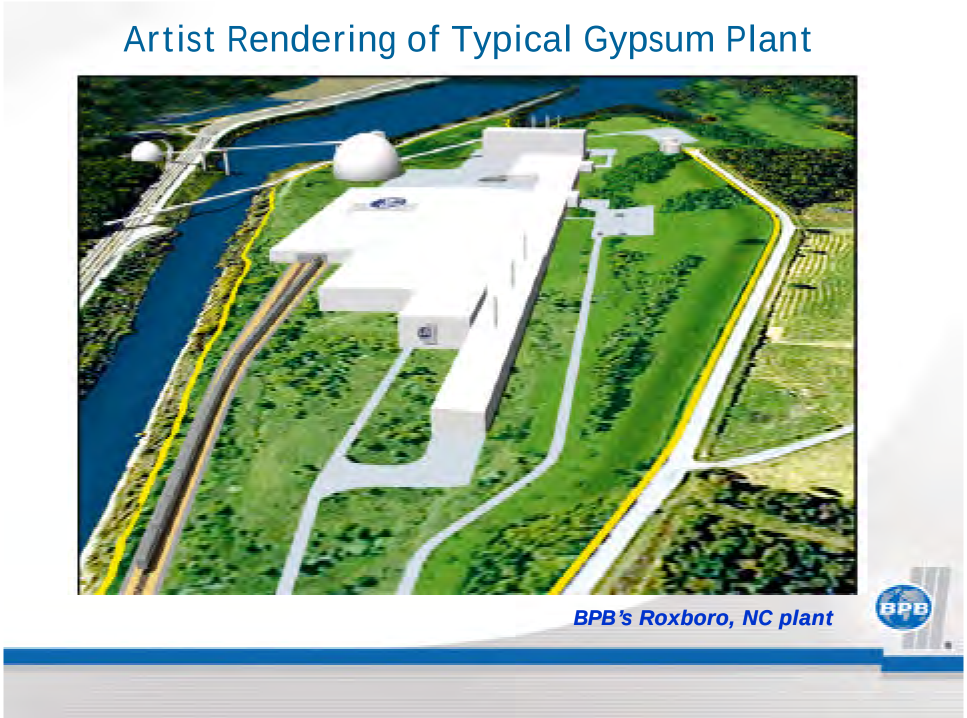
BPB and Progress Energy decided to work together very early in the FGD program. BPB was impressed by the integrity and professionalism PE displayed in the early meetings and its willingness to work exclusively with BPB. BPB and Progress Energy had similar goals and styles and were able to reach a long-term agreement for gypsum supply.

THE ROXSBORO GYPSUM BOARD PLANT PROJECT

The gypsum supply agreement was signed in February 2004. The scrubber installation schedule determines the start-up of the gypsum board plant. Ground breaking at the board plant is scheduled for this summer and the plant will be on line in July 2008. The board plant will start up when PE can supply a continuous stream of gypsum. This gypsum will be generated in the scrubbers and filtered approximately 1 mile from the gypsum board plant. All of the quality control measures are performed at this point. A conveyor carries the gypsum directly to the board plant. Most of the gypsum produced at the Roxboro

Plant will be consumed. Small amounts not used will be stored for future use or sold on the open market.

The gypsum transfers ownership at a weigh station at the end of the conveyor belt. In the board plant the gypsum is dried and then calcined. The calcined product is slurried with water and sandwiched between 2 continuously moving sheets of paper. The gypsum sets. The board is cut and transferred to dryers. All of the excess moisture is removed. The product is stacked and ready for shipment. The product board will be shipped from the plant to market *via* truck or rail. Approximately 100 truckloads of product will leave the plant in a day.



Artist Rendering of Typical Gypsum Plant

BPB's Roxboro, NC plant

This plant will produce approximately 700,000,000 square feet of gypsum board per year and consume over 600,000 tons of gypsum. The plant will also use 300 GPM of water and 240,000 square feet of recycled paper per hour. The process is truly a "green" process as 99% of its components are considered recycled or by-products.

CONCLUSION

Although this project is still in its early stages the groundwork has been laid for a relationship that must last for more than 20 years. Beneficial use of the power plants by-products gypsum is the driving force for both companies. If all goes well "as it is expected to" BPB will have consumed nearly one square mile of gypsum stacked 24 ft. high by the end of the first term of the contract. This is a lot of landfill not placed, one large quarry not opened and a lot of gypsum board made close to its market.

Industrial minerals development in Ghana: A potential catalyst for socio-economic emancipation of the rural communities

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ABSTRACT

A number of industrial minerals occur in each of the ten administrative regions of Ghana.

The geological setting of some of the occurrences such as brown clays and aggregate which occur in nearly all the 138 administrative districts of the country and others such as kaolin, limestone and dolomite which occur in specific geologic environments is described.

It is the belief of the authors, that the resource delineation, evaluation, declaration, development and exploitation of these commodities when effected in sustainable, medium to large scale operations, will create job opportunities in the rural areas where these deposits occur and curb the rural-urban migration which is a major problem in most developing countries including Ghana.

- Click here for the presentation (~5.5 MB) – MS PowerPoint format only

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Amoako, P.Y.O., and Amanor, Joe, 2006, Industrial minerals development in Ghana: A potential catalyst for socio-economic emancipation of the rural communities, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey

The Earth systems science education revolution in North Carolina

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ABSTRACT

The presentation traces the successes and continued challenges of Earth systems science education in North Carolina. North Carolina was the first state to mandate Earth science for all students. This mandate was enacted as a result of broad support from multiple constituents. This presentation will trace the rallying of this support and how it can serve as a model for other groups to influence the development of strong Earth systems science curriculum in their state.

The new graduation requirement moved North Carolina toward a truly comprehensive high school science curriculum aligned with the National Science Education Standards. Implementation of the mandated graduation requirement was designed to be implemented in a variety of ways and may be designed locally to encourage the study of local Earth/environmental issues with the caveat that the course must address all of the competency goals designated in the Earth/Environmental Science course in the North Carolina Science Standard Course of Study.

This broad interpretation presents a number of problems including: the preparation of teachers who meet the No Child Left Behind definition of highly qualified, the selection and development of educational materials, and providing assessment instruments designed to measure student achievement and program successes.

The presentation will describe the teaching materials and inquiry-based laboratory activities developed by the North Carolina Department of Public Instruction (NCDPI), the publishing industry and the university community. It will further trace efforts to develop assessment instruments and to develop partnerships with distinguished scientists, university faculty, museums, and the NCDPI to explore and experience learning in stimulating ways that translate into new approaches to the art of teaching earth systems science with programs like the Kenan Fellows and Science House located at North Carolina State University.

Tucci, William, J., and Watson, Mary E., 2006, The earth systems science education revolution in North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey

INTRODUCTION

Wouldn't it make sense to give consumers and planners the technical knowledge derived from earth science to evaluate the place in which people typically make their largest investment, that symbol of the American Dream—a home? But for the actions of a few people 20 years ago, earth science in North Carolina would have been dropped from the public school curriculum. This paper traces the history of the elimination – and eventual restoration of earth science in North Carolina's Standard Course of Study and highlights some of the efforts of various agencies that played a role.

During the late 1950's interest began to grow nationwide in the earth sciences. The National Science Foundation funded many (Watson and Tucci, 2002) earth science projects including the most successful and influential Earth Science Curriculum Project (ESCP) (American Geological Institute,1967). ESCP was largely responsible for the national development of the earth sciences as a course of equal significance to the physical and life sciences (Watson and Tucci, 2002).

EARTH SCIENCE IN NORTH CAROLINA

In North Carolina, Earth Science (earth science topics in the eight grade curriculum?) was established as a required course at the eighth grade level in 1962. During the next twenty years earth science instruction was delivered in the eighth grade classrooms of North Carolina.

In 1982 the North Carolina State Board of Education and the North Carolina Department of Public Instruction (NCDPI) evaluated the effectiveness of the State's Science program. A Science Curriculum Study Committee (Committee) was established to make recommendations to improve the total science program in North Carolina's public schools. After a two-year study by business and industry leaders, representatives of higher education, superintendents, principals, local supervisors and teachers, the Committee recommended that Earth Science be moved to high school. Administrators who opposed this curriculum change argued that earth science instruction would reduce participation in Advanced Placement, Chemistry and Physics courses and resisted its implementation.

In 1985, Charles "C.Q" Brown, East Carolina University, Professor of Geology, realized that North Carolina was in effect removing earth science instruction from the classrooms of North Carolina. Brown decided to oppose decision and began to assemble a group of scientists, educators, and representatives from business and government. After fifteen years of persistent effort, Brown's group won a victory for earth science education that profoundly changed science education in North Carolina and continues to serve as a national model (Watson and Tucci, 2002). In 1997, the State Board of Education approved making a course in earth and environmental science one of the three science courses required of the state's students for high school graduation.

At the core of Brown's group were Fred Allen (Executive Director of the North Carolina Aggregates Association), Floyd Mattheis (an East Carolina University science educator), and Fred Beyer (Cumberland County Science Supervisor). This group formed the nucleus of the Education and Industry Committee for Earth Science in North Carolina (Committee), that became the prime mover in the effort to restore earth science to the state's curriculum at all grade levels, and to make earth science a North Carolina graduation requirement (Watson and Tucci, 2002). This group recognized the need to dispel the image that they did not represent the vested interest geologists but needed to show that earth sciences were fundamental to a sound science education.

The group quickly expanded to include a broad coalition of earth science professionals and educators from industry, the North Carolina public school system, NCDPI, the North Carolina Aggregates Association, the North Carolina Mining Commission, the North Carolina Geological Survey, the state Department of Environment and Natural Resources, the state's colleges and universities both public and private, and private consultants. The Committee also attracted support and membership from federal agencies, the National Oceanic and Atmospheric Administration, the National Weather Service and the Environmental Protection Agency. As the Committee grew it became more active and began a lobbying campaign directed at the State Board of Education, local school boards, superintendents, principals and chairs of science instruction. Telephone calls, emails, one–on–one meetings, fact sheets, publicity and a statewide and national letter writing campaign as well as members attendance at local school board, 4-H, Boy- and Girl Scout events spread the message that Earth science instruction is essential to develop a scientifically-literate citizenry.

State Board of Education

The North Carolina Department of Public Instruction (NCDPI) conduced a major study of the status of Earth Science in the schools of North Carolina in 1988. Findings from the study demonstrated high student interest, high teacher interest, and confidence on the part of teachers in their ability to teach the subject. The study showed there was an adequate supply of teachers with over 70% of earth science teachers holding comprehensive certification and 22% holding earth science certification only.

By 1992, it was time for the State Board of Education School Board to consider revising the North Carolina Science Standard Course of Study that state statute requires every five years (http://www.ncpublicschools.org/curriculum/science/scos/2004/05preface). The Committee, at that time headed by Alex Glover, a geologist for Vulcan Minerals Company, recognized the opportunity to lobby for earth science to be a graduation requirement for all high school students.

Glover's leadership led to a strategic compromise that was essential to the Committee's success and decided to lobby to formally include environmental science in their lobbing efforts. The result was not for simply an earth science class but a request for an earth and environmental science class. This change in approach gained the support of the environmental, marine, space and atmospheric scientists (Watson and Tucci, 2002).

Changing the Graduation Requirement

In 1992, the State Board of Education made numerous changes in the high school graduation requirements. Included was Biology for all students and increasing the number of science courses required for graduation from two to three, presenting the opportunity of including an earth and environmental science course as this third laboratory science course. (North Carolina State Board of Education, Minutes of December 1992).

In the summers of 1992 and 1993, two major forums were held involving over 200 stakeholders (teachers, principals, superintendents, higher education representatives, business/industry representatives) interested in the pending revision of the state science curriculum. At both of these meetings, the consensus was reached that Earth/Environmental Science (as it was now termed) be added to the high school graduation requirements as the third elective science.

The argument was further strengthened by two major publications. In 1993, the American Association for the Advancement of Science published *Benchmarks for Scientific Literacy* that called for the exposure of high school students to the life sciences, earth sciences, and physical sciences.

- http://www.project2061.org/tools/benchol/bolintro.htm, and

The National Academy of Sciences (1996) published the *National Science Education Standards*, which called for the exposure of high school students to the earth sciences, physical sciences and the life sciences.

- http://www.nap.edu/books/0309053269/html/index.html.

By the fall of 1994, a survey of all North Carolina Public School Superintendents indicated only two superintendents expressing concern about the proposed Earth / Environmental Science requirement.

STATEWIDE SUPPORT

In 1995, the High School Principals Advisory Council, representing the high school principals of North Carolina, unanimously supported the idea of designating an Earth/Environmental Science as the third required science course at their spring meeting. In 1994-95, the State Board of Education from business received over 100 letters, industry and government leaders supporting the requirement. The North Carolina Science Teachers Association went on record in 1995 and 1996 supporting this graduation requirement.

The North Carolina Science Leadership Association endorsed the concept in 1995 and 1996. When contacted in 1994-95, strong support was voiced by a large majority of higher education institutions, and none expressed opposition. A survey of high school science department chairpersons taken over a five years period showed overwhelming support (96 percent) for the requirement. Based this robust support, the proposal was presented to the State Board of Education which took final action on September 4, 1997, approving the change in high school science graduation requirements to include one elective unit in the earth/environmental sciences.

The North Carolina Rules Review Commission approved the proposed change making an earth/environmental science elective of the three science courses required for graduation in December 1997. This requirement was to become effective with the high school graduating class of 2002.

In March of 1998 the State Board of Education delayed the implementation of the new graduation requirement, mandating that the requirement would be implemented with the entering high school class in the fall of 2000 to better align with the implementation revised Standard Course of Study. It should be noted that this requirement does not specify a single course but rather may be satisfied by a locally designed course with the one of a series of courses included.

IMPLEMENTATION

Several groups and organizations continue to develop curriculum materials and provide professional development opportunities for science educator to facilitate the implementation of the graduation requirement.

North Carolina Department of Public Instruction

Standard Course of Study

A document that provides the goals and objectives of the Standard Course of Study and delineates what students should know and be expected to do by the end of the course. This document is available at www.NCPublicSchools.org.

Earth/Environmental Support Document Curriculum Support Document

This document was developed in response to the expressed needs of earth/environmental science teachers for materials to enhance the teaching of the revised North Carolina Standard Course of Study for Science. The materials provide a guide for translating the goals and objectives of the earth and environmental science curriculum into good instructional design. A group of dedicated and talented science teachers spent many hours developing these materials. The result is this resource that will facilitate the implementation of the North Carolina Science Curriculum. A special thanks to the authors of these materials:

- Laura Berube, Kenan Fellow
- Susan Escobar, Lincoln County Schools
- Lynn Gronback, Orange County Schools
- Dick Hilliard, Henderson County Schools
- Rick Johnson, Moore County Schools
- Debbie Michael, Lincoln County Schools
- Judy Pope, NC Office of Environmental Education
- Lee Stroupe, Watauga County Schools
- William J. Tucci, Kenan Institute
- North Carolina Office of Environmental Education

Reference Tables

This 28-page document includes selected North Carolina specific maps, formulas, and physical data. It is to be used as a reference for instruction and classroom assessment and to aid, enhance, and encourage an inquiry approach to teaching and assessing the Strands, Goals and Objectives of the Earth/Environmental Science curriculum. Printed copies may be purchased in packages of 10 through the NCDPI Publications Section (telephone 800.663.1250). The material can be downloaded from the Internet at:

www.ncpublicschools.org/docs/curriculum/science/scos/1999/earthsci/earth_science_tables.pdf

The NC Office of Environmental Education

The Office of Environmental Education is an agency in the Department of Environment and Natural Resources, worked closely with the Education and Industry Committee for Earth Science in North Carolina and the Science Consultants in NCDPI to develop the Earth/Environmental Science requirement for high school graduation in North Carolina. The Office felt it was critical that environmental science content and environmental education concepts be integrated into the curriculum's competency goals in order to assure a scientifically and environmentally literate citizenry. The Office also felt that the addition of environmental education concepts would strengthen student retention and understanding of both earth science and environmental science content. The resulting curriculum (1999) included a competency Goal 7 that focused on human affects on the environment and stewardship of the environment. The Office of Environmental Education has also contributed resources to the "Support Document and Suggested Resources" that will accompany the Standard Course of Study Goals and Objectives for Earth/Environmental Science.

North Carolina Geological Survey

The North Carolina Geological Survey (NCGS) has several general interest and recreational geology documents. In cooperation with the North Carolina Department of Public Instruction, each of these NCGS publications has a correlation of the text with the Earth/Environmental Science – Grades 9-12 Curriculum Strands and provide for the teaching of the content of the Goals and Objectives of the North Carolina Standard Course of Study www.NCPublicSchools.org/science/curriculum.

As the state's official geology agency, the mission of the North Carolina Geologic Survey (NCGS), Division of Land Resources, helped with lobbying effort to create an education and outreach program specifically for teachers of earth science and to collaborate wherever we could offer our expertise to programs that would serve the new curriculum.

These efforts included collaborating with:

- NCDPI to draft first version of the first version of the standards and objectives for Earth/Environmental Science in the NC Standard Course of Study (1998-1999).
- NCDPI to compile a listing of more than 100 free or low-cost resources correlated them to the 2,000 curriculum and published the resource guide on its Web page http://community.learnnc.org/dpi/science/archives/curriculum_science/index.php.
- NCDPI to create documents to support the Earth/Environmental Science curriculum such as the *North Carolina Through Time* poster (2000).
- NCDPI to correlate NCGS popular publications to the NC Standard Course of Study to extend the value of popular publications as teaching documents. These publications include *A Geologic Adventure along the Blue Ridge Parkway in* NC (2001) and *When the Ground Moves: A Citizen's Guide to Geologic Hazards* (2006).

- North Carolina Department of Forest Resources to design *The Talking Rocks Trail* at Clemmons Educational Forest, for which the NCGS received the Prazen Living Legend Award in 1996.
- North Carolina Museum of Natural Sciences to design content for the Fossil Hall and North Carolina Treasures exhibits.

As part of its ongoing education and outreach effort, the North Carolina Geological Survey:

- Administers the Outstanding Earth Science Teacher Award for traditional and non-traditional educators in conjunction with the North Carolina Mining Commission. The award provides money, recognition and resources for teachers annually.
- Wrote the grant for, designed and constructed the *North Carolina Rock Kit* (1994). The original grant provided a kit for every elementary and middle school in the state. Since its inception this program has distributed more than 6,000 rock kits to educators statewide. The program is currently operated by the Minerals Research Laboratory (Asheville) of North Carolina State University (1994) [www.engr.ncsu.edu]
- Won funding from the North Carolina Mining Commission's Education Sub-Committee to supply free, high-quality curricular resources at the North Carolina Science Teachers Association's annual conference. During this program, more than 100,000 items have been supplied tour state's earth science teachers.
- Distributes educational items through its Publications Office http://www.geology.enr.state.nc.us

The North Carolina Geological Survey (NCGS) published several recent general interest and recreational geology documents in cooperation with the North Carolina Department of Public Instruction (Carter and others, 1988, North Carolina Geological Survey1989, 2001, 2005, Wooten and others, 2003, Reid and others, 2006). Most of these NCGS publications have a correlation chart of the text with the Earth/Environmental Science - Grades 9-12 strands and provide for the teaching of the content of the Goals and Objectives of the North Carolina Standard Course of Study (1999 Revision:

http://www.NCPublicSchools.org/curriculum/science.

Kenan Fellows

The Kenan Fellows Program is an innovative professional development model that entails working closely with university scientists and the North Carolina Department of Public Instruction (NCDPI) to promote teacher leadership, improve North Carolina's retention rate of quality teachers, and advance K-12 science, mathematics, and technology education.

Since its inception in 2000, the Kenan Fellows Program has received widespread acclaim, including recognition by NSF as a national model for teacher professional development. In addition to cultivating teacher-leaders and creatively engaging more stakeholders in the teaching profession, the Program results in web-based instructional materials co-created by teachers (Fellows) and university scientists (their Mentors) that address areas of the NC Standard Course of Study identified by NCDPI as in greatest need of support.

The cutting-edge content, caliber, and integration of localized datasets into these online modules render them equivalent to products developed through such federal initiatives as the National Science Foundation's (NSF) Instructional Materials Development program, but at a fraction of the cost and with an adaptability to the interests of North Carolina schoolchildren that would have been cost-prohibitive and technologically inconceivable a decade ago.

The Kenan Fellows curriculum products are available at www.kenanfellows.org Two of the several web sites designed to assist teachers implement the earth / environmental science graduation requirement are:

- http://www.ncsu.edu/kenan/fellows/2001/syoung/
- http://www.ncsu.edu/kenan/fellows/2002/dmassengill/

North Carolina Power Shift Initiative

Kenan Fellow Lynne Gronback designed and implemented a web site called the *North Carolina Power Shift Initiative***.** The site and associated activities will provide North Carolina high school earth and environmental science teachers with information on global climate change, sustainable economic development and the introduction of renewable energy opportunities. The Power Shift Initiative (i) is a cooperative project that incorporates the expertise of Dr. William Schlesinger, Dean of the Nicholas School of the Environment at Duke University, Tim Toben, of Carolina Green Energy, Jeff Brooks, of NC GreenPower, and Kirk Bergstrom, of WorldLink Media. This web link will be available at www.kenanfellows.org in July 2006.

Over the past 18 months, more than 400 teachers in North Carolina have received a 26-minute, magazine style video entitled ***Power Shift.*** The video serves as a centerpiece for curriculum support materials that provide a structure for teaching about global climate change and its potential impact on North Carolina's agricultural and natural resource industries. Additionally, the Power Shift Initiative provides a way to connect students to communities in a service-learning module that serves to educate the public on green power options in our state.

The Free Air Carbon Exchange (FACE) project housed in the Duke Forest has been a focal point of study and a feature of the North Carolina Department of Public Instruction's Curriculum Support Documents as an example of how scientists are researching the effects of elevated CO_2 levels on trees and soils in a managed forest setting http://www.life.uiuc.edu/plantbio/wimovac/related.htm.

In the summer of 2005, 30 teachers and interested adults participated in a field trip to the FACE forest. For many teachers, it was the first time to see and hear about the findings of the many research projects. The FACE forest field trip was a motivator for many teachers to choose to teach in a more inquiry oriented way. The FACE forest is the perfect classroom and it served as a model for how local school-based research projects could be set up and maintained.

In addition to learning about global climate change, teachers were also educated about NC GreenPower (Figure 1) a non-profit renewable energy company dedicated to developing a renewable energy industry in North Carolina. NC GreenPower is supported by the major utilities in the state. In the North Carolina Power Shift Initiative, students explore the necessity of developing renewable energy sources as a way to supplement our current energy budget. Students are assessed for their current understanding of fossil fuel use in North Carolina. The results are used to guide them through several projects and investigations where they learn about the different types of renewable energy services being developed. To learn more about NC GreenPower, visit www.ncgreenpower.org.

The work is notable because the NC PowerShift Initiative is a project about beginnings. Students who begin to see how the world can be a better place as well as an economically viable place have the opportunity to be problem solvers and movers and shakers in our state. Teachers and students can “Be the Difference”.

North Carolina Virtual Field Trip

Kenan Fellow Sam Fuerst is designing and will implement a web site called, *A North Carolina Virtual Field Trip* that will be available in July 2006**.** The site is designed to assist earth/environmental science teachers expose their students to field experiences with out the expense and difficulty of managing students in the field. The site highlights geological points of interest, photographs and describes each site description with:

- What the rocks are;
- The story the rocks tell; and
- Why the rocks are important.

When the site is completely operational, the home page will contain a geological time scale and geologic map of North Carolina. The North Carolina geologic sites will be accessible by geologic era and period through the time scale and can be located on the geologic map. Initially, the web site will include ten field trips with the intent of adding additional sites and itinerates in the future.

GROWTH IN ENROLLMENT

Earth/Environmental Science enrollment trends for grades 9-12 show a steady increase from the 1999-2000 School Year (SY) until enrollment of students in Earth Science courses reaches parity with enrollment in the Life Sciences for the School Year 2004-2005 (Figure 2). Achieving parity is one way we can count a victory in earth science as it demonstrates that earth science courses are reaching all the state’s high school students.

Satisfaction of the earth/environmental science requirement may be designed locally to encourage the study of local earth/environmental issues. Specific examples of courses that may satisfy this requirement include: Standard Course of Study Earth/Environmental Science, AP® Environmental Science, or IB Environmental Systems (www.ncpublicschools.org/docs/curriculum/science/scos/2004/07purpose.pdf. Any course that satisfies this requirement must include all of the competency goals designated in the Earth/Environmental Science course in the Science Standard Course of Study.

For the earth science community, North Carolina is a success story that shows how a group of earth scientists can influence their state’s science curriculum. Giving students a chance to pursue earth science investigations of real-life conditions in their own neighborhood — that is what the issue was all about.

The new graduation requirement moved North Carolina toward a truly comprehensive high school science curriculum. Educators and earth science professionals are determined that students will acquire the knowledge and skills to deal with the ever-increasing litany of environmental problems they will face. Geologists say that we prevailed because we showed the curriculum change was not in our self-interest that it was in the public's interest.

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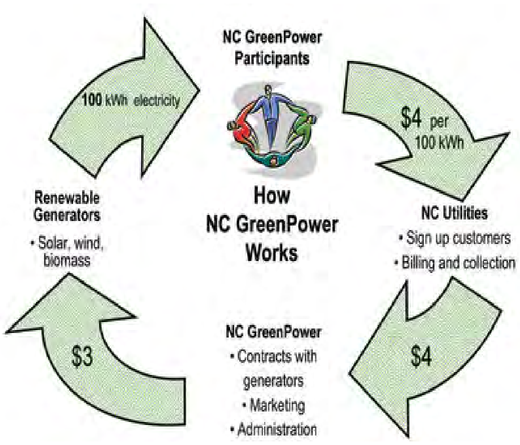

FIGURE 1 Enrollment in Earth Science *vs.* Life Science Courses, School Years 1999-2005.

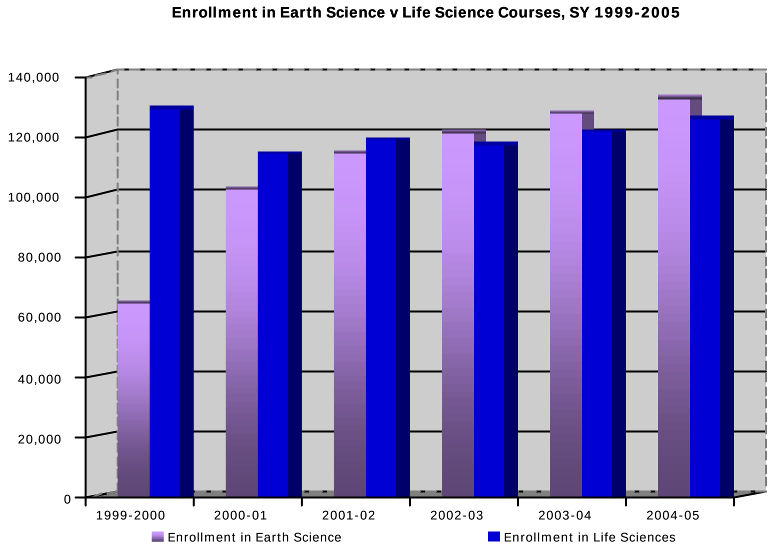

FIGURE 2 Trends in Enrollment in High School Earth Science Courses plotted against Enrollment in Life Science Courses. Data source: www.NCPublicSchools.org/statisticalprofile.

Posters

North Carolina's major industrial mineral districts

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ABSTRACT

Principal industrial mineral districts in North Carolina are shown along with illustrations of many operations. North Carolina produced $846 million in 2005 (not including ultrapure quartz and synthetic gemstones), the latest year for which reporting statistics are available. This is ~5% of the state's appropriated budget. The annual direct and indirect economic impact of mineral resource extraction is estimated at $11.3 billion.

All mining is from 785 permitted active mines that cover 112,857 permitted acres, or only about 0.37 % of the state's ~48,000 square miles of land area. This is about $7,400 per permitted acre.

Despite the state's relative high population density recent mineral discoveries have been made by industry (heavy minerals and decorative flagstone) and collaborative work by the NC Geological Survey and NCSU's mineral research laboratory (garnet, glass sand, Iota-grade high purity quartz, quartz and feldspar).

Spodumene is not currently mined nor are some dimension stone and glass sand deposits. Identified new resources are heavy minerals resources (rutile, ilmenite, zircon, leucoxene), glass sand, frac sand and abrasives (garnet).

Speculative industrial resources include diamonds, uranium, and combined mixtures of sodium- and potassium-feldspar plus silica to make glass, and absorbent clay, and rare-earth elements contained in monazite. Unexploited mineral fuels include coal-bed methane in Triassic basins, and offshore oil and gas, and gas hydrates in federal waters. Current elevated gold prices may stimulate reevaluation of historic gold districts.

North Carolina offers good ports for international commerce, inland ports, rail and road systems, international airport cargo hubs, and economic development zones. The ocean ports of Morehead and Wilmington may become hubs for ocean delivered aggregates from elsewhere on the US East Coast or even Canada. Several industries provide value added to industrial and metallic minerals including specialty steel production, fiberglass insulation, fiber optic production.

- Click here for the poster (~39.9 MB) – MS PowerPoint format

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Reid, Jeffrey C., 2006, North Carolina's major industrial mineral resource districts, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34: North Carolina Geological Survey

State of North Carolina mining permit application process

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ABSTRACT

The extraction of minerals by mining is a basic and essential activity making an important contribution to the economic well-being of North Carolina and the nation.

As required by the North Carolina Mining Act of 1971, anyone affecting one acre or more of land for the purpose of mining must obtain a mining permit. Obtaining a mining permit requires the submittal and approval of a complete mining permit application. The application must include information concerning the mining operation, a detailed mine map, and a final reclamation plan for the restoration of all affected land.

All mining permit applications are submitted to the North Carolina Department of Environment and Natural Resources, Land Quality Section Central Office, located in Raleigh, North Carolina, distributed to the technical review staff and subsequently routed to a number of state and federal agencies for their review and comments. After a 30-day time period, the review staff compiles all comments from the agencies and performs a technical review for completeness. If the application is incomplete, or if additional information is needed, the technical review staff writes a letter to the applicant requesting the required information.

Upon receipt of all requested information and prior to the issuance of a mining permit, the applicant is required to post a reclamation performance bond or other security to guarantee the final reclamation of the site.

Mining permits can be issued for up to ten years and renewed within two years of their expiration. A mining permit may be modified at any time during the life of the permit.

The poster illustrates the mining permit application requirement and process, and provides an example of a typical mine map.

- Click here for the poster (~39.9 MB) – MS PowerPoint format

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Williams, Floyd, Wehner, Judith A., and Hicklin, Kristin M., 2006, North Carolina mining permit application process, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Geology for the people: Improving employee morale and productivity through socially relevant projects at the North Carolina Geological Survey

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ABSTRACT

In 2005, the North Carolina Geological Survey (NCGS) adopted a strategic vision titled "Geology for the People." This vision developed from the original organic act that created the NCGS, the first geological survey in the United States, as well as the first survey to produce a state geologic map. In 1824, our first State Geologist Denison Olmsted, described his strategic vision as conducting geologic studies not only for identifying geologic resources, but more importantly, to *"give an account … of their uses and their value, in relation to domestic convenience and economy, or to commercial enterprise."* In other words, "Geology for the People." The world has changed a lot in the 182 years since Olmsted's report, but geology still remains an important part of everyone's lives. Now, more than ever, we know and appreciate the close connection between geology and the atmosphere, hydrosphere, and biosphere.

However, the geologic profession is only peripherally involved in long-term planning and land use decisions. In order for our profession to really make a difference in planning decisions that affect the public's health and well being, we need to dramatically increase our involvement in the decision-making process. We know our work as geoscientists is important, but we must educate the rest of the world by showing "added value." As it relates to the NCGS, "added value" means not only conducting geologic research, but also actively disseminating that geologic knowledge to a variety of "users" in a customer-friendly format.

Common sense dictates that your products or services will be desired if someone wants or needs them. If you consistently deliver useful and timely products or services, your organization will develop a good reputation with consumers and the need for your products or services will increase. With increased need for your products, comes increased need for funding. In addition to improved agency recognition and potential increases in funding, "socially relevant" projects increase employee morale. Numerous studies have concluded that the number one reason people stay at a particular job is the belief that, "what I do at work makes a difference."

By combining the concepts of intellectual curiosity with "value added" science that is socially relevant, the NCGS has increased agency recognition, increased funding opportunities, and most important to our success, created happy employees. Happy employees who feel their work is important are productive employees.

Click here for the poster (~10.0 MB) – MS PowerPoint format

Clark, Timothy W., 2006 Geology for the People: Improving employee morale and productivity through socially relevant projects at the North Carolina Geological Survey, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals Information Circular 34, North Carolina Geological Survey.

Evaluation of the Bakersville Eclogite, Mitchell County, North Carolina for its suitability as an abrasive-grade garnet

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ABSTRACT

A heavy mineral garnet concentrate, suitable as an abrasive, was produced from a 2 kg sample of garnet-rich material from the Bakersville eclogite, Mitchell County, North Carolina.

The bench scale laboratory process consisted of crushing, grinding, and gravity separation to separate the heavy minerals from the light minerals. The sample was ground to pass US 30-mesh and the minus 30-mesh fraction was subjected to sink float separation using a heavy liquid with density of 2.96 g/cc. The sink fraction (heavy mineral concentrate) composed mainly of garnet was subjected to mineralogical evaluation to determine garnet grade. The results of the heavy liquid separation process indicated that about 85% by weight of the original material reported as heavy mineral concentrate.

The garnets are red, subhedral, and average 2 mm in diameter. Microprobe compositions are $Py_{32}Alm_{47}Grs_{22}Sps_{<1}$ [rims] and $Py_{27}Alm_{49}Grs_{24}Sps_{<1}$ [cores] (Willard and Adams, 1994).

DRY PARTICLE SIZE ANALYSIS OF GARNET - (+ 200 MESH SINKS)

Particle Size		Weight	Weight	Cum. %	Cum. %
US, mesh	microns	g	%	Retained	Passing
16	1180	0.10	0.1	0.1	99.9
30	595	7.40	8.3	8.4	91.6
40	420	20.50	23.1	31.5	68.5
50	300	18.80	21.2	52.7	47.3
60	250	7.90	8.9	61.6	38.4
100	150	17.30	19.5	81.1	18.9
Pan	-150	16.80	18.9	100.0	
Total		88.80	100.0		

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- Click here for the poster (~2.9 MB) – MS PowerPoint format

Mensah-Biney, Robert, Baldwin, Robert, and Reid, Jeffrey C., 2006, Evaluation of the Bakersville Ecologite, Mitchell County, North Carolina, for its suitability as an abrasive-grade garnet, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

A GIS model of crushed stone quarry development in the Carolinas, USA

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ABSTRACT

New quarry sites for aggregate are usually developed where suitable sources of natural materials exist, are located within a reasonable distance from the market areas where aggregate is predominately used, and where a good transportation infrastructure between the quarry site and the market is in place. Many sites containing quality natural resources are not developed for a wide range of land development and socioeconomic reasons.

A regional spatial analysis model has been developed to evaluate potential future sources of crushed stone aggregate. The model is based on a series of geologic, economic, and socio-political factors. The model defines these factors for a site as well as its economic viability based on anticipated future demand for aggregate in a specific area. The model can be used as a land-management planning tool that will assist interested parties, including industry and local government representatives, in the decision making process regarding mine permitting.

The spatial analysis model uses regional geologic maps, existing aggregate operations maps, transportation network maps, and census tract population density data as variables using model parameters derived from data in the New England region of the United States (Robinson and others, 2004, Natural Resources Research, v. 13, no. 3, September 2004, p. 143-159). In this study, the model is applied to the Blue Ridge and Piedmont provinces of North and South Carolina to evaluate the relative degree of likelihood for crushed stone quarry development throughout the region. The distribution pattern of current crushed stone quarries in the Carolinas agrees well with the model results calibrated using New England data.

Using data on current levels of aggregate production at existing quarry sites and population density and transportation infrastructure information, the model provides an estimate of average aggregate production levels that are likely to occur at new quarry sites developed in specific areas. As some of the major variables change with time, the spatial analysis model can be easily adjusted to reflect these changes and update the analysis. The model can also be used for similar analyses in other regions of the country.

- Click here for part 1 of the poster (~16.4 MB) – Adobe Acrobat .pdf format
- Click here for part 2 of the poster (~8.7 MB) – Adobe Acrobat .pdf format

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Robinson, Gilpin R., Larkins, Peter, and Tepordei, Valentin, 2006, A GIS model of crushed store quarry development in the Carolinas, USA, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Tidewater export opportunities for bedrock aggregate resources near the Port of Belledune, on Canada's east coast

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ABSTRACT

Strategically situated on Canada's east coast, New Brunswick has the potential to become a major international supplier of high quality aggregate to the eastern seaboard of North America, the Gulf coast, and elsewhere. As the demand for these materials continues to increase, and even exceed local domestic supply in some regions, so does the reliance on offshore sources.

An extensive and accessible high quality bedrock resource, well suited for a wide range of construction applications, is found immediately adjacent the major port facility of Belledune in northern New Brunswick. Mafic intrusive and volcanic rocks in the area have satisfied regional demand for quality construction materials for almost two decades. The port, operating year round, is a modern and expanding deep water facility with sufficient storage capacity and proven load-out capability to efficiently transfer large tonnage cargoes to variously sized ocean-going vessels. Regional rail service, proximal to the proposed primary aggregate resource area, offers an alternative link to major aggregate consuming centers throughout northeastern North America and beyond.

Supportive infrastructure, a reliable service sector, and an experienced, well trained industrial based workforce would be among other features favoring the export of aggregate materials at Belledune. A significant portion of the proposed aggregate resource in the area is situated on Crown land, owned by the Province of New Brunswick and managed by the Department of Natural Resources. Land allocation and environmental regulatory procedures on these lands are well defined.

Satisfying many important criteria that support the launch of a dynamic tidewater aggregate enterprise, the Belledune area is destined to become an important international supplier of quality, processed construction material.

- Click here for the poster (~12.4 MB) – Adobe Acrobat .pdf format

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Allard, Serge and Webb, Tim, 2006, Tidewater export opportunities for bedrock aggregate resources near the Port of Belledune, on Canada's east coast, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey

Evaluation of vein quartz, Montgomery County, North Carolina for its suitability as a quartz resource

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ABSTRACT

Stock work vein quartz ~20 kg samples from metavolcanic rocks from Montgomery County, North Carolina, were evaluated for their quartz resource suitability.

Preliminary processing evaluation and chemical analysis of the quartz concentrates from the two samples indicated low impurity levels to justify further chemical treatment to produce ultra-high purity quartz. The processing steps involved crushing, grinding to produce 60 x 140 mesh, flotation to remove mica, iron minerals and feldspar impurities, magnetic separation of the clean quartz, sizing and hydrofluoric/hydrochloric acid leach to produce ultra-high purity quartz product (Iota Grade).

The chemical analysis of the quartz concentrates before and after leaching is shown in the table below (unleached product is after magnetic separation, leached product is after leaching with HF/H_2SO_4). Although chemical leaching resulted in significant reduction in Fe and Mg, the impurity level for Al, Ca, Na, K was too high for ultra-high purity quartz. Additional process evaluation is needed to remove additional Al, Fe, Ca, K, and Na to produce high-pure quartz (Quintas Grade).

Granular high purity quartz (HPQ) is used in the manufacture of optical glasses and for high purity silica glasses for semiconductor silicon in silicon computer and memory chip production (high purity crucibles for growing the silicon), for high intensity lighting applications and for standard and fiber optical components. HPQ chips (lascas) are used in the manufacture of piezo-electric quartz crystals (cultured quartz). Some of the lower purity HPQs are used in the ceramic industry for high heat intensity applications such as the heating tile for the space shuttle.

The quartz composition is shown in the table below. No gold was detected at the ppb level in three composite bulk samples or one duplicate bulk sample.

Sample	Leached	Al (ppm)	Ca (ppm)	Fe (ppm)	K (ppm)	Li (ppm)	Na (ppm)	Ti (ppm)	Mg (ppm)	Zr (ppm)
Mill Creek #1	Unleached	15.4	15.6	5.26	1.57	0.31	14.70	0.31	0.21	0.29
Mill Creek #1	Leached	12.0	7.57	0.08	1.23	0.36	10.80	0.17	0.09	0.01
Little River	Unleached	19.3	7.74	3.69	1.70	0.25	22.50	0.43	0.19	0.14
Little River	Leached	15.8	3.80	0.03	1.88	0.67	19.70	0.37	0.09	0.01

- Click here for the poster (~2.2 MB) – MS PowerPoint format

Mensah-Biney, Robert and Reid, Jeffrey C., 2006, Evaluation of vein quartz, Montgomery County, North Carolina for its suitability as a quartz resource, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Suitability of Pinehurst Formation as a glass sand, Richmond County, North Carolina

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ABSTRACT

Split-spoon samples of six drill cores 0 to 60 feet deep within 2,800 acres from the Pinehurst Formation, Richmond County, North Carolina, were evaluated for glass sand raw material potential. The Pinehurst Formation, as mapped on the 1985 Geologic Map of North Carolina, covers approximately 120,660 acres in Richmond, Scotland, Moore and Hoke counties. Commercial glass sand has been produced from a nearby site from the Pinehurst Formation. Minerals were identified with a binocular microscope and by powder x-ray diffraction. Trace amounts of heavy minerals found in the raw material included schorl (a member of the tourmaline group), rutile, and zircon. Less abundant trace minerals were goethite, hematite, muscovite, kaolinite, and chromite. The major mineral present in these samples was quartz, averaging 60-73% of each sample.

Several physical separation processes were necessary to make a product suitable for glass application. These included attrition scrubbing, sizing, flotation, heavy liquid separation, and magnetic separation to remove impurities such as iron and titanium minerals, mica, organic matter, feldspar, trace elements, and other impurities.

The glass sand product after attrition scrubbing, sizing, and magnetic separation contained 0.13-0.16 % Al2O3, 0.02 – 0.04% Fe2O3, < 0.01 – 0.02% TiO_2 and traces of other minor elements. Further reduction of impurities will be obtained from separation processes that include flotation. This product is well within the specifications for typical glass sand and is suitable for many glass sand applications. A glass plant is located only a few miles away.

Subsequent ongoing collaborative work by the NC Geological Survey and the NCSU Mineral Resources Laboratory are investigating the suitability of the Pinehurst Formation as a frac sand – a higher value product. The proximity of a nearby railroad and the Port of Wilmington, NC provide worldwide market access.

- Click here for the poster (~2.6 MB) – MS PowerPoint format

Mensah-Biney, Robert, Carpenter, Leigh Ann, Miller, J. William, Allen, Benjamin J., and Reid, Jeffrey C., 2006, Suitability of Pinehurst Formation as a glass sand, Richmond County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

The effects of synthetic gemstones on the U.S. natural gemstone market

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ABSTRACT

The marketing of synthetic gemstones has had significant effects on natural gemstone markets in the United States. Synthetic gemstones are becoming a larger portion of the total U.S. gemstone production with each successive year. With recently developed technologies for consistently manufacturing higher-quality, synthetic gemstones at lower costs than their natural counterparts can be mined, synthetic gemstone manufacturers stand poised to increase their share of U.S. gemstone markets. The first practical, reproducible synthesis of gemstones was achieved around 1900 with the development of the flame fusion process of growing boules of corundum. Since then, technologies for growing gemstones such as alexandrite, aquamarine, beryl, cubic zirconia, diamond, emerald, garnet, moissanite, opal, ruby, sapphire, spinel, star ruby, star sapphire, turquoise, and others have been developed. As technologies have been further refined and improved, energy costs reduced, and the gem quality improved, synthetic gemstones have become competitive with their natural counterparts.

Based on the dollar value of domestic gemstone production and markets over the past 15 years, synthetic gemstones have increased from 17% to 76% of the U.S. gemstone production, while synthetic gemstones have only accounted for between 0.5 % and 2.0% of apparent consumption of gemstones in the United States.

The most recent synthetic gemstones to enter into the market are moissanite (a diamond simulant with gem properties of its own), synthetic gem-quality diamonds created using high pressure-high temperature methods, and synthetic gem-quality diamonds created using chemical vapor deposition. These three will probably have a major impact on natural gemstone consumption as their production technologies improve, and they are marketed to the public. In 2004, the possible market impact of diamonds produced by chemical vapor deposition was made more likely by the improvement of using microwave plasma technology. This improvement allows for lower cost, much faster growth rates of the synthetic diamonds, as well as allowing for multiple crystals to be grown simultaneously.

- Click here for the poster (~275kb) – MS PowerPoint format

Olson, Donald W., 2006, The effects of synthetic gemstones on the U.S. natural gemstone market, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

“The Moissanite Story”

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ABSTRACT

Charles & Colvard is the sole producer of Moissanite gemstones worldwide. It enjoys a worldwide market and is supported by patents in North America, Europe, Mexico, Russia and the Far East. Although Moissanite, also known as silicon carbide, is found in nature, these crystals are too small for use in jewelry. Our jewels are made exclusively in our Morrisville, North Carolina facility.

Raw material is received form two sources. We grade each ingot of material individually to determine if it meets our standards for color and clarity. Once the material has been graded for optimum usage, it is then cut into individual pre-forms using Computer Numerically Controlled (CNC) machinery. This ensures accuracy and repeatability with minimal material waste.

After the material has been cut into pre-forms, it is then sent to the Far East for faceting. Each one of our jewels is hand faceted to exacting dimensional standards formulated specifically for Moissanite. Faceting to these exact dimensions ensures that each jewel will exhibit maximum brilliance, fire and luster.

After faceting, the jewels are returned to the Morrisville facility in order to be graded as a finished stone. Each finished stone is individually graded for cut and clarity. After grading they placed in inventory ready to fill customer orders.

In addition to gemstones, Moissanite is also being used as anvils in high pressure experiments. Moissanite anvil cells allow maximum sample volumes that are 1000 times larger than those allowed by diamond anvil cells. The optical, thermal, electrical, magnetic and x-ray properties of Moissanite rival those of diamond.

- Click here for the poster (~680 KB) – Adobe Acrobat .pdf format
-

Hines, Earl, and Abate, Steven, 2006, “The Moissanite Story”, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Forty years of mining at PCS Phosphate-Aurora, Beaufort County, North Carolina

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ABSTRACT

The Phosphate deposits in Beaufort County North Carolina were first discovered in the early 1950's. Many companies conducted exploration programs and attempted to initiate mining operations in the late 1950's and early 1960's. PCS Phosphate and its predecessors have mined and processed phosphate ore at the Aurora Phosphate Mine in Aurora, North Carolina since 1965. The open-pit mine is located in the central coastal plain, near the Pamlico River. The history of the mining operation is one of continuous change, expansion and improvement.

The current mining sequence includes the removal of forty feet of unconsolidated overburden using bucket wheel excavators followed by the removal of seventy-five feet of overburden and thirty-five feet of phosphate ore by three large walking draglines (77, 72 and 50 cubic-yard bucket capacities). The large draglines re-handle and stockpile the mined ore for further processing. The stockpiled ore is slurried and pumped to the mill for concentration.

Mining began in December of 1965. From 1965 to 1979, one 17 cubic yard dragline and two 19 cubic-yard draglines were utilized to remove the unconsolidated overburden ahead of the draglines and to re-handle and stockpile the mined ore for pumping. One large (72 cubic-yard) dragline was used by the mining operation for the production requirements. A second large (50 cubic-yard) dragline was added to the mining operation in 1976 to increase production capacity.

From 1979 to 1990, two thirty-inch dredges were utilized to remove the unconsolidated overburden. A third large (77 cubic-yard) dragline was added to the mining operation in 1986 to increase production capacity.

From 1990 to present, two bucket wheel excavators are utilized to remove the unconsolidated overburden ahead of the draglines. The current mining operation handles approximately 38 million tons of total overburden, 11 million tons or phosphate ore and processes 5 million tons of phosphate concentrate.

- Click here for the poster (~9.6 MB) – Adobe Acrobat pdf format

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Gilmore, I. K., 2006, Forty years of mining at PCS Phosphate-Aurora, Beaufort County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey

Minerals Research Laboratory (North Carolina State University) – Asheville, North Carolina

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ABSTRACT

The Minerals Research Laboratory (MRL), located in Asheville, North Carolina, is a part of the North Carolina State University's College of Engineering. The main focus of MRL's research is the beneficiation of industrial minerals, applied separation technology for coal combustion by-products, and recovery of high-value products from industrial by-products on bench-scale and continuous pilot plant testing. MRL's experience in industrial minerals is unmatched by any university laboratory in the United States. This laboratory is unique in the sense that it exemplifies the much sought after partnership between industry, government and academia in conducting effective research. Most of MRL's research efforts are conducted for corporate sponsors, although public service projects are also undertaken. MRL has conducted projects in several different commodities for sponsors in several different countries all over the world. MRL's state-of-the-art facility is equipped with mineral processing equipment for bench-scale and pilot plant testing, and an analytical support facility for mineral characterization. As part of a Land Grant Institution, technical assistance and service to the public is also part of the MRL mission.

- Click here for the poster (~3.3 MB) – MS PowerPoint format

Mensah-Biney, Robert, 2006, Minerals Research Laboratory (North Carolina State University) – Asheville, North Carolina, 2006, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Restoring productivity to agricultural soils following mineral sands mining, Dinwiddie and Sussex Counties, Virginia

W. Lee Daniels [1], Zenah Orndorff[2], Mark Alley[3], Kelly Meredith[4], Lucian Zelazny[5] and Chris Teutsch[6]
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ABSTRACT

Significant deposits (> 4,000 ha) of heavy mineral sands were discovered in the Coastal Plain of Virginia and North Carolina in 1989. The majority of these lands support highly productive row crop agriculture, and the development of restoration protocols that will return these lands to agricultural use is considered critical to the long term sustainability of mining operations. Virginia Tech worked closely with all stakeholders to develop appropriate restoration protocols and to coordinate their implementation. In the mid-1990's, working closely with the mining company, we installed a replicated field-scale soil reconstruction experiment on backfilled mining test pits. In this field experiment we compared 25 cm of topsoil return against a topsoil substitute strategy where 112 Mg/ha of yardwaste compost was mixed directly into the reclaimed tailings surface. All treatments were deep-ripped, limed and fertilized, and then compared with directly adjacent undisturbed prime farmland soils. Over four cropping seasons, productivity of the reclaimed mine soils was approximately 80% of undisturbed land for the rotation studied (wheat/soybeans/ corn/cotton).

Full-scale mining operations at the Old Hickory Project in Virginia were initiated in 1997 by Iluka Resources Inc., and approximately 750 ha of land are in various phases of backfilling and final reclamation. Return of these lands to agricultural row-crop production has been complicated by lateral variability in mine soil physical conditions, excessive compaction, and limited topsoil return. However, a series of tailings deposition and soil reconstruction practices have been developed and implemented that significantly improve post-mining soil productivity.

Within the past year, we have successfully established a large (40 ha) research-demonstration farm at Old Hickory on recently reclaimed land. Various soil reconstruction strategies (topsoil vs. organic additions vs. conventional lime and fertility) are being directly compared in two replicated experiments managed for row-crops and hay, respectively. Corn yields in 2005 indicate that properly reconstructed mine soils can easily exceed county average yields, and may approach 85% of the very best prime farmland soils. We expect that productivity of these very young mine soils will improve with time as they become better aggregated, accumulate organic matter, and develop a stable microbial biomass.

- Click here for poster (~ 1.9 MB) – MS PowerPoint format

Daniels, W. Lee, Orndorff, Zenah, Alley, Mark, Kelly, Merideth, Zelazny, Lucian and Teutsch, Chris, 2006, Restoring productivity to agricultural soils following mineral sands mining, Dinwiddie and Sussex Counties, Virginia *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

The Interstate Mining Compact Commission's "What Do All These Places Have in Common?" Reclamation Education Poster

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ABSTRACT

The Interstate Mining Compact Commission (IMCC) developed the poster, "What Do All These Places Have in Common? They Are All Reclaimed Mining Sites!" as part of our educational outreach program guided by IMCC's Education Work Group. This project falls under the education mandate included in the work of the IMCC. The poster was initially developed for, and presented at, a series of IMCC-sponsored teacher workshops where representatives from the member states worked together to present teachers with practical hands-on earth science activities and information for use in their classrooms, including identification and uses of rocks and minerals and the processes of mining and reclamation. The poster has since been used by federal agencies, such as the federal Office of Surface Mining, and other organizations and has become nationally recognized. The front of the poster features actual photos of mining sites which have been reclaimed to various post-mining land uses, including a golf course, school, recreational lake, wetlands, wildlife habitat, agriculture, housing development, open space and a hospital. The sites and commodities mined are identified on the back. Sites in the states of Illinois, Maryland and Texas are featured. Commodities mined included: sand and gravel, coal, lignite and shale.

The back of the poster features before, during and after photos of a mining site with an explanation about the process of reclamation written at the 5th grade level of understanding. Instructions for a "Chocolate Chip Cookie Mining" activity along with a sample worksheet are also on the back of the poster. Our intent was to make this a factual and useable resource for teachers and a "think piece" for other interested parties.

The IMCC is a multi-state governmental organization representing the natural resources and environmental protection interests of its member states. IMCC was established in April of 1971 following eight years of discussion and developmental action by a group of interested mining states under the auspices of the Southern Governors Conference. IMCC presently consists of 19 member states (AL, AR, IL, IN, KY, LA, MD, MO, NY, NC, ND, OH, OK, PA, SC, TN, TX, VA, WV) and 3 associate member states (NM, UT, WY), all of whom have significant interests in the mining of both coal and non-coal minerals.

IMCC acts through several committees that have responsibility for particular subject matter or policy areas including: Environmental Affairs, Mine Safety and Health, Abandoned Mine Lands, Minerals Education, Resolutions and Finance. The Governors, who serve as Commissioners, are represented on these committees by duly appointed delegates from their respective states. IMCC has become an organization of national scope serving as the spokesperson for the mining states in Washington, D.C.

(continued)

Interstate Mining Compact Commission poster:

- Click here for the front side of the poster (~19.3 MB) – Adobe Acrobat pdf format
- Click here for the back side of the poster (~20.3 MB) – Adobe Acrobat pdf format

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Botsis, Beth A., 2006, The Interstate Mining Compact Commission's "What Do All These Places Have in Common?" Reclamation Education Poster, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

New Bern reclamation project, Craven County, North Carolina

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ABSTRACT

The reclamation work at New Bern Quarry (NBQ), the largest project ever undertaken by Martin Marietta Aggregates, occurred over a ten-year period beginning with the release of the middle pit in 1989. The project won the 1990 National Mined Land Reclamation Award from the National Association of State Land Reclamationists for the First Stage work on the "Middle Pit". The completed project won the 2000 Mining Sewardship Award for Outstanding Reclamation from the NC Mining Commission. Over 900 acres of previously mined property were reclaimed and released by the Division of Land Resources, NC Department of Environment and Natural Resources (DENR)

The purpose of the reclamation guidelines contained in the North Carolina Mining Act of 1971 are to insure that mined property is restored to a useful, aesthetically pleasing condition suitable for future use. The NBQ was reclaimed to meet and exceed the requirements outlined in the Mining Permit issued by the Division of Land Resources. Many areas were sloped at 6:1, much flatter than the 2:1 and 3:1 slopes often required. The flatter slope helps retain sediment runoff, aids establishment of vegetation and offers extensive wildlife habitat. In many areas, the 6:1 slope was extended below the final water elevation to insure stability and add shallow areas for wetland creation and wildlife habitat. Earthen berms used as visual/noise screens, removed during reclamation, offer adjacent property owners direct view into the property.

North Carolina Wildlife Resources Commission biologist recommendations were followed and often exceeded to respect and enhance wildlife during reclamation. Grading work done throughout the project took advantage of the varying ground elevations to provide extremely large areas of deep water for larger fish, shallow pools for breeding and wetland creation, and miles of shoreline for amphibians and wading birds. Islands were developed to offer safe nesting habitat for certain bird species. Vegetated areas offer open areas for mammals to hunt and many forested areas remain to offer shelter.

The final shoreline distance around all three pits is about 12.8 miles. About 85% of the shoreline distance had to be finely graded and vegetated. Due to heavy tree growth in some areas, the remaining 15% was left in a natural state. Much of the grading work was done concurrently as the quarry operation wound down. The final water level elevation had to be established to determine sloping requirements into the water. Many areas that would eventually be under water were seeded to prevent premature erosion. Slope drains and rip-rapped channels were also installed in many locations to transport storm water over the graded slopes.

The City of New Bern will use part of the property as a tertiary water processing system designed to mesh environmentally with the surrounding water body. Long-term plans include picnic areas, sports facilities and walkways for public use.

(continued)

During 38 years of continuous operation, NBQ had no record of non-compliance with the requirements and conditions of the mining permit or notice of violation or civil penalty from either the Water Quality or the Air Quality Sections of DENR.

Martin Marietta Aggregates poster:

- Click here for the poster (~58.4 MB) – Adobe Acrobat pdf format

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Willson, Horace, 2006, New Bern reclamation project, Craven County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Refractory minerals (pyrophyllite, andalusite), mining, processing and uses from paleohydrothermal centers in the Hillsborough and Efland 7.5-minute quadrangles, Orange County, North Carolina

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ABSTRACT

Recent detailed field mapping of Proterozoic metavolcanic rocks in the Hillsborough and Efland 7.5-minute quadrangles has shown a close relationship between the pyrophyllite ore bodies and paleohydrothermal centers. Bedded, quartzite-like siliceous rocks with a distinctly hot spring texture exist just west of the current mining operation. Three distinct units can be seen in outcrop – a lowermost thick-bedded massive quartzite-like siliceous rock, overlain by a medium-bedded quartzite-like siliceous rock mixed with radial pyrophyllite rosettes. The uppermost unit is a distinctly bedded siliceous rock consisting of round nodules of fine-grain quartzite, suggesting primary sedimentary features.

A large lenses-shaped body of pyrophyllite and andalusite is being exploited by Piedmont Minerals, a division of Resco, Inc., in Hillsborough, North Carolina. The ore body parallels the regional strike of the metavolcanic and metasedimentary rocks. The ore body contains, pyrophyllite, quartz, andalusite, diaspore, topaz, sericite, lazulite, pyrite, rutile, and secondary phosphate minerals. Numerous cubic molds of pyrite crystals are now partly filled with iridescent goethite.

The pyrophyllite and andalusite are processed at the mine site. The high alumina refractory minerals are then transported to Greensboro, North Carolina. In Greensboro a new kiln has recently started operation to produce refractory bricks and blocks. The amount of Al_2O_3 used in the bricks and blocks ranges from 33.3% to 51.1%. The pyrophyllite and andalusite are desirable due to their chemical inertness, high dielectric strength, high melting point and low electrical conductivity. The use of the high alumina minerals decreases the thermal expansion and moisture expansion of the product during high temperature service, provides excellent volume stability and resistance to deformation at high temperatures, increases the firing range of the blocks and therefore decreases firing shrinkage, and increases the strength of the fired blocks and bricks.

- Click here for the poster (~41.06 MB) – MS PowerPoint format

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Gay, Kenny, 2006, Refractory minerals (pyropyllite, andalusite), processing and uses from paleohydrothermal centers in the Hillsborough and Efland 7.5-minute quadrangles, Orange County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

GIS database for modeling occurrence, mineral-chemistry, and geologic distribution of clay deposits: Southeastern United States

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ABSTRACT

A regional database for determining potential resources of clay minerals based on geologic setting, mineralogy, and geochemistry is being developed for selected deposit lifecycle models occurring in the southeastern United States. The models include compilations of geologic, geochemical, geophysical, hydrological, and engineering information pertaining to the behavior of geologically similar mineral deposits prior to clay removal, during processing and waste disposal, and after mining. For a given site, critical factors for developing geologic and economic lifecycle models for clay deposits are identified. The information contained within lifecycle models is useful for establishing pre-production baselines, assisting in mine-planning, and identifying potential surface effects. Such data can be used by land-use planners when dealing with remediation and reclamation issues concerning abandoned pits and permitting of future deposits.

Clay deposits and occurrences can have a controlling influence on contaminant mobility in the surficial environment because of the distinctive physical and chemical properties of clay minerals and associated Al-oxyhydroxide minerals. Sortive properties, ion-exchange capacities, and complex provenance can cause clay minerals and deposits to act as regulators, transport agents, and reservoirs of environmental pollutants or contaminants such as metals (lead, zinc, cadmium, arsenic, and copper) and organics (including pesticides, dioxin, bacteria, viruses). In this respect, large volume deposits of raw clays can pose potential problems when disturbed by man or nature if they have sorbed contaminants that can be released into the surface environment.

As new sites for clay resources are developed, clays from distinctly different deposits may be blended to ensure a consistent marketable product. A thriving clay industry may require raw materials from a variety of source rocks. Thus, included in the database is a genetic classification of each clay deposit or occurrence, in terms of source rock geology, mineralogy, and mineral chemistry, which can be used to predict alkali- or acid-generating potential, associated trace metal suite, alkali or acid-buffering capacity of host rocks, and natural, pre-mining background characteristics and weathering products. The database and models in preparation are presented in ARC-GIS formats that can be used as land management planning tools to assist State and Federal agencies and industry.

- Click here for the poster (~22.3 MB) – MS PowerPoint format

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Foley, Nora K., Virta, Robert L., Auerbach, David, GIS database for modeling occurrence, mineral-chemistry, and geologic distribution of clay deposits: Southeastern United States, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

GIS database for modeling the geologic provenance, distribution, mineralogy, and chemistry of historical arsenic producers and smelters

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ABSTRACT

A national database of historical arsenic producers and smelters is being developed for the United States. The database includes information on arsenic sources and the type of geologic deposits used in the production of arsenic-trioxide (As_2O_3). The status of this effort will be presented with an emphasis on the Eastern United States. Historic smelter locations (1) in the East include Brinton, Floyd County, Virginia (1917-1918) and Perth Amboy, Middlesex County, New Jersey (1920-1925). Inorganic arsenic occurs naturally in bedrocks and soils and can be carcinogenic when it occurs in anomalously high contents in ground and surface waters, soils, and sediments. Residues from use of arsenic-containing pesticides (used for example in insect control, as a crop desiccant, livestock dipping) and the chromated copper arsenate (CCA) wood preservation process are thought to have contributed to anomalously high contents of arsenic in surface environments.

Arsenic-trioxide, the principal smelter by-product, was produced mainly from domestic sources prior to 1985 as a by-product of the operation of a small number of widely distributed copper and lead-ore smelters (1). Arsenic trioxide concentrates produced at the smelter sites were used in the manufacture of arsenical pesticides for agricultural practices and wood preservatives for treating lumber intended for exterior construction. Various smelters employed different production practices and used ore materials from distinctly different types of ore deposits. The ores supplied to the smelters varied greatly over time as a result of economic conditions and availability from local deposits.

The GIS database of historical arsenic producers and smelters is intended to provide a means to characterize the material inflowing into the smelters from the different mine districts. This may provide a way to constrain the geochemical signatures of the arsenic trioxide, and ultimately, to provide information necessary to monitor the compositions of historical arsenical pesticides according to their geologic provenance. This information may be useful in distinguishing anthropogenic vs. natural sources of arsenic, establishing pre-agricultural baselines in soils and sediments, and possibly, as a tool for tracking the distribution of agricultural chemicals containing arsenic.

Loebenstein, J.R, The materials flow of arsenic in the United States. Bureau of Mines Information Circular 9382, 1994, pp. 1-12.

- Click here for the poster (~2.9 MB) – MS PowerPoint format

Foley, Nora K, Ayuso, Robert, Auerbach, David, and Colvin, Anna, 2006, GIS database for modeling the geologic provenance, distribution, mineralogy, and chemistry of historical arsenic producers and smelters, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Texture: Its what makes Spruce Pine Granite special

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ABSTRACT

Texture [igneous rocks]: describes the appearance of a rock; including the size, shape, and mutual relations of crystals in the rock.

The granites (the rocks are, strictly speaking, granodiorites) of the Spruce Pine Mining District in western North Carolina are characterized by their large grain size. Large crystals of feldspar, muscovite and quartz are found in pegmatites that occur in coarse-grained granites and in the enclosing schist and gneiss country rocks of the Spruce Pine District. Mining (and hand sorting) of these large crystals at Spruce Pine started with Native Americans thousands of years ago. Complex figures of people and animals cut from large sheets of muscovite from Spruce Pine pegmatites are found in many collections of Native American artifacts from the mound-building culture. The coarse grain size of the muscovite also attracted the attention of early European settlers and a cottage-scale mining "industry" started to supply isinglass for windows in stoves and ovens. For much of the twentieth century the large books of Spruce Pine mica were mined for use as an insulator in electric motors and vacuum tubes in the electronics industry.

Coarse-grained feldspar (both Na-Ca plagioclase and K-feldspar) is also found in the Spruce Pine pegmatites. The large grain size allowed the hand sorting of both feldspars for use in the ceramic industry. There was no regular demand for the coarse grained quartz at Spruce Pine during most of the twentieth century and the quartz was discarded or left in the mines. The purity of the Spruce Pine quartz (and the coarse grain sized that allowed for hand sorting) did attract some special interests. Quartz from one Spruce Pine pegmatite was used to make the large reflecting mirror for the telescope at the Mt. Palomar Observatory in California. The ill-fated first attempt at making this 200-inch mirror is on display at the Corning Museum of Glass in New York.

The flotation method for separating minerals revolutionized mining at Spruce Pine in the days following WWII. Now high grading of the ore by hand sorting was not required and the mining emphasis shifted from the pegmatites to the larger bodies of granitoid rock that continues today. Another change in the Spruce Pine mining industry came late in the twentieth century with the recognition that the Spruce Pine quartz was suitable for use in the production of high purity silica glass for use in the electronics industry. Today high purity quartz, feldspar and mica are produced from the granitoid rocks at Spruce Pine.

But what makes the Spruce Pine granites so special? Why are these granites the source of feldspar and quartz when any granite, by definition, is made of these same minerals? Part of this answer is the historic location of the mines and processing plants (along with the various issues of markets and transportation). But the rest of the answer may lie in the texture of the Spruce Pine granites.

(continued)

Many (all?) of the Spruce Pine granites were recrystallized following their formation crystallization from a magma. This post-magmatic recrystallization results in a mortar structure where relatively large grains of feldspar, quartz and muscovite are enclosed in a fine-grained recrystallized matrix of feldspar, quartz and muscovite. Also found in this fine-grained matrix are grains of epidote formed by removal of Fe from muscovite during recrystallization. Post-magmatic recrystallization of the Spruce Pine granites produced a rock where minerals grains are more easily separated and, perhaps, a rock with cleaner quartz.

- Click here for the poster (~6.4 MB) – MS PowerPoint format

Swanson, Samuel E., and Veal, W. Brian, 2006, Texture: Its What Makes Spruce Pine Granite Special, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Beryl (aquamarine, emerald, green and yellow) and tourmaline of the Crabtree Pegmatite, Spruce Pine District, Mitchell County, North Carolina

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ABSTRACT

The Crabtree pegmatite in the Spruce Pine district of North Carolina is a beryl (emerald, green beryl, aquamarine and yellow beryl) and tourmaline-bearing granitic pegmatite. It is texturally unzoned with a weakly developed differentiation of the slightly coarser grained segregations and aplitic units, and variously assimilated xenoliths. Brown to black tourmaline is common in the pegmatite margin, in random sunburst patches in the pegmatite and as radiating sprays from the xenoliths. Emerald and green beryl occurs in the biotite and chlorite selvage and the pegmatite margin, whereas aquamarine and yellow beryl occurs in the pegmatite core. Green and purple fluorite, white mica, almandine-spessartine composition garnet and xenotime are accessory minerals. It has been sporadically mined for gem-quality beryl from 1894 to the late 1970's and has produced a number of good quality emeralds, one of which was 70 carats.

The pegmatite intrudes at the boundary between garnet-titanite-zoisite bearing hornblende-plagioclase gneiss (blastomylonite) and plagioclase-quartz-biotite-white mica porphyroclastic gneiss. These have been hydrothermally altered adjacent to the pegmatite and associated aplite introducing chlorite and calcite at the expense of biotite, garnet, hornblende, titanite and zoisite.

Emerald hosts abundant, randomly oriented, tabular and rounded quartz and plagioclase inclusions, some of which contain biotite-phlogopite microlites. Green beryl occurs as subhedral to euhedral crystals with biotite and white mica inclusions and has fewer quartz and plagioclase inclusions than the emerald. Inclusion-free aquamarine is subhedral with minor fractures while euhedral hexagonal prisms of yellow beryl have thin fractures and minor inclusions of quartz and plagioclase.

MgO and Na_2O are higher in the emerald than in the green and yellow beryl whereas Fe_2O_3 predominates in aquamarine. Emerald contains significantly higher amounts of Cr (1564 ppm) and Cs (1066 ppm) than do the other beryl varieties. V, Rb and Ni are higher in the emerald than in the yellow beryl and aquamarine while Zn concentrations are the highest in the aquamarine (140 ppm).

The tourmaline is intermediate between dravite-schorl and has elevated F concentration with values reaching 0.8 apfu in the pegmatite margin. Mg in tourmaline in the exocontacts and the margin is high (up to 2.1 apfu) while Fe is highest in the xenolith tourmaline (2.0 apfu). Cr in the tourmaline tends to have high concentrations in the exocontacts, reaching 0.14 apfu. The Crabtree pegmatite represents an albitic magma having Be, B and F that intruded a Cr enriched protolith to produce emerald.

(continued)

- Click here for the poster panel one (~5.5 MB) – MS PowerPoint format
- Click here for the poster panel two (~3.3 MB) – MS PowerPoint format

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Tappen, Christine, Smith, Michael S., and Dockal, James A., 2006, Beryl (aquamarine, emerald, green and yellow) and tourmaline of the Crabtree Pegmatite, Spruce Pine District, Mitchell County, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Bandana Dolomite Marble, Mitchell County, Spruce Pine District, North Carolina

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Author contact: jjm0884@uncw.edu

ABSTRACT

The Bandana dolomite marble is a coarse-grained, apatite-phlogopite-dolomite marble with non-mimictic, granoblastic texture. Chemical analysis indicates almost pure dolomite with exceedingly low silica, alumina and iron (<0.25 wt.% total). Although extent (0.5 M tons estimated), and location of the deposit limits its uses for dimension stone, the marble has been mined for monumental stone. Enclosed within amphibolite facies (locally kyanite grade) metasedimentary and metavolcanic rocks of the Ashe Metamorphic Suite, it is intruded along its length by a muscovite-class pegmatite possibly related to the Spruce Pine Plutonic Suite. The marble-pegmatite contact is sharp, suggesting intrusion at depth.

Prograde decarbonation of the marble formed tremolite and a minor amount of forsterite. Pegmatite intrusion into the Si-poor dolomite marble resulted in bimetasomatic formation of a magnesian exoskarn. The exoskarn is heterogeneous in composition, texture, and spatial relationship with respect to sample areas. Exoskarn envelope width varies from 1.0 cm to 0.5m. Compositional zonation varies from tremolite/actinolite ± calcite ± quartz ± diopside ± apatite to monomineralic actinolite at the marble-pegmatite contact. This zonation was due to mobilization of Si, Al, and volatiles from the pegmatite, and local chemical equilibrium. Localized intercalation of garnet-quartz-white mica-biotite schist provides a Fe component as well as being a conduit for fluid infiltration during retrograde conditions. Talc is observed along fracture planes. Endoskarn formation is less obvious in the pegmatite, indicated by desilicification in the pegmatite and diffusion of Ca from the marble. Occurrence of scapolite and idocrase in one area indicates localized fluid flow and interaction of quartz and plagioclase with halogens. A combination of infiltration and diffusion processes helps explain the size and compositional variance observed in the exo- and endoskarn.

The marble has slight LREE>HREE enrichment and a moderately negative Eu anomaly (Eu/Eu* avg = 0.499504). Ba (<20ppm) and Sr (44-95ppm) concentrations are low. Combined with stable isotope results for d^{18}O (18.57-23.77‰ V-SMOW) and d^{13}C (2.40-3.47‰ V-PDB), the data suggests a marine carbonate protolith.

- Click here for the poster (~70.0 MB) – MS PowerPoint format

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Millington, Jason A., Dockal, James A., Smith, Michael S., and Thayer, Paul A., 2006, Bandana Dolomite Marble, Mitchell County, Spruce Pine District, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Methods for valuing previous exploration programs during consideration of prospective mineral ventures

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ABSTRACT

Few if any problems in the practice of valuation for potential company acquisition are more difficult and uncertain, and cause more ambiguity, than that of placing a monetary value on previously done mineral exploration. Not the least of this uncertainty comes from the related questions “Value to Whom?” and “Value for What Purpose?” Not just previous **cumulative expenditure** on exploring the mineral prospect, but whether or not **something of real value** has been reliably discovered, establishes exploration value to the potential mineral venture acquisition.

The “Multiples of Exploration Expenditure” method was first proposed in Australia in key papers by Onley (1994) and Lawrence (1994). It established the Prospectivity Enhancement Multiplier or PEM concept. This method shows promise to give an organized, repeatable, objective allocation of value (or lack thereof) to previous exploratory expenditures for prospective acquisition of mineral ventures. Several examples will be given for selected anonymous southeastern U. S. industrial mineral ventures which have recently been considered.

- Click here for the poster (~218 kb) – Adobe Acrobat pdf format

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Gregg, L.T., and Pickering, Sam M., 2006, Methods for valuing previous exploration programs during consideration of prospective mineral ventures, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

“Oral history of mining in western North Carolina”
and
“History of the Minerals Research Laboratory of North Carolina State Univerisity (1946 through 2004)”

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ABSTRACT

This poster summarizes two important historical mining history contributions that are contained in the proceedings of the 42nd Forum on the Geology of Industrial Minerals, but that were not presented in oral sessions.

The “Oral history of mining in Western North Carolina attempts to capture through personal interviews early mining history in Western North Carolina through interview with key individuals whose lives and actions made the history.

The “History of the Minerals Research Laboratory,” chronicles its history beginning with its establishment in 1946 to the present – 60 years of service to the mining industry beginning in Western North Carolina with service that has now spread worldwide. Here’s to the next 60 years!

- Click here for the poster (~204 kb) – MS PowerPoint format

- Click here for the “Oral history of mining in western North Caorolina” (~397 kb) – Adobe Acrobat pdf format

- Click here for the “History of the Minerals Research Laboratory of North Carolina State University (1946 through 2004)” (~69 kb) – Adobe Acrobat pdf format

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Minerals Research Laboratory staff, 2006, “Oral history of mining in western North Carolina” and "History of the Minerals Research Laboratory of North Carolina State University,” *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey

Recent status of the Denizli travertine in the natural stone sector of Turkey

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ABSTRACT

Recent and Quaternary travertine deposits are common in the Denizli graben basin, western Turkey. NW-trending basin is located in the east of Aegean extensional province. The hot spring travertine occurrences are generally followed along the north-northeast margins of the basin. The travertine deposition in shallow lake environments are the most common, and they are alternated with red-green mudstones, conglomerates and paleosol horizons, which extend laterally and horizontally (Özkul et al., 2002). Modern and fossil travertine deposits in the Denizli graben basin are important both in view of tourism and natural stone industry. Modern Pamukkale travertines, which are included to the world heritage list of UNESCO, are visited by ten thousands of tourists every year. In addition, there are a lot of fossil travertine occurrences in the same basin. There were only a few operating quarries until the middle of 1980's. Nowadays, these numbers have reached up more than 60 and many of them are clustered in the region of Ballik locality, near Kaklik, where is located in the northeast of the basin. The aim of this study is to summarize status of natural stones of Denizli travertines. Among the travertine localities in Turkey, the Denizli travertines are foremost in the natural stone industry. Other the most important travertine localities take place around Burdur, Kayseri, Sivas, Konya, Afyon, Kütahya, Ankara and Kirsehir provinces.

More than 20% of Turkey's total natural stone production belongs to this area and raw block production reaches up to 25.000-30.000 m^3/year in some quarries. Turkey is one of the most important travertine producers in the world. Since the beginning of the middle of 2002, travertine production end export values are more than other total Turkish marbles export values (Yüzer and Angi, 2005). Annual commercial raw block travertine productions from different quarries have been calculated as 400.000 m^3 in Denizli province.

Different companies are located in the region to export travertine products approximately up to 60 countries around the world. USA is the first among these travertine importing countries. About 50 % of travertine needs of United States are provided from Turkish natural stone market.

Özkul, M., Varol, B., and Alçiçek, M. C. (2002) Depositional environments and Petrography of Denizli Travertines, Bulletin of the Mineral Research and Exploration, 125, 13-29, IV Plates.
Yüzer, E. and Angi, S. (2005) Natural stone sector in Turkey. Special attention to Turkish travertine. (Editors: Özkul, M, Yagiz, S. and Jones, B.) Proceedings of 1st Internatioal Symposium on Travertine,September 21-25, 2005, Denizli, Turkey, p.3-13.

- Click here for the poster (~215 kb) – Adobe Acrobat .pdf format
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Tasdelen, Suat and Ozkul, Mehmet, 2006, Recent Status of the Denizli travertine in natural stone sector of Turkey, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Geologic and economic significance of Cayirbag-Meram magnesite deposits, Turkey

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ABSTRACT

Cayirbag-Meram magnesite deposits are located in a zone 13km southwest of Konya, Turkey. Six economic and four potentially important magnesite quarries occur along this zone.

All magnesite formations in the serpentinized ultrabasic rocks overlie carbonated rocks . The source of Mg accumulation in the discontinuous zones is washed dunite and harzburgites rocks by the thermal waters. The main also magnesium source is ultramafic rocks. Geochemical analysis indicate that altered serpentinite units close to the magnesite occurrences are depleted in Mg, Ca, Al, Ni and Co. Due to the magnesite mineralization large amount volume increase have taken place in the mineralization site Mineralization is characterized with two different types in the study area. The first type, Argit type mineralization,is characterized by vein deposits, formed in the less altered green serpentinites. The second type, Helvacibaba magnesites were deposited in the highly altered brownish serpentinites. The Argit type deposits show characteristics of the Helvacibaba type. All magnesites have nodular structure with massive view and some magnesites have been grounded along the young fault zones.

Cayirbag–Meram magnesites show amorphous structure; the largest magnesite grain is 75µ. Magnesites formed in different three stages. The magnesite formed at the first stage has vein and thick stock-work type and was cut from the secondary formed thin stock-work magnesites. White primary magnesites, geochemicaly homogeneous, were affected by ascending hydrothermal fluids along the fault zones during this stage. These are enriched Sb, Cu, Zn, Ba and other minor elements. The secondary magnesites are pink-colored and have heterogeneous components, poor in SiO_2 but enrriched in Fe, Mn, Ni and Co. The quartzite filons within the magnesite veins indicates separation of magnesium from serpentinites and secondary silicification. The paleosurface conditions were affected by the forming secondary magnesite.

The third stage magnesites, common in the Neogene sediments in this area, have rare nodular and very thin felons and are not economically important. The table shows deposition shape and % MgO contents of the magnesites.

(continued)

Argit Type

Location	Deposition shape	Ore Grade %MgO	Magnesite % MgO
Argit	vein +stockwork	7.01	46.74
Koyakçi Tepe	vein +stockwork	13.24	44.15
Kozagaç	vein +stockwork	5.64	47.01
Toppinar	vein +stockwork	5.59	46.59

Helvacibaba type

Location	Deposition shape	Ore Grade %MgO	Magnesite % MgO
Helvacibaba	Stockwork	9.17	45.87
Kirankaya	Stockwork	9.20	46.00
Keklik Pinari	Stockwork	9.25	46.25
Çayirbagi	Stockwork	7.02	46.81
Yurtyeri	Stockwork	9.22	46.08
Araphasan	Stockverk	9.14	45.68

The Cayirbag-Meram magnesites are produced for sinter magnesite (magnesia), costic calsine magnesite, sedimentary magnesium carbonate, magnesium hydrocsite, magnesium chlorite and magnesium sulfate. It is produced approximately 300 000 metric tones/year magnesite.

Note: No poster available at time of publication

Gedikoglu, Atasever and Tuncay, Afet, 2006, Geologic and economic significance of Cayirbag-Meram magnesite deposits, Turkey, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Detailed quadrangle mapping aids in identifying kaolin - bauxite mineral potential in Paleocene age Upper Coastal Plain sediments of southwestern Georgia

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ABSTRACT

During the past seven years, twenty-five 7.5' quadrangles in southwestern Georgia have been mapped in detail from just east of the Flint River west to the Chattahoochee River. Paleocene sediments contain the presently producing Andersonville, GA and Eufaula, AL kaolin-bauxite districts, as well as the poorly known Springvale district. Paleocene age sediments hosting the kaolin and bauxite deposits in the Andersonville and Springvale districts belong to estuarine and fluvial facies of the Nanafalia Formation. Kaolin and bauxite-bearing sediments within the Eufaula district are found overlying the paleokarst surface of the Lower Paleocene Clayton Formation, but were probably derived from sediments of the Nanafalia Formation. Within the Andersonville district, kaolin and bauxite clasts found in overlying fluvial facies of the Nanafalia Formation and the nearshore sands of the Eocene Claiborne Formation were derived by erosion of the underlying sediments.

Prior to this mapping, the geology and distribution of these Paleocene sediments in southwestern Georgia was poorly known. Mapping and limited drilling have identified two previously undocumented or undefined areas that contain kaolin and bauxite-bearing sediments, as well as large angular to subrounded clasts of kaolin and bauxite within the Nanafalia Formation. As in the Andersonville district, these clasts probably were derived from underlying or nearby kaolin and bauxite deposits. The largest of these areas extends approximately 12 miles from north to south and should be a prime area for further mineral exploration.

- Click here for panel one of the poster (~25.4 MB) – MS PowerPoint format
- Click here for panel two of the poster (~15.2 MB) – MS PowerPoint format

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Cocker, Mark D., 2006, Detailed quadrangle mapping aids in identifying kaolin -bauxite mineral potential in Paleocene age Upper Coastal Plain sediments of southwestern Georgia, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

The potential of Suriname, South America, for industrial minerals

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Suriname is part of the Guiana Shield of Northeast South America. The Shield represents a deeply weathered belt of metamorphosed sediments, felsic and mafic volcanic and intrusive rocks of Archean and Lower Proterozoic age. Much of industrial mineral potential is related to repeated cycles of deep weathering. Suriname is the 10th largest producing bauxite region in the world. Current production is from low hills of the coastal area near Moengo in east Suriname and on both sides of the Suriname River near Paranam in North Central Suriname. Buried deposits below a young Coastal Plain cover at Lelydorp, near the Suriname River, have lower iron contents and thus better grades than the exposed, high iron bauxite. Alcoa blends the two types of ore at the plant at Paranam. Plateau bauxite in the interior of Suriname form large reserves of high iron bauxite. BHP and Alcoa are evaluating a plateau bauxite district in west Suriname with a recently announced resource of over 300 million tons of ore. Since existing resources are limited and nearing depletion, this resource will be needed. Minimal exploration has been done in the last 40 years. New buried deposits may exist, but they are not being explored.

Excellent quality kaolin is found below the bauxite layers in all bauxite deposits. In the Moengo area, a local company is evaluating kaolin from depleted bauxite mines that were not yet reclaimed. Clays are used locally to produce brick and a use in ceramics is possible. The red mud left from bauxite production form a large mud resource that has been evaluated for producing bricks. White sands formed due to leaching during weathering areas cover large areas of the upper Coastal Plain. Sampling suggests the possibility for glass sand. The sand is currently shipped to town for construction and to Rosebel Gold Mine for tailings dam construction. The white sand is also a significant aquifer from which water is being pumped bottled for export and domestic consumption. Sand and shell layers are mined from the younger Coastal Plain near the Coast for fill and construction purposes.

Suriname has unique dimension stone. In the late 1990's some of this blue granite from Patamacca was shipped to North Carolina for cutting and polishing. Ownership problems hindered the development of this resource and this issue still remains. Other areas have good potential for quality dimension stone, but infrastructure and capital are needed. Crushed stone is used for roads and construction and is hauled long distances from the interior to town. Feldspars from granitic rocks and pegmatites have been evaluated for extraction, but sites are too remote for economic extraction. A kyanite resource was outlined in the 1980's but not developed. In west Suriname, apatite lenses in gneisses form a non-economic phosphate resource.

- Click here for the poster (~5.6 MB) – MS PowerPoint format

LaPoint, Dennis J., Holder, Emro and Glenn Gemerts, 2006, The potential of Suriname, South America, for industrial minerals, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

Geology of the Fletcher limestone quarry, Fletcher, Henderson Country, North Carolina

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Several discontinuous lenticular carbonate bodies of problematic origin occur within the Brevard fault zone of southwestern North Carolina. The largest of these bodies is currently quarried by the Fletcher Limestone Company for its commercial carbonate content. The marble body lies within a northeast trending belt of poly-deformed graphitic and white mica rich phyllonite.

The quarried marble is generally white, foliated, fine to medium crystalline dolomitic (66%) to calcitic (13%) and contains few mineralogical impurities. A 1:2,500-scale geologic map and cross-sections illustrate that the marble body is a fault bounded dismembered formation which forms a tectonic horse block within the Brevard fault zone. Hand samples and thin sections indicate that the marble was subject to multiple deformational events, manifested in at least three overprinting meso- and microscale fabrics.

The marble contains a primary mylonitic to blastomylonitic texture and what resembles a graphite and white mica preferred orientation foliation. Microbrecciation and damage zones filled with cataclastic paste crosscut the earlier mylonitic fabric. Later stage fracture cleavage along with dolomite and calcite filled veins crosscuts the cataclastic domains by propagating along prior developed cataclastic veins. Later stage high angle brittle reverse dip-slip faulting crosscuts the ductile fabrics and fracture cleavage, forming sharp fault contacts and fault gouge between the marble and the encompassing phyllonite.

Kinematic indicators suggest that the marble body was incorporated in southwestward strike-slip motion during dextral shearing of the Brevard fault zone. Cataclasis by microbrecciation of the marble body likely occurred as the marble was translated through a ductile-brittle transition within the Brevard fault zone. Late-stage thrusting synchronous with Rosman faulting, displaced the marble body to the northwest.

- Click here for panel 1 (~9.9Mb) – Adobe Acrobat pdf format
- Click here for panel 2 (~35.7Mb) – Adobe Acrobat pdf format
- Click here for panel 3 (~27.7Mb) – Adobe Acrobat pdf format

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Kaltenbach, Kelly John, 2006, Geology of the Fletcher limestone quarry, Fletcher, Henderson Country, North Carolina, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey

Regional sand and gravel resource assessment on Native Land Allotments, South Central Alaska

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ABSTRACT

The Bureau of Indian Affairs-Alaska Regional Office requested an assessment of sand and gravel potential of the more than 15,000 Alaskan Native land allotments. This presentation focuses on methods employed in a study of approximately 225 of these allotments in south central Alaska. As a result of the study, two rankings will be given to each allotment. The first is based on the geology and the probability of finding quality sand and gravel. The second is based on market conditions including size and location of the land allotment.

Phase one of the study includes a literature review and compilation of a database of geologic, soil survey, and other pertinent maps. These maps are georeferenced using GIS and overlain on allotment locations to aid in identifying favorable deposits. Additionally, geomorphic analysis is conducted using stereo photography and topographic maps to identify glacial, glaciofluvial, and alluvial sand and gravel bearing landforms.

Phase two of the study involves reconnaissance fieldwork on sites identified during phase one that are accessible to market and appear to contain sand and gravel. Field work is conducted to confirm information gathered through literature review and geomorphic analysis, obtain material descriptions, and collect samples. Three engineering tests, sieve analysis, Los Angeles abrasion, and sodium sulfate soundness will be used to gain a preliminary estimate of material quality.

The final product will consist of a report, maps, and a GIS database that can be used to identify allotments of high priority for detailed resource evaluations, aid in trust land management, and provide information to the landowner.

- Click here for the poster (~60.0 MB) – MS PowerPoint format

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Jenks, Nathan K., 2006, Regional sand and gravel resource assessment on Native Land Allotments, South Central Alaska, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.

The 43rd Forum on the Geology of Industrial Minerals, Rocky Mountain Industrial Minerals, Then and Now

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ABSTRACT

In 1979, Colorado hosted the 15th Forum on Industrial Minerals. In 2007 the Forum returns to Colorado with a focus on the many changes in the minerals industry over the past three decades. Technical sessions will cover topics such as geology of industrial minerals in the western states, industrial minerals – then and now, aggregate and construction materials, industry perspectives, and a potpourri of other intriguing topics. Forum participants will have the option to participate in a two day trip through the heart of Colorado and into Wyoming to visit gypsum, nahcolite, and trona mines, and several one-day and half-day trips to local stone and aggregate quarries, clay mines and production facilities, and a cement plant. Spouses and guests will be treated to a wide variety of shopping, cultural experiences, scenic tours, and local entertainment - including an evening of fun in the famed historic mining-town-turned-casino-town of Central City.

The 43rd Forum will be held in Boulder, Colorado, USA, located 35 miles northwest of downtown Denver. Boulder is a haven for research, education, and recreation. At 5,430 feet above sea level, Boulder's outdoor-oriented cityscape serves as a gateway to the rugged beauty of the Rocky Mountains. The Forum will be hosted at the Millennium Harvest House Hotel in central Boulder - just minutes away from a multitude of fabulous attractions, such as miles of open space parks and trails, Pearl Street outdoor pedestrian mall, Celestial Seasonings, the Dushanbe Teahouse, and the University of Colorado Boulder campus.

- Click here for the poster (~34.3 MB) – Adobe Acrobat .pdf format

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Cappa, James A., and Widmann, Beth L., 2006, The 43rd Forum on the Geology of Industrial Minerals, Denver, Colorado, *in* Reid, Jeffrey C., editor, Proceedings of the 42nd Forum on the Geology of Industrial Minerals: Information Circular 34, North Carolina Geological Survey.