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ON THE GEOLOGY OF
INDUSTRIAL MINERALS

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THE MID-ATLANTIC STATES

J. D. Glaser and J. Edwards, Editors

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## CONTENTS

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foreword, by Kenneth N. Weaver</td>
<td>1</td>
</tr>
<tr>
<td>Maryland's Mineral Resources: Past, Present, and Potential,</td>
<td>3</td>
</tr>
<tr>
<td>by Karen R. Kuff</td>
<td></td>
</tr>
<tr>
<td>Industrial and Miscellaneous Silica Resources in Virginia,</td>
<td>11</td>
</tr>
<tr>
<td>by Palmer C. Sweet</td>
<td></td>
</tr>
<tr>
<td>Pennsylvania's Slate Industry: Alive and Well,</td>
<td>23</td>
</tr>
<tr>
<td>by Samuel W. Berkheiser, Jr.</td>
<td></td>
</tr>
<tr>
<td>Cement Production and Related Raw Material Consumption</td>
<td>35</td>
</tr>
<tr>
<td>in the Middle Atlantic States, by Wilton Johnson</td>
<td></td>
</tr>
<tr>
<td>Geology and Mining of Gypsum in Virginia, by Roger D. Sharpe</td>
<td>41</td>
</tr>
<tr>
<td>Maryland's Carbonate Rocks: Alpha and Omega, by Robert V. Demicco</td>
<td>51</td>
</tr>
<tr>
<td>Nonfuel Mineral Industry in Virginia, by Palmer C. Sweet</td>
<td>59</td>
</tr>
<tr>
<td>The Chromite Industry of Maryland, Past and Future,</td>
<td>69</td>
</tr>
<tr>
<td>by J.R. Brooks</td>
<td></td>
</tr>
<tr>
<td>Rates of Preemption of Sand and Gravel Deposits in an Urban Area,</td>
<td>73</td>
</tr>
<tr>
<td>by Karen R. Kuff</td>
<td></td>
</tr>
<tr>
<td>Industrial Minerals of New York State, by William M. Kelly</td>
<td>81</td>
</tr>
<tr>
<td>Limestone Resources for the Coal Industry: An Evaluation of</td>
<td>87</td>
</tr>
<tr>
<td>the Newman Limestone on the Cumberland Overthrust Block, Southeast</td>
<td></td>
</tr>
<tr>
<td>Kentucky, by Garland R. Dever, Jr., Jack R. Moody, and Thomas L. Robl</td>
<td></td>
</tr>
<tr>
<td>Non-metallic Mineral Deposits of Alpine Peridotite-Serpentinite Bodies, by E. Wm. Heinrich</td>
<td>95</td>
</tr>
<tr>
<td>Geology of Sodium Sulfate Deposits of the Northern Great Plains,</td>
<td>105</td>
</tr>
<tr>
<td>by Laurie A. Slezak and William M. Last</td>
<td></td>
</tr>
<tr>
<td>Refractory Dolomite Production in a Geologically Complex Area,</td>
<td>117</td>
</tr>
<tr>
<td>by David A. Hopkins</td>
<td></td>
</tr>
<tr>
<td>Urban Encroachment on Dolomite Resources of the Chicago Area, Illinois, by Donald G. Mikulic and Jonathan H. Goodwin</td>
<td>125</td>
</tr>
<tr>
<td>Potential Markets for Lime and Limestone in Sulfur Control,</td>
<td>133</td>
</tr>
<tr>
<td>by Subhash B. Bhagwat</td>
<td></td>
</tr>
<tr>
<td>The Environmental Geology of Glasgow, Scotland - a Legacy of Urban Surface and Subsurface Mining, by M.A.E. Browne and J.H. Hull</td>
<td>141</td>
</tr>
</tbody>
</table>
FOREWORD

The 20th Forum on the Geology of Industrial Minerals was held May 15 through 18, 1984 in Baltimore, Maryland, under the sponsorship of the Maryland Geological Survey. The Forum consisted of a symposium on Industrial Minerals of the Mid-Atlantic States as well as papers on industrial minerals in the U.S. and other parts of the world. The papers are grouped in this Proceedings Volume in the order of presentation at the Forum.

This meeting marks the 20th Anniversary of the Forum. From its inception in 1965 in Columbus, Ohio, the Forum has had no formal organization. The chairmanship has been passed from host organization to host organization from year to year with each host organization being responsible for publishing the Proceedings Volume. That this informal process has endured and prospered is an indication of the dedication of the participants in the Forum as well as their long and abiding interest in industrial minerals.

It is the nature of businesses which rely on nonrenewable raw materials to experience wide fluctuations in their business cycle. At the time this meeting was held, the industrial minerals industry was just coming out of a deep slump, the metal mining industries were still in a deep depression, and the petroleum industry, as far as exploration is concerned, was also down. Although none of us can predict the future, we know that these lows will have to be reversed. The industrial minerals industry will be called upon to provide the raw materials for housing, offices and factories for the "baby boom" generation. Additionally, the interstate highway system which began in the Eisenhower years now needs repair and replacement. The younger generation is rediscovering our long-neglected cities and they are again becoming vibrant places to live and work through a combination of saving the best of the old and building anew. All of these trends lead to a renewed demand on our industrial raw material storehouse which in turn will increase the pressure on geology and geologists to find and develop sources of industrial minerals.

We suspect that the next twenty years of the Forum will be at least as dynamic and interesting as have been the last twenty.

Kenneth N. Weaver
General Chairman
Kenneth A. Schwarz
Co-Chairman
MARYLAND'S MINERAL RESOURCES: PAST, PRESENT, AND POTENTIAL

Karen R. Kuff
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ABSTRACT

The first geological report of Maryland's mineral resources was made in 1834 by Ducatel, the State Agriculturalist, who reported on a number of small operations for lime, marl, and building stone. Subsequently, Maryland has become a source of many other industrial rocks and minerals, including crushed stone, sand and gravel, clay and shale, cement, lightweight aggregate, shells, soapstone, chromite, industrial sands, barite, rutile, ochre, and diatomite. Not all of these industrial minerals are being mined today, inasmuch as economics and new technologies have changed the importance of various resources. Construction materials are now the primary commodity. Some materials, such as potash, diatomite, and glass sand, although not currently being mined, have a potential use.

Sources of industrial rocks and minerals can be found in all of Maryland's physiographic provinces. The Paleozoic sedimentary rocks of the Appalachian Plateau and Valley and Ridge Provinces are a source of crushed stone, dimension stone, limestone for cement and lime, clay, shale, and glass sand. The igneous and metamorphic rocks of the Piedmont and Blue Ridge Provinces have provided crushed stone, dimension stone, crushed marble, marble and limestone for cement and lime, lightweight aggregate, and soapstone. Historically, many other minerals have been mined. The Mesozoic sedimentary rocks of the Gettysburg Basin have been a source of clay and shale, dimension stone and crushed stone. The unconsolidated materials found east of the Fall Line in the Coastal Plain Province are major sources of sand, gravel, and clay for the Baltimore-Washington Metropolitan area. Glass sand, ochre, and diatomite have also been mined here.

The history of mining in Maryland is a long one, with a continuing demand for materials in an urban location. The overriding concern is the availability of these resources in the future. While there may be a plentiful supply of a potential resource, the political, social and economic realities may prevent its utilization.

INTRODUCTION

The mining industry has played an important part in Maryland's growth. Mining in Maryland began in colonial days when Cretaceous clays provided dyes and brick material. Since then, over 30 different types of industrial rocks and minerals have been mined from time to time in Maryland. Figure 1 shows the value of industrial mineral and rock production in Maryland from 1950 to 1983 (U.S. Bureau of Mines). The preliminary 1983 value of $201,879,000 is an all-time high. Figure 2 shows the unprocessed value and total tonnages produced from 1979 to 1983 (Surface Mining Division, Department of Natural Resources).

The purpose of this paper is twofold: 1) describe the geologic setting of Maryland's industrial rocks and minerals, and 2) describe Maryland's past, present and potential mineral resources.

GEOLOGY

The rocks in Maryland were greatly influenced by the Appalachian orogeny, a complex interplay of deposition, deformation and metamorphism. This orogen records the rifting, widening and ultimate closing of an ocean basin. Appalachian structures were truncated by rift-valley development in the Mesozoic, and the entire orogen has since
been deeply eroded. Part of the erosional debris now comprises the unconsolidated Coastal Plain sediments of eastern Maryland which onlap the older rocks.

The five physiographic provinces of Maryland can be grouped into three distinct geologic regimes: 1) Appalachian Plateau, Valley and Ridge, and Blue Ridge; 2) Piedmont; and 3) Coastal Plain (Fig. 3). The first two regions are underlain by rocks which, to the east, become older, more deformed, and higher in metamorphic grade. East of the Fall Line, these rocks are buried by generally unconsolidated Coastal Plain sediments.

In the west, the Appalachian Plateau is composed of gently folded Devonian to Permian sedimentary rocks. These are dominantly shales, sandstones and siltstones with some limestones and coals preserved in structural basins. The sedimentary rocks in the Valley and Ridge are more strongly folded, with shales and sandstones predominant in the western half. Cambrian and Ordovician rocks which are primarily limestones and dolomites form the Great Valley section near Hagerstown. Ordovician shale makes up the core of this synclinal valley. The rocks of the Blue Ridge Anticlinorium are quartzites, phyllites and metavolcanic greenstones which disconformably overlie a core of granitic basement rocks of Grenville Age.

The gently deformed Mesozoic basins of the western Piedmont Province are composed of red sandstones, shales, siltstones, and some limestone conglomerates. The rest of the western Piedmont is made up of phyllites, schists, metavolcanic rocks, limestones, marbles, and quartzites. In the vicinity of Frederick, Cambro-Ordovician limestones are dominant and form the Frederick Valley. The rest of the western Piedmont is composed of
metamorphic rocks, probably also of Cambro-Ordovician age. Recent mapping of this area has shown complex thrust contacts between many of the units. Mesozoic diabase dikes are also found in this area.

The eastern Piedmont is composed of highly metamorphosed Precambrian and Lower Paleozoic crystalline rocks. These include high-grade schists, gneisses, granitic gneisses, ultramafics, and marbles. These rocks lie unconformably on granitic Grenville basement rocks and have been intruded by pegmatites.

Seaward of the Fall Line, slightly dipping Cretaceous to Quaternary sediments form an eastward thickening wedge of sand, silt, clay and gravel. The oldest deposits (Cretaceous Potomac Group) are found along the Fall Line, and the sediments become younger to the southeast. In undissected areas, a thin veneer of Quaternary sand and gravel overlies the older deposits.

MINERAL RESOURCES

The preceding brief description of Maryland's geology highlights the varied selection of sources for industrial rocks and minerals. There are other industries established in Maryland which use imported materials. These include steel, gypsum, talc, vermiculite, and the paint industry.

Present Mineral Resources

The primary industrial materials presently produced in Maryland are crushed stone, sand and gravel, clays and shale, cement, lime, dimension stone, lightweight aggregate, industrial sand, calcium carbonate, steatite, ball clay, and peat. Figure 4 lists past and potential industrial mineral resources, and shows them in relation to Maryland's physiographic regions. The production value of crushed stone, sand and gravel, and all other materials mined are shown in Figure 1.

Crushed stone is the most important or valuable industrial material produced in Maryland. Figure 5 shows the distribution in Maryland of rocks with present or potential use for crushed stone on a simplified geologic base map. Rocks available for crushed stone include limestones, marbles, granitic gneisses, sandstones, and mafic rocks. There are more than 24 crushed stone quarries (Fig. 5) for construction material, cement, and lime manufacture. Most have been in existence for a number of years. There is one underground mine for crushed limestone.

A number of non-production related problems have recently arisen for Maryland's crushed stone industry. They include: 1) presence of asbestos in some of the mafic rock, and 2) difficulty in obtaining public (zoning) approval to expand or establish new sites. An example of this latter problem is the denial of access to the unique Boyds diabase sill located near Washington, D.C.
A novel attempt has recently been made by a county planning department to establish a mineral resource zone overlay, thereby encouraging and controlling mining at the same time.

The second most valuable mineral resource in Maryland is sand and gravel. Sand and gravel deposits are located in the Coastal Plain Province. The black area in Figure 6 depicts those deposits that may contain economic quantities of gravel. These deposits represent ancient coalescing river deltas with interfingering lenticular beds of clay and silt; therefore, not all of the area shown contains economic amounts of sand and gravel. Younger terrace deposits and upland river deposits contain sand and gravel in proportions related to their proximity to a source. Gravels therefore tend to predominate in deposits found closer to the Piedmont source. All of these areas have been worked for a number of years and the operations are too numerous to be shown here.

The dotted area in Figure 6 represents sand and gravel deposits with lesser proven economic value. It includes lowland deposits, lower river terrace deposits, and alluvial gravels found in channel fillings covered with other sediments. Much of this sand and gravel is of poor quality.

Sand and gravel deposits close to major urban markets are becoming increasingly difficult to find. They have been mined, preempted, adversely zoned, or bought by someone who does not want to develop it. In addition, environmental issues and questions have arisen. As a result of these problems, sand and gravel is currently being imported into the Baltimore Metropolitan region. Bitler (1975) predicted a 35-year life span for the sand and gravel industry in the region. (See also Kuff, this proceedings).

Sources of clay and shale can be found throughout Maryland (Fig. 7), but the most important clay deposits are those found in the Coastal Plain. Weathered shale is quarried for use in brick, terra cotta pipe, and tile manufacture from the Mesozoic shales in Frederick County and the Martinsburg shale near Hagerstown in the Great Valley. Shale beds in the Frederick Valley are quarried for lightweight aggregate. Current mining operations are shown on Figure 7.

Other past sources of clay and shale in Maryland were residual soils in limestone ter-

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Figure 3. Physiographic Provinces of Maryland.
Figure 4. Maryland's industrial rocks and minerals: past, present and potential. Portrayed by physiographic province. Active producers marked by asterisk.

Figure 5. Simplified geologic boundaries of sources for crushed stone in Maryland. Active quarries are shown.
Figure 6. Sources of sand and gravel in Maryland. Areas in black include the Potomac Group, Upland Gravels, and some River Terrace Gravels. Stippled area includes river terraces, Pleistocene to Recent, and Lowland Deposits.

Figure 7. Sources of clay and shale in Maryland. Areas shown include: fire clays, Rockwell Shale, Devonian shales, Martinsburg Shale, Gettysburg and New Oxford Shales, shale member of Frederick Limestone, clays of Potomac Group, Marlboro Clay, Peach Bottom Slates, St. Mary's Formation, and Pleistocene clay beds.
rane, and shales associated with the coal measures of the Appalachian Plateau. If economic conditions change, potential sources are the Devonian shales, and bloating clays in the St. Mary's Formation in Southern Maryland.

Crushed stone, sand and gravel, clay and shale are the major mineral resources mined in Maryland today. The remainder are briefly outlined below. Portland cement is manufactured from limestones in the Frederick and Great Valleys. The cement industry reportedly had a "banner year" in 1983. Figure 1 reflects this sharp increase. Potash is produced as a byproduct of cement manufacture. Hydrated lime is calcined in the Frederick Valley. Calcium carbonate is being mined underground from calcite deposits in the eastern Piedmont north of Baltimore. Steatite is produced in Harford County. The dimension stone industry today produces primarily flagstone, veneer, and rough construction stone. Slag, for lightweight aggregate, is a byproduct of the steel industry.

Potential Mineral Resources

There are two types of potential resources 1) undeveloped areas of known deposits, such as the Oriskany glass sand, and 2) deposits not at present economic, but which may become valuable in the future. These include deposits mined in the past but which will need some change in economic, social or political conditions in order to again become viable. Some examples of this last type of potential resource may include: bloating clays in the St. Mary's Formation, diatomite in Southern Maryland, glauconite (greensand), talc in serpentinite bodies, and crushed stone from the Boyds diabase sill.

CONCLUDING REMARKS

The industrial rock and mineral industry in Maryland is surviving. Value of production and output has increased in the past few years. The proximity of the Nation's capital, and the up-and-coming Baltimore market is creating a continuous demand for construction material. The major overriding concern for industrial mineral resources in this area is that without some form of public land use controls or policy, the mining industry will continue to experience great difficulty in expanding or finding new sites to mine.
SELECTED REFERENCES


Williams, G.H. (1893) Mines and minerals, in Maryland, its resources industries, and institutions: Sun Job Press, Baltimore, Maryland, p. 89-153.
INDUSTRIAL AND MISCELLANEOUS SILICA RESOURCES IN VIRGINIA

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Charlottesville, Virginia

ABSTRACT

Industrial silica is presently produced from the Valley and Ridge and Coastal Plain Provinces in Virginia for glass manufacture, foundry and engine (traction) uses, for filter beds, conversion to cristobalite, and for a metallurgical flux. Additional past uses include electrical porcelain, oscillator-grade quartz crystals, ferrosilicon, silica flour, as a component in fiberglass, cleansers, and as an abrasive for sandblasting and stone-sawing. The most prevalent use of industrial sand in Virginia has been and continues to be for glass manufacture.

Future utilization of silica resources in Virginia may include frac-propping sand, additional markets for filter sand, and use of large quartz vein or pegmatite core material as raw material for metallurgical flux, fiber optics, etc. Numerous localities, especially in the Valley and Ridge, Blue Ridge and Piedmont Provinces, have been investigated. Sieve and/or chemical analysis, physical properties, and transportation facilities, plus available markets, indicate a potential for growth of the industrial silica industry in Virginia.

INTRODUCTION

Although there is an abundance of silica in the Earth's crust, only a relatively small percentage of this is of commercial interest as the various industrial consuming industries require unique chemical and physical specifications. A product must generally meet a minimum silica content and a maximum alumina, iron, titanium, calcium, and magnesium oxide content. Iron, one of the main contaminants, is present as metallic particles abraded from grinding and handling equipment, from iron-bearing minerals such as limonite, magnetite and ilmenite, or present as a constituent of complex silicates such as garnet, biotite or tourmaline. Components such as arsenic, chromium, cobalt, and phosphorus are also detrimental. Tolerance on specifications for certain types of silica raw materials may vary due to proximity to markets, necessity, etc. Some industries require a sand material while others may require sized lumps (Table 1).

Industrial silica is presently produced from the Valley and Ridge, Plateau, and Coastal Plain Provinces in Virginia for glass manufacture, foundry and engine (traction) uses, for filter beds, conversion to cristobalite, and for a metallurgical flux. Additional past uses include electrical porcelain, oscillator-grade quartz crystals, coal washing, ferrosilicon, silica flour, as a component in fiberglass, cleansers, and as an abrasive for sandblasting and stone sawing. The most prevalent use of industrial sand in Virginia has been and continues to be for glass manufacture.

PRESENT AND FUTURE INDUSTRIAL SILICA OPERATIONS IN VIRGINIA

In 1983, industrial silica was produced by six operations in Virginia. Metallurgical flux material, glass, foundry, and traction sand, and recrystallized silica (cristobalite) were produced in Dickenson, Frederick, Prince George, and Wythe Counties and the city of Virginia Beach (Sweet, 1983). In early 1983, Saltville Silica Inc. in Smyth County produced glass sand, sand as an ingredient in mineral wool production, and sand for refractory brick.
Table 1. General specifications for silica/quartz by end use (%).

<table>
<thead>
<tr>
<th>End use</th>
<th>min SiO₂</th>
<th>max Al₂O₃</th>
<th>max Fe₂O₃</th>
<th>max CaO/MgO</th>
<th>Grain size</th>
</tr>
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<tbody>
<tr>
<td>Glass sand</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>99.5</td>
<td>0.008</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Colorless domestic</td>
<td>99.5</td>
<td>variable</td>
<td>0.013</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Container/flat</td>
<td>98.5</td>
<td>0.1-0.5</td>
<td>0.030</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Foundry sand</td>
<td>88-99</td>
<td>-----</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silica flour</td>
<td>97-98</td>
<td>0.5</td>
<td>0.2</td>
<td></td>
<td>micron sizing</td>
</tr>
<tr>
<td>Silicon carbide</td>
<td>99.5</td>
<td>0.06-0.25</td>
<td>0.1</td>
<td>absent</td>
<td>+100 mesh</td>
</tr>
<tr>
<td>Silicon</td>
<td>98.0</td>
<td>0.4</td>
<td>0.2</td>
<td>0.2 each</td>
<td>1 inch diameter</td>
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<tr>
<td>Ferrosilicon</td>
<td>96</td>
<td>0.4</td>
<td>0.2</td>
<td></td>
<td>1 inch diameter</td>
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<tr>
<td>Silica brick</td>
<td>96-98</td>
<td>0.1</td>
<td>low</td>
<td>-8</td>
<td></td>
</tr>
<tr>
<td>Sodium silicate</td>
<td>99</td>
<td>0.25</td>
<td>0.03</td>
<td>0.05</td>
<td>20-100 mesh</td>
</tr>
<tr>
<td>Silica flux</td>
<td>90</td>
<td>1.5</td>
<td>1.5</td>
<td>0.2</td>
<td>5%-1 inch</td>
</tr>
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The outlook for additional industrial silica operations in Virginia depends on future oil and gas exploration, industrial expansion, development of new markets and technologies, competition, etc. Future utilization of silica resources in Virginia includes frac-proping sand, additional markets for filter sand, and use of quartz vein or pegmatite core material as raw material for metallurgical flux, fiber optics, etc. Numerous localities, especially in the Valley and Ridge, Blue Ridge and Piedmont Provinces, have been investigated. Sieve and/or chemical analysis, other physical properties, and transportation facilities plus available markets determine the potential for growth of the industrial silica industry in Virginia.

Following are brief descriptions of some of the better exposures, exclusive of the Antietam or Erwin Formation of Cambrian age, that appear to be most potentially suitable for future exploitation in Virginia.

**Ridgeley Sandstone**

In the extreme west-northwestern part of Virginia, the Ridgeley Sandstone of Devonian age is thick - over 300 feet in places. This high-purity unit has been produced at several localities for use as glass sand. The rock is predominantly a white to light-tan to light-gray sandstone that in places contains a calcareous matrix. An abundance of jointing and fracturing has allowed downward percolating waters to leach the cementing material and reduce the rock to a friable sandstone or loose sand. Up and down the Valley and Ridge Province this rock unit may be suitable for industrial silica uses; some localities where silica exceeds 99% are noted in Fig. 1. Unimin Corporation in Frederick County, northern Virginia, is presently the only active operation quarrying the Ridgeley for use as glass sand.

**Tuscarora and Keefer Sandstones**

The Tuscarora (Clinch) Formation of Silurian age consists of very fine- to very coarse-grained sandstone and quartzite, with quartz pebbles in places. The rock is usually well indurated; however, at some localities, the rock is poorly cemented and weathers to
sand. The Keefer Sandstone member of the Rose Hill Formation is white to brown, very fine to medium grained, and ranges from an indurated quartzite to a friable sandstone. Quartz grains are bonded by a quartz weld and are commonly cemented by quartz overgrowths. Figure 2 indicates some locations where the silica content exceeds 99%. The Tuscarora has been exploited along Clinch Mountain from near Wardell in southwestern Tazewell County to Mendota and Silica at the Washington-Scott County line to Kermit in Scott County. The unit is basically a gray to white, fine-grained sandstone which trends northeast-southwest, and dips from 30° in Washington County to 70° in southern Scott County at Kermit. Along strike the sandstone varies in thickness as well as in degree of consolidation, and thus reserves over a large area are hard to determine. The Tuscarora Sandstone has a general unit thickness of approximately 360 feet, but in the past only a zone about 25 to 50 feet thick which contains the most friable material has been quarried (Figure 3). Reserves estimated by Gildersleeve and Calver (1945) may be millions of tons. A portion of the northern end of Clinch Mountain in Smyth County is in the Clinch Mountain Wildlife Management Area. A very friable sample of Tuscarora from Monterey Mountain in Highland County in Western Virginia was analyzed to contain 99.6% silica (Sweet, 1981, p. 5).

Lee Formation

The lower sandstone unit of the Lee Formation of Pennsylvanian age that runs along Pine Mountain in northwestern Dickenson and Wise Counties has been exploited principally at two points.

The sandstone has been quarried near the Kentucky-Virginia state line, south of Elkhorn City, Kentucky by the Silica Corporation of America; both glass sand and heavy-media sand for coal washing were produced in 1960-1962. Pine Mountain is capped by the lower unit of the Lee Formation, which is

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Figure 1. Silica sample locations of the Ridgeley Sandstone.
conglomeratic at the base with pebbles up to 1 inch in diameter, but grades upward into white, fine- to medium-grained sandstone. The unit has a strike of N20°E and a dip of 30°SE. Studies of the deposit, including test data, are noted in McGrain and Crawford (1959), and Hollenbeck and others (1967). Chemical analyses of nine samples of raw sandstone from the quarry and the immediate vicinity ranged from 97.78 to 99.30% silica and 0.05% iron. Minor amounts of zircon, tourmaline, rutile, kyanite, fluorite, and opaque material were also noted. Hollenbeck and others (1967) report a sieve analysis that indicates 79.5% of the grains falls between 40- and 100-mesh.

The Lee Sandstone was also mined north of Pound in Wise County off the southeast side of Pine Mountain. This quarry was probably in the middle sandstone member and was mined for coal washing sand. A chemical analysis of this material indicated 98.5 to 99.2% silica (E.E. Musgrove, personal communication 1969). The site was last worked in 1974 by Southwest Sand Company, Inc.
Former operators of the property in the early 1960's were C.E. Robertson and Skyline Sand Company, Inc. An exposure of the upper quartz sandstone (Bee Rock Sandstone) in Breaks Interstate Park, Dickenson County, is noted in Figure 4. The majority of the land along the east flank of Pine Mountain and along the northwestern Dickenson and Wise County boundaries is within the Jefferson National Forest. There are numerous privately-owned tracts within these boundaries, and in some of the National Forest tracts, the mineral rights are privately held.

Quartz Veins

Formerly-active as well as undeveloped quartz veins have been examined by companies looking for silica with low iron content and also for use as metallurgical flux material. Quartz veins in Albemarle, Campbell, Fluvanna, and Patrick Counties are of particular interest. Quartz in the cores of pegmatites may also be of interest, and several have been noted in Amelia and Bedford Counties.

The Otter River quartz vein (Figure 5) appears to be at least 0.4 mile long, 100 feet wide, and 150 feet high and probably contains about 2.6 million tons. There has been interest in contracting for 2.5 million tons of material to be marketed in West Virginia. Palmyra Stone Company's quarry in Fluvanna County (Figure 5) was productive in 1964 and estimates of material available from this vein are in excess of one million tons. Analysis by the Virginia Division of Mineral Resources indicates the quartz contains 99.05% silica, 0.57% alumina, and no iron. The vein at this location has a strike of N15°E and dips steeply to the southwest. Quartz is also present on the hill 0.1 mile southeast of the quarry and is probably a continuation of the vein.

A quartz vein (Figures 5, 6), located just off the Blue Ridge Parkway south of Meadows of Dan, Patrick County, was exploited in 1964 for metallurgical material to be utilized in the Pittsburgh area. The vein is exposed for 400 feet, with a width of 75 feet. Soil covers an additional 900 feet of vein which has a strike of N35°E and a dip of 60°SE. A Virginia Division of Mineral Resources analysis of a sample of this quartz ran 99.1% silica, 0.57% alumina, and no iron. A quartz vein west of Carter's Bridge in Albemarle County (Figure 5) has a strike of N60°E and is exposed discontinuously for about 0.3 mile with an exposed width of about 70 feet.

Quartz from the cores of pegmatites ranges from clear to milky. Locations that may be of interest include the Champion, Jefferson No. 3, and Pinchbeck No. 1 mines in Amelia County (Chula 7.5-minute quadrangle), and the Wheatley mine in Bedford County (Moneta 7.5-minute quadrangle) (Figure 5).

Demand for industrial silica resources has increased between 1975 to 1979 from 25 million tons to 33.5 million tons per year mainly due to the increased demand for glass and foundry sand. As the unit price of most of the specialty sands precludes distant transport, the delivered price is very important. Thus, regional competition is stiff, and industry is secretive about production grades and prices. The major markets for silica sand are the industrialized areas of the north-central and southern parts of the USA. Transporta-
tion of sand for more than 200 miles is rare.

With the increasing use of transmitting messages by means of light waves along thin silica strands rather than by electrical signals along copper wire, quartz veins are of interest as raw material for optical fibers. In 1983, a cable only the thickness of a finger and containing 144 optical fibers was activated between New York and Washington. Eventually such optical cables will have the capability to carry up to 240,000 simultaneous transmissions, which is almost twice the number that can be carried by 2.25-inch standard copper cable. Suitability of raw material depends on its capacity to withstand thermal stress or nonuniform temperature distribution.

USES OF SILICA RESOURCES

Glass Sand

High silica content is important; iron content as low as 0.008% to as high as 1% is acceptable depending on whether the final product will be optical or amber glass. Iron oxides may form crusts or coatings on quartz grains which can usually be removed by washing, scrubbing or flotation. Grain-size specifications have all material passing through a 30-mesh screen with only a small amount passable through a 100-mesh. Uniformity of grain size may actually be more important than the size of the grains themselves. Grain shape is not critical and it may range from round to angular. The majority of fines are lost through washing; however, too many fines will cause a rapid first reaction and liberation of carbon dioxide which will cause the batch to foam excessively. Too many fines may also form a fine persistent seed in the glass. If the sand has a few coarse grains, it will not flux readily and oversize grains may remain unmelted. High alumina is a detriment for optical glass, and six parts per million (ppm) of chromium is the maximum allowed in the melt. Sweet (1978, p. 69) notes that 0.0002% cobalt will produce a distinct tint in the glass.

There have been many producers of glass-grade material in Virginia in the past; however there is presently only one active operation, Unimin Corporation near Gore, Frederick County, which is quarrying the Ridgeley (Oriskany) Sandstone. Glass sand producers in the past have been located throughout the Valley and Ridge, Plateau and Piedmont Provinces. Most recently, Saltville Silica, Inc. near Saltville, Smyth County, in southwest Virginia, produced material for glass, refractory brick and as an ingredient in mineral wool. Container glass was the largest consumer of silica sand in 1982, accounting for 8,865,000 tons. Competition from
cans, plastic, and paper cartons will probably hurt the glass container market in the future. Flat glass markets tend to run with the general economy. Prices of glass sand vary from $8 to $13 per ton FOB.

**Abrasive Sand**

Most natural sands are suitable for grinding. Individual grains should be round and closely sized with the angularity depending upon specific requirements, such as: sand blasting, stonesawing, glass grinding, or banding (the second grinding of plate glass). Some of the abrasive grinding and airblasting sands can be recycled.

Due to regulations regarding siliceous materials instituted over the last several years, the trend is toward using other materials for abrasives (e.g., nepheline syenite from Ontario, Canada). Hardness and durability is being sacrificed for material that is more easily accepted by industry. Material from the Tuscarora Formation at Clinch Mountain Silica Sand Corporation was marketed in 1930 as abrasive material for sawing marble (Gildersleeve and Calver, 1945).

![Figure 6. Drill hole in quartz vein, Meadows of Dan, Patrick County.](image)

**Metallurgical Flux**

Silica is used as a fluxing agent for basic oxides in various smelting operations, as a source of silicon in ferrosilicon alloy manufacture, and for making elemental silicon.

During silica fluxing operations, the iron and basic oxides will react with the silica to form a silicate slag. Users generally prefer a quartzite with at least a purity of 98% silica and only small amounts of iron, alumina, and traces of other oxides. Iron, alumina and other oxides reduce the percentage of available silica. Compounds of arsenic, phosphorous, and sulfur are objectionable because of poisonous gases they create in the furnace. Alumina when present, is difficult to reduce in the electric furnace and produces a sticky slag that may contaminate the material produced. Silica flux should be tough and not crumble or contain fines. Metallurgical grade material has size requirements of 1 inch by 4 inches.

Raw material for ferrosilicon was produced in 1918 at the Reynolds Quarry in Washington County. Five thousand tons of quartzite analyzing 98% silica was produced from Lick Mountain, south of Wytheville in 1941, from the Archer Quarry. Reserves of metallurgical-grade material are estimated at 2 million long tons in Lick Mountain. Presently, material is being produced by Locher and Company, Inc., at Lots Gap, Wythe County (Figure 7). Good grade metallurgical quartzite is also present along the west flank of the Blue Ridge Mountains near Waynesboro, Augusta County.

**Filter Sand**

Filter sand is used to remove sediment, suspended matter, and bacteria from municipal and industrial water supplies; and in sewage treatment and swimming pool purification. In a filter bed succession it is used as the upper layer which performs the filtering function, while the coarser, lower layers act as a support.

Uniformity of grain size, usually between 45- and 25-mesh, is required but grain shape requirements are not critical. Angular to rounded grains are permitted; however, flat or elongated grains must be less than 1%. Specifications for filter sand set by the Virginia Department of Health are 99 to 100% of the sand passing through the 4-mesh, 0 to 2% through the 80-mesh and 0 to 1% through the 100-mesh. Sand should be high in silica and free of grain coatings such as iron and manganese which would react with chemicals used in the water treatment. It should also be free of clay, silt or organic matter. Solu-
bility of the sand, usually less than 5% in hydrochloric acid, is governed by the pH of the water to be filtered. Material marketed for filtration purposes is produced by a sand and gravel operation south of Richmond and east of Petersburg, Virginia.

**Engine (Traction) Sand**

Engine sand is used on slippery rails for traction and to remove soot from the flues of oil-burning locomotives. Clean silica sand with round to subrounded grains, between 20- and 80-mesh, and with very low clay content is employed so that it will run free with no caking.

An operation in eastern Virginia markets to a major railroad in the State from their pit near Oceana all sand material that is retained on a 60-mesh sieve. River sand in southwest Virginia is also used as a traction material on the rails for mine cars in the coal mines. In the early 1940's Clinch Mountain Sand Corporation, located on Short (Beartown) Mountain, part of Clinch Mountain in southern Tazewell County near Wardell, produced a "friction" sand for use on mine haulage systems. Engine sand was formerly produced by Locher Silica Corporation at Goshen in Rockbridge County. Some other counties with production in the past include Giles, Hanover, Rockingham, Scott, and Spotsylvania.

**Furnace (Fire) Sand**

Furnace sand is employed to line the walls and floors of open-hearth steel furnaces. Material should be clean and of high silica content (95%) to furnish the necessary refractory properties. Grain size should vary from fine to coarse to allow close packing. A small amount of bonding material (clay) is necessary to hold the sand in place in the furnace and to make the hearth more impervious. Spent molding sand is often used as furnace sand, and in many cases may be preferable to new sand due to the increase in fines, resulting from molding sand bond. In Virginia, furnace sand has been produced in Hanover, Henrico, New Kent, Pulaski, and Wythe Counties.

**Foundry (Molding) Sand**

This is for use in foundries to make cores and molds for casting of common metals, and as a component of refractory products. Four to five tons are utilized per ton of metal poured.

Raw material for foundry sand is required to have a minimum silica content of 95 to 96%; however, the standard specification is trending towards 98 to 99%. Allowable impurities are 6 to 10% alumina and 4% iron; loss on ignition should be less than 0.4%. Proportions of clay and iron are important; too much causes the mold to shrink and crack, whereas too little will make the mold dry and crumbly. Particles should range from fine to coarse; however, grain size ranging toward fine is most important for proper texture. Material must be refractory to withstand heat and must be cohesive to hold together. Silica sand should have the strength to resist the pressure from the molten metal being poured and must be porous enough to allow gases to escape. The texture and composition of the sand allows the mold to be smooth.

Material of lacustrine and of marine origin as well as dune sands may be suitable. An operation located in Virginia Beach produces a product that passes a 60-mesh screen, with the correct amount of fines. This material is used in a shipyard and can be recycled. In the past, molding sand was produced at Locher Silica Corporation in Rockbridge County. Some other counties with past production include Augusta, Campbell, Caroline, Charles City, Chesterfield, Dinwiddie, Giles, Henrico, Prince George, Pulaski, Rockingham,
Scott and Spotsylvania, as well as the city of Alexandria.

The foundry sand market has suffered during the recent recession as consumption dropped to almost 3 million tons from almost 10 million in 1981. The sand market, following the economy, is expected to recover slowly in the mid 1980's. Prices on foundry sands are normally less than glass sands; finely ground sand for core facings averages $17 to $18/ton.

Hydraulic Fracturing (frac or propping) Sand

Hydraulic fracturing utilizes a sand-water mixture forced into wells under high pressure in order to break up petroleum-bearing formations and open bedding planes, which in turn allows the oil or gas to move more freely. Approximately 1,470,000 tons of industrial-quality silica frac sand was mined from a select group of sandstone formations in the U.S. in 1981.

For early fracturing treatments, construction sand from gravel pits was used as a proppant to hold open the fractures in the rocks that had been enlarged by pressurized fluids. Later, propping agents such as crushed and rounded walnut hulls, high-strength glass beads, aluminum, pellets, steel shot and other materials were evaluated. However, it was eventually discovered that certain sandstone formations yielded a silica grain that performed reliably in well stimulation. Such characteristics as particle size (90% of the material should be between 20- and 40-mesh), roundness, solubility (less than 5% soluble in hydrochloric acid), and crushing resistance must be evaluated. A uniformly graded sand was found to give the best permeability. Whether mined from open pits or underground, frac sand must be washed and processed to ensure clean unconsolidated quartz grains.

The use of sand grains in hydraulic fracturing is undergoing continual research to further improve efficiency. New fracturing fluids, surfactants, emulsions and other substances combined, serviced with even more sophisticated equipment, should improve the economics of oil fields in the future.

After a depressed drilling industry in 1982 and 1983, the indicated upturn in the oil and gas industry in the Appalachians and the Eastern Overthrust Belt makes the prospect of locating sources of fracturing sand in the Southwestern Virginia area viable. Suitable resources may be present in the Ridgeley Sandstone or in portions of the Erwin Formation where the sandstone is coarse grained.

Coalwashing Sand

For coal washing, sand is mixed with water to form a slurry into which raw coal is fed. By movement of a revolving agitator, the sand is kept in suspension while the coal, with a specific gravity of about 1.50, floats near the surface of the fluid mixture until it reaches the discharge point. The heavier impurities will sink.

The sand should be washed and graded to be free of clay and organic matter. Grains must be subangular to round and must range in size between 30-mesh and 140-mesh, with at least 90% between 3- and 100-mesh. The minimum specific gravity should be 2.64. Raw material from the Lee Formation of Pennsylvanian age was produced in 1960-1961 by the Silica Corporation of America from a quarry in Kentucky just west of the Dickenson County line.

Sand-Lime Brick

A white standard-size brick used for ornamental facing brick is composed of silica sand (80 to 85%) and moist lime which react under heat (steam) and pressure to form a hydrous calcium-silicate bond. Ten percent of the sand should pass 140-mesh, with all passing the 20-mesh. Sand may contain 2% clay, but no more than 5%. It should be angular, clean and free from organic matter. The most attractive brick is provided with white sand free from dark-colored grains. In Virginia a company in Princess Anne County, now the city of Virginia Beach, was a sand-lime brick producer in 1915.

Refractory Brick

Silica or refractory bricks are composed of 96% to 98% silica sand or quartzite fired
with lime for bond. Specifications note that alkalies should be less than 0.3% with less than 1% alumina and the combined iron and alumina under 1.5%. A suitable size distribution should have 55% of the material fall between 4- and 30-mesh, 20% between 30- and 70-mesh, and 25% less than 70-mesh. Refractory ganister refers to fine-grained quartzite while refractory pebble includes granule to pebble (2 mm to 64 mm) size material.

The most important property is the ability of the brick to support loads at high temperatures. Uses include roofs for basic open-hearth steel furnaces and glass-melting tanks, lining for coke ovens, and refractory as well as other types of furnaces. Raw material for refractory brick was supplied by Saltville Silica, Inc., Smyth County in the early 1980's. Sand from this operation would first be melted (fused brick) so that expansion and contraction properties would be eliminated.

Ground Silica (silica flour, ground quartz)

A representative chemical analysis (McLaws, 1971, p. 34) for ground silica would be as follows:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Silica</td>
<td>99.80%</td>
</tr>
<tr>
<td>Iron</td>
<td>0.02%</td>
</tr>
<tr>
<td>Alumina</td>
<td>0.06%</td>
</tr>
<tr>
<td>Titania</td>
<td>0.013%</td>
</tr>
<tr>
<td>L.O.I.</td>
<td>0.09%</td>
</tr>
</tbody>
</table>

Raw material can be sand, quartzite or sandstone and should be angular and fine grained. The better grades have greater than 95% passing through 325-mesh. The raw material is ground to micron sizes, usually in a ball mill. Ground silica is used as an extender in paint and varnish, as a filler in insecticides and fertilizers, in pastewood filler, fiberglass, cement mixtures, refractory cement for oil wells, tile, plastic and rubber, and as an abrasive ingredient in soaps and scouring powders. Its refractory and inert properties are utilized in the manufacture of gypsum wallboard where it also imparts whiteness. Ground silica is an important ingredient in ceramics and porcelain where its use reduces drying time, fire shrinkage and deformation. Material for electrical porcelain was produced in 1930 by the Clinch Mountain Silica Sand Corporation in Scott County. Similar material was produced from the Reynolds Quarry in adjacent Washington County around 1918.

Silica flour was marketed in the mid-1960's by Locher Silica Corporation at Goshen, Rockbridge County for use in fiberglass. In 1982, fiberglass markets consumed 1,457,000 tons of sand. The average price for fiberglass sand is about $23/ton.

Miscellaneous

Cristobalite, a crystalline form of silica, is produced by CED Process Minerals at a plant near Gore, Frederick County, west of Winchester. The Ridgeley (Oriskany) sandstone is obtained from an out-of-state quarry. Impurities are removed by magnets and the material is heated to between 1500° and 2950°F to recrystallize the quartz. The finished product is bagged in both 90-mesh and 325-mesh sizes and is shipped by rail to the Great Lakes area and to the port of Baltimore. End uses for the material include filler for paint, lime, etc.

Crystal Quartz

Quartz crystals have been utilized as oscillators, for filter and telephone resonators and increasingly as timing devices in watches. Oscillator-grade quartz crystals are sliced into thin plates and used to stabilize the frequency of oscillator circuits. Crystal production occurred in Virginia during World War II when the material was utilized in radio transmitters for military use. Almost 135 pounds of quartz crystals were produced from Carroll, Floyd, Patrick and Pulaski counties at a 1943 value of $830.70 (Mertie, 1959). A large quartz crystal is present in the wall of the Buffalo Mountain Church, Carroll County (Figure 8). Reserves of crystal quartz are probably small with only low grades present in scattered occurrences.

There is no present U.S. production of natural quartz suitable for electronic or optical applications, although lasca is produced from Arkansas. Lasca is a natural nonelectronic-grade quartz used as a feedstock for growing cultured quartz crystals. Domestically grown or cultured quartz crys-
tals, of which the U.S. is the world production leader, have taken over most of the demand for natural quartz crystals. Natural quartz is still required for specific electronic applications requiring an extremely high Q-factor. The main use for quartz crystals is in frequency-controlled oscillators. Future uses include timing devices for microprocessors, clocks and video games.

Ornamental Aggregate

Over the years many raw materials have been produced in Virginia for use as exposed aggregate and as terrazzo. In the early 1960s, the majority of material was produced by two companies that opened numerous quarries in quartz veins, mainly in the Piedmont Province. Economy Cast Stone Company set up two plants around Richmond and over a period of 15 years, have operated 4 quarries. Stone and Mineral Corporation of Warrenton, set up a crushing plant in Madison County and has operated 11 quarries over the years. Records indicate that approximately 50,000 tons of material valued at more than $600,000 were produced. More recently, the cost of quarrying this material has decreased,

but the use of cast panels utilizing exposed aggregate has also decreased. Some white quartz pebbles, mainly from sand and gravel operations in Caroline County have been utilized over the last few years.

REFERENCES


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PENNSYLVANIA'S SLATE INDUSTRY: ALIVE AND WELL

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ABSTRACT

The slate industry of Lehigh and Northampton Counties, in eastern Pennsylvania, is alive and very well while the Peach Bottom district, in the southeastern part of the state, remains idle. Favorable geology and aggressive marketing combine to make the famous blue-gray slate of the Lehigh-Northampton district competitive in the continental U.S. market. The industry produces more than $4-million worth of slate products annually from the upper portion of the Martinsburg Formation in Pennsylvania.

Mineralogically, this slate is composed of roughly equal amounts of quartz and mica with lesser amounts of chlorite, and minor amounts of a feldspar such as albite, and carbonates. Minor kaolinite is also present locally. Two grades of slate are mined: clear and ribbon. The clear stock is the most desirable. It is characterized by homogeneous claystone-slate beds, up to about 30 ft thick, having an exceptionally uniform grain size. Ribbon stock is distinguished by having darker carbonaceous and lighter quartzose laminations that are preserved bedding planes. Axial-plane cleavage generally prevails and forms the floor of most quarries in a folded nappe-type terrain. The quarries today can be developed to a depth of about 600 ft and the remaining resources are more than adequate for long range production plans.

The Lehigh-Northampton district is unique as it is the only producer of electrical and billiard slate in the United States at the present time. Such production is made possible by the structural relationship between bedding and cleavage in the homogeneous claystone-slate beds and by the ease of milling and finishing of this slate. However, the principal items produced from these quarries are structural products, roofing, flooring, and blackboard slates.

Although the total tonnage of production has generally declined in the past decade, the value of the slate produced has increased significantly as the U.S. trends away from synthetic products and toward increased restoration work. Demand for various slate products is cyclic, and flexibility in mining, milling, and marketing is a key to survival.

INTRODUCTION

There are two significant slate districts in Pennsylvania. The active Lehigh - Northampton district is located in east-central Pennsylvania in Lehigh and Northampton Counties (Fig. 1). It is alive and well, producing more than $4-million worth of famous blue-gray slate products annually (Kebblish and Tuchman, 1983), mostly from the Pen Argyll and Slatedale areas. This slate production nationally ranks second in value (H.A. Taylor, Jr. pers. com., 1984). The district is located in gently rolling hills near the northern boundary of the Great Valley Section of the Valley and Ridge Physiographic Province. The now-idle Peach Bottom district produced mainly black roofing slate and roofing granules from southeastern Pennsylvania in York County and to a lesser degree Lancaster County (Fig. 1). This district is also located in a gently rolling terrain, but is located in the Piedmont Uplands Section of the Piedmont Physiographic Province, where the slate forms a resistant ridge.
The older Peach Bottom district may have experienced significant quarrying around 1785 or before when this slate was used as a roofing material for a local church (Behre, 1933). Behre also reports that Joseph Hewes, a signer of the Declaration of Independence, laid a roof in Peach Bottom of which portions were still in use in 1933. There should be little question as to the durability of slate used for roofing. By 1850, the slate-quarrying industry was developed in both districts as a result of entrepreneuring Welshmen who persuaded experienced slaters from Wales to immigrate to the New World (Behre, 1933; and Miller and Behre, 1941). However, the now-active Pen Argyl portion of the Lehigh-Northampton district was not developed until 1854 when a Mr. Kellow started development of the United States Quarry (Anonymous, 1982). By 1858 there were 29 quarries in the Peach Bottom district, while the Lehigh-Northampton district had 2 active quarries near the Delaware Water Gap, and 6 active quarries near the Lehigh Water Gap (Rogers, 1858).

LEHIGH-NORTHAMPTON DISTRICT

Geology

Quarries in the Lehigh-Northampton slate district produce from a dark-gray to medium-gray, even-bedded claystone slate from the upper of three members of the Upper Ordovician Martinsburg Formation. This formation has been estimated to represent an apparent thickness of about 10,000 to 13,000 ft of fine-grained basinal sediments (Drake and Epstein, 1967). Faulting and bed repetition in a nappe-type terrain make true thickness estimates difficult.

Historically, most slate has been mined from the upper Pen Argyl Member of the Martinsburg Formation, which yields the classic "blue-gray" homogeneous slate beds. These beds are rhythmically interlayered with thin beds containing more calcite, quartz, and carbonaceous-rich slate ("ribbons"). This upper member is estimated to be about 5,000 ft thick (Epstein, 1973) and is the only part of
the formation currently being exploited. Historically, in the eastern part of the district near Bangor and Slateford, the upper part of the graywacke-rich underlying Ramseyburg Member was mined for slate and the basal Bushkill Member, also more graywacke-rich than the Pen Argyl Member, has yielded some minor slate production.

Mineralogically, the producing beds of the Pen Argyl Member are composed roughly of equal amounts of fine-grained quartz and mica with lesser amounts of chlorite, a feldspar such as albite, carbonates, and minor kaolinite. Pyrite is present locally. Low-carbon beds used for electrical slates may contain less chlorite and pyrite (R.C. Smith, II and J.H. Barnes pers. com., 1983).

This portion of the Great Valley is believed to be composed of a series of recumbent, alpine-type nappe systems, generally overturned to the north or northwest, which have Precambrian crystalline cores (Drake, 1978). The Lehigh-Northampton district has been interpreted to form the nose of the Musconetcong nappe in eastern Pennsylvania (Fall, in progress). A well-developed axial-plane cleavage generally prevails throughout this Martinsburg terrain. Most major faults in the slate quarries appear to be subparallel to bedding. Most current producers have at least a 50-year supply of slate in or adjacent to their active quarries.

Mining

Three companies are known to be mining slate in the Commonwealth, and all three are located in the Lehigh-Northampton district (J. Lee pers. com., 1983). The largest producer is Anthony Dally and Sons, Inc., with five operating quarries and at least six distinct milling operations in the Pen Argyl area. The Pen Big Bed Slate Company produces further west from one slate quarry and associated mill north of Slatedale. A third and smaller producer in Wind Gap apparently does business intermittently.

Two grades of slate are mined: clear and ribbon. The clear stock is the most desirable. It is characterized by a fine-grained, gray, homogeneous appearance. Ribbon stock is characterized by closely-spaced dark-colored carbonaceous and/or light-colored quartz or calcite-rich laminations and bands. Clear beds are devoid of ribbons and generally have thicknesses of at least 10 ft in the Pen Argyl area but can be up to about 30 ft thick further west. The Diamond and Albion runs are the main series of clear beds mined in the Pen Argyl area. The clear bed presently mined in the Pen Argyl area is the Manhattan run.

The prevailing axial-plane cleavage is the plane along which the slate evenly splits and also forms the floor of the quarries in the Lehigh-Northampton district. Long "runs" in the clear beds may be expected when the cleavage is parallel or subparallel to bedding, as in the limbs of anticlines and synclines. Because the cleavage plane forms the floor of these quarries, it is desirable to mine a recumbent, isoclinally folded, syncline or anticline. Apparently, high-amplitude folds prevail in the Pen Argyl area where most quarry floors are nearly horizontal, bedding is generally near vertical, and little folding is apparent in the quarry faces (Fig. 2). In the Slatedale area the quarry floors are inclined up to 45° as a result of low-amplitude, overturned folds that can be defined in a single quarry face (Fig. 3).

Quarrying techniques have changed little through the years. Channeling machines, which drill holes used to split and free slate blocks, were replaced with wire saws by the early 1930's. The former are still used in freezing weather. The lever and fulcrum are essential tools of mining, as are wing and feather plugs. Blasting, if done, is with small black-powder charges of usually 4 oz or less (A. Dally pers. com., 1984).

Typical benches or drifts measure about 12 ft thick by 14 ft wide and 45 to 65 ft long. The bench size is determined by two parameters: 1) the thickness of the clear bed, and 2) the service life of the steel wire in the saw. After coring 3-ft diameter keyholes at the four corners of a bench to a depth of about 14 ft, the wire saw and its support is placed in these holes to cut the sides of the bench (Fig. 4). The wire saws use standard 1/4" braided wire and the abrasive is a white sand. The homemade core-hole bits and barrels use imported steel shot as the cutting medium. Usually the bench is separated at its base from the bedrock by drilling and wedging. Once separated
from the parent rock there is less chance of accidently damaging the underlying virgin slate. Watersplits (surfaces with weeping moisture) are used where possible as planes along which the slate blocks are removed in layers from the top of the bench. They probably formed along cleavage as a result of unloading. The slabs are further reduced in size by splitting perpendicular to the slaty cleavage along the "grain" or "sculp". This is accomplished by pneumatic drilling and wing and feather plugging in a line usually parallel to the short face of the bench. Freed blocks are wedged with the aid of a lever and fulcrum enough to get a chain underneath for hoisting.

The rough slate stock is hoisted from the hole to the landing, from which a truck transports it to the appropriate mill. The hoisting equipment is generally rated to about 35 tons. The normal slabs are about 4 ft thick, 5 ft long, 6 ft wide and weigh about 6 to 7 tons. All mined slate, both waste and millstock, is generally removed from the hole. Sometimes, if the working hole is contiguous to an abandoned deep hole (up to 850 ft deep), some waste is dumped directly into this hole to avoid hoisting. In the past, mined waste could account for up to 85% of the removed material, and was piled along with mill waste on huge surface dumps. Today, waste is generally limited to not more than about 65% unless stripping overburden. Also, both mill and mine waste are generally dumped in nearby abandoned quarries. Over 400 such abandoned quarries are located in the Lehigh-Northampton district.

Moisture plays an important role in both the mining and milling of slate products. The slate must be kept wet if it is to be split easily and efficiently. Hence, when the humidity is low, exposed benches are covered with wet burlap or straw, which in the winter keeps this moisture from freezing. An idle quarry face or bench, if allowed to dry, can have as much as 3 ft of unusable slate behind it. Conversely, too much moisture is also a problem, especially during winter, when falling ice is a hazard to the quarry workers below. Daily removal of ice buildups consists of excellent marksmanship and occasional black-powder charges for particularly stubborn
Figure 3. The Penn Big Bed slate quarry near Slatedale in the Lehigh-Northampton district.
   a) Showing axial-plane cleavage causing the floors and benches to dip up to 45°.
   b) Anticlinal structure on eastern face.
buildups. An early thaw in February of 1984 required 10 cases of shells with steel shot to remove ice from just one quarry.

**Milling**

Slate products produced in the Lehigh-Northampton mills from the rough stock include flagging, flooring tiles, blackboards, billiard tops, roofing, electrical, and structural slates. Structural slates include products that are used for laboratory and sanitary ware, wall tile, fireplace veneers for hearths and mantels, panels, and sills. Rough slate is transported to the mill, which produces the product for which that block is best suited or as back orders dictate. Roofing slates require rough slate blocks with about 14" between ribbons. Widths less than 14" can be used for flooring tiles. Clear beds are used for electrical, blackboard, and structural products while ribbon stock is used for billiard slates and flagging. Overhead electric cranes generally move the larger slate stock through the mill. Water-cooled diamond saws initially trim waste and cut the quarry slabs into usable "pillars" in most mills. Periodic swabbing of the stock is required to keep it moist. The craft of splitting the pillars usually follows. This splitting, regardless of the end product, is done by hand using hammer and chisel and a great deal of human experience. Normally pillars and subsequent splits are continuously halved until the desired thickness is obtained. Roofing slates are split to 3/16" using this method (Fig. 5). Usually eight roofing slates are split from a single 1.5" thick block called...
Other products require varying thicknesses of stock such as 0.5", 1", and 2". Some products such as roofing, flooring, paneling, and flagging use the natural cleft surfaces and only require trimming to the appropriate size after splitting. Roofing slates are trimmed to standard sizes by a heavy steel-bladed cutter which resembles a huge paper cutter. Some of these trimmers are still treadle-operated. Roofing splitters and trimmers usually work in pairs (Fig. 5), switching duties after lunch. Nail holes are punched by treadle-operated machines.

For some of the thicker slate products, split slates can be gauged to the desired thickness by a planing machine. This machine uses a worm or hydraulic drive and carbide-tipped blade to shave off successive layers of slate to the desired thickness. This shaved surface is used on the underside of some structural slate products to facilitate setting and anchoring.

Traditionally, further gauging and a smoother surface can be provided by rubbing beds (Fig. 6). These 14-ft circular iron tables are rotated in a horizontal plane by wooden gears and provide a "sand-rub" finish that is equivalent to a 60-grit smoothness. Gauging is accomplished by selectively weighting areas of the slate to adjust the thickness. Quartz sand is the abrasive. The rubbing beds are gradually being phased out because of expensive maintenance and low productivity. Italian-made automated diamond planers produce a gauged and honed finish more efficiently. Most billiard slates are finished on this newer type of equipment. Flooring tiles and some other structural products that have a natural cleft finish on the intended exposed surface are gauged to exact thicknesses with smaller diamond honing machines on the backside. Blackboard slates are honed with a diamond- abrasive head and the final writing surface is lapped with a locally manufactured honing stone. This provides a smooth writing surface which, if properly maintained, will last indefinitely.

Low-carbon slate used for manufacturing electrical insulators on transformers, made by both General Electric and Westinghouse, is a growing market. The Diamond run in Pen Argyll produces this slate. Unusual-shaped plates, gauged to exact tolerances (up to .0002"), are bound together and stacked in various configurations to make these insulators. Special machining and care is needed to craft slate for this use.

The mills and quarries generally are operated on a five and one-half day work-week. The mills have no central heating system. Today quarry time is generally from 7:00 AM to 3:30 PM. Worker dedication and productivity are phenomenal. Early retirement is age 65. It is not uncommon to see 80-year-old men still working in the mills.

Marketing

The Structural Slate Company of Pen Argyll is the aggressive marketing arm of both Anthony Dally and Sons and the Pen Big Bed Company. Mr. John Lee, their General Man-
Figure 6. A typical rubbing bed which provides a sand rubbed finish equivalent to a 60-grit smoothness. A white abrasive sand is visible in the hopper on the left.

ager, states that some of the apparent reasons for Pennsylvania's blue-gray slate success are the economics of mining clear beds and attention to quality control. Pennsylvania producers can competitively compete throughout the continental U.S. market. Much lab testing and characterization of its physical and chemical properties by the Pennsylvania industry has shown the superior durability and strength of slate over most manmade composites. Six- to nine-month backlogs in production of roofing slates attest to the demand for a natural fire-resistant roofing material. Furthermore, because of its dark color and easy milling characteristics, passive solar applications of slate should increase in the future. Efforts to find new applications and products assure that Pennsylvania will continue to be a leading slate-producing state.

PEACH BOTTOM DISTRICT

Geology

The idle Peach Bottom slate district is also believed to be mostly Upper Ordovician in age (Berg and others, 1983). It is dark (grayish-black to medium-dark-gray), homogeneous, high-lustre, claystone slate that has a characteristic ring to it when struck. Bedding is difficult to identify and rarely recognized in outcrops or quarries due to the absence of quartzose or carbonaceous interbeds or laminations. Knopf and Jonas (1929) estimated the Peach Bottom Slate to be about 1,000 ft thick. Mineralogically, representative slate samples from the waste dumps contain major mica (probably muscovite), chlorite, and quartz, minor feldspar (such as albite), kaolinite, and trace feldspar such as microcline (L.T. Chubb and R.C. Smith, II pers. com., 1983). Behre (1933) also observed fine-grained andalusite, graphite, pyrite, magnetite, rutile, and zircon in thin section. Trace chalcopyrite and rare galena occur in quartz veins found on the dumps of the abandoned Faulk Jones quarry. A composite of vein samples from this site contains 141 ppm Cu and 304 ppm Pb (A.W. Rose pers. com., 1984).

Structurally the Peach Bottom slate occurs in a tightly folded sequence of rocks
variously described as a south-dipping overturned syncline (Agron, 1950) or the nose of an overturned anticline (Higgins, 1972). The syncline hypothesis generally prevails, but it is complicated by a major fault on the north limb of the structure and poorly understood facies relationships of the underlying Wissahickon Group. Axial-plane cleavage may prevail; however, the absence of recognizable bedding makes this determination difficult. Cleavage in the abandoned quarries is near vertical and presumably subparallel to bedding. Many samples appear to have a lineation on the major cleavage surface.

**Mining**

The mining of slate in the now-idle Peach Bottom district was different from that in the Lehigh-Northampton district due to the relationship between structure and
cleavage (Fig. 7a, b). Here, near-vertical cleavage is apparently subparallel to bedding in a tightly-folded syncline. This near-vertical inclination of cleavage and bedding means mining of the slate was accomplished by prying loose slabs from a near-vertical dip slope. Not only does this appear to be dangerous, but it also produces an uneven quarry floor and is more conducive to development along strike rather than down apparent dip. Long, narrow quarries are typical of the Peach Bottom district. The abandoned "Funkhouser" quarry (Fig. 7a), which was most recently operated by GAF Corporation for roofing granules, is developed for about 4,500 ft along strike. Trucks were the predominant mode of transportation carrying slate from the quarry to the mill. Subhorizontal quartz-filled fractures generally form the floors and benches of most quarries in this district. Some "ironstone" (probably weathered Mesozoic diabase) was reported to have been encountered.

Milling

The Peach Bottom district claimed to have produced one of the best roofing slates in the world. In fact, it was awarded the highest premium at the Crystal Palace exposition in England in 1850 (Behre, 1933). However, the characteristics that make this hard slate so valued as roofing material also led to the demise of the Peach Bottom district. Its apparently higher metamorphic grade and hardness limit its uses. The difficulty and expense of milling cannot economically compete with the Lehigh-Northampton district. Only rough-finished grave vaults and covers, steps, and risers were ever produced in any significant quantity. Common quartz-filled fractures, both cross-cutting and parallel to cleavage, also increase the waste-to-stock ratio.

CONCLUSIONS

Favorable geology and aggressive marketing combine to make slate from the Lehigh-Northampton district competitive in U.S. markets. Demand for various slate products is cyclic and flexibility in mining, milling, and marketing is a key to survival. The current trend away from synthetic products coupled with increased restoration work has increased the value of slate products as well as the relative demand. The mining and milling of slate in Pennsylvania is steeped with tradition. The pride of craftsmanship is exhibited in every hand-finished product. No two pieces of roofing slate are exactly alike. The quarry faces themselves have a unique rhythmic hand-crafted finish (Fig. 7b). Pennsylvania is a leading quality producer of traditional, as well as new, slate products.

ACKNOWLEDGEMENTS

Dr. Robert C. Smith II, of the Pennsylvania Geological Survey provided encouragement, X-ray and mineralogic interpretation, color slides, and was a willing field assistant. Mr. John H. Barnes and Mr. Leslie T. Chubb, also of the Survey, provided laboratory support. In addition, Mr. Barnes critically read the manuscript. Dr. Arthur A. Socolow, State Geologist, initially suggested and supported the project.

We are indebted to Mr. John H. Lee, General Manager, The Structural Slate Company; Mr. Al Dally, Vice President, Anthony Dally & Sons, Inc.; Mr. Orlando Modolo, Quarry Superintendent, Doney No. 2 quarry, Anthony Dally & Sons, Inc.; and Messrs. John and Tom Babyak, President and Vice President, and Mr. Pete Papay, Vice President of Penn Big Bed Company for their enthusiastic cooperation and support.

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CEMENT PRODUCTION AND RELATED RAW MATERIAL CONSUMPTION IN THE MIDDLE ATLANTIC STATES

By
Wilton Johnson
U.S. Bureau of Mines
Washington, D.C.

ABSTRACT

This paper provides an overview of the U.S. cement industry, focusing on that segment of the industry comprising the Middle Atlantic Region, namely the States of Delaware, Maryland, New Jersey, New York, Pennsylvania, and Virginia. It discusses the geographic distribution of the cement industry within the Middle Atlantic States and presents a comparative analysis of the region's share of cement production capacity in relation to that of other cement producing regions and the United States as a whole.

Raw materials are an indispensable part of cement manufacture. The location of plant facilities is dictated by the availability of primary raw materials. The paper addresses raw material requirements for cement production, including the amount and type consumed.

Cement alone has limited utility; however, when combined with certain mineral aggregates, it forms the basis for production of a variety of concrete products critical to the building, public works, and other segments of the construction industry. The paper discusses cement consumption for manufacturing various types of concrete products, drawing comparisons of materials consumed by regions with that consumed nationally.

THE INDUSTRY

The term "cement," in the building and construction trades, denotes a substance that can be used to bind together sand, gravel, crushed stone, or other aggregates into a solid mass. Portland cement is by far the most widely produced cement, representing over 96 percent of total U.S. cement production; masonry cement used for stucco and mortar accounts for the balance.

Portland cement manufacture requires the use of a variety of mined minerals as well as industrial products for use as raw materials. The manufacturing process involves crushing, grinding, mixing, and burning raw materials, in proportioned amounts, in rotary kilns to about 2,700°F (1,500°C) to form a precursor of cement called clinker. The clinker is then ground and mixed with small amounts of gypsum to form finished portland cement.

Regions referred to in this paper are Bureau of the Census regions, except for the Middle Atlantic and South Atlantic, which were modified to correspond to the regions defined for this forum (Figure 1).

The U.S. cement industry, in 1983, comprised 48 companies and one State agency operating 145 plants in 40 States. Annual clinker production capacity in the United States was about 88 million short tons (Table 1). Capacity is determined by maximum output per kiln per day, allowing for downtime for scheduled maintenance and replacement of refractory brick. At the regional level, the Middle Atlantic Region ranked fourth among the nine domestic cement producing regions, with 14 percent of production capacity. Regions having capacities greater than 14 percent were Pacific, 16 percent; West South Central, 16 percent, and East North Central, 15 percent. The State of Pennsylvania ranks...
first in production capacity among States within the Middle Atlantic region and third among the 40 cement producing States. The Middle Atlantic region utilized 92 percent of its capacity, compared with 80 percent utilization by the industry as a whole. Within the region, the four cement producing States had, in descending order, the following percentage capacity utilization: Pennsylvania, 46 percent; New York, 24 percent; Maryland, 14 percent; and Virginia, 8 percent.

U.S. production of finished portland and prepared masonry cement in 1983 was 70 million tons valued at approximately $3.5 billion. Five States: Texas, California, Pennsylvania, Michigan, and Florida, accounted for 44 percent of total shipments by producers. On a regional basis, the Middle Atlantic region ranked second in production with 16 percent of total shipments by producers. The West South Central region ranked first with 19 percent. Producer shipments by other regions were Pacific, 14 percent; East North Central and West North Central, 13 percent and 12 percent, respectively; South Atlantic, 11 percent; South East Central, 8 percent; Mountain, 7 percent; and New England, less than 1 percent (Table 2). Pennsylvania was the larg-
est cement producing State within the Middle Atlantic region and ranked third nationally with 8 percent of total U.S. production. Only Texas and California produced more cement than Pennsylvania, accounting for 14 percent and 11 percent of production, respectively.

**RAW MATERIAL CONSUMPTION**

Typical composition of cement is shown in Table 3. Standards are quite rigorous, requiring careful selection of raw materials. For example, the MgO content must be low, making dolomite and most dolomitic limestone unsuitable.

Various raw materials provide the basic ingredients for production of portland cement (Table 4). Calcareous ores composed primarily of calcium carbonate and argillaceous materials composed primarily of silica comprise more than 90 percent of raw material requirements for cement manufacture in the United States. In instances where essential chemical components needed in the cement raw mixture are not present in the primary raw material in the required amount, other mined minerals or industrial products may be used as additives to correct these deficiencies.

The number and type of raw materials required for cement production depend upon their composition and the type of cement being produced (Table 5). Careful blending and continuous sampling are required to make sure that the desired composition is maintained.

Limestone is the predominant variety of calcareous raw material used to produce cement clinker. Aragonite from shallow marine deposits or coral reefs is an important source of calcareous material. Argillaceous limestone, often referred to as cement rock, is a significant source of calcium carbonate, silica, alumina, and iron oxide, the essential ingredients for cement manufacture. Freshwater marl deposits, oystershell beds, and coral are also important sources of calcareous materials.

Noncalcareous materials required for cement manufacturing are silica, alumina, and iron oxide. Many limestone deposits contain chert, a form of silica, and some contain iron minerals. Sand, quartz, and sandstones are used to maintain the proper silica ratio. Clays and shale are common sources of alumina and silica. Pumice, tuff, and other volcanic materials are used to some extent for their silica and alumina content, together with staurolite and alumina dross. Bauxite is used mostly in high-alumina cements. Iron ore is the predominant source of iron oxide, followed by pyrite, cinders, and mill scale.

<table>
<thead>
<tr>
<th>Region and subregion</th>
<th>Shipments</th>
<th>Percent of total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thousand short tons</td>
<td></td>
</tr>
<tr>
<td>Northeast:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New England</td>
<td>215</td>
<td>0.3</td>
</tr>
<tr>
<td>Middle Atlantic</td>
<td>10,843</td>
<td>15.5</td>
</tr>
<tr>
<td>Total</td>
<td>11,058</td>
<td>15.9</td>
</tr>
<tr>
<td>South:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlantic</td>
<td>7,770</td>
<td>11.1</td>
</tr>
<tr>
<td>East Central</td>
<td>5,445</td>
<td>7.8</td>
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<tr>
<td>West Central</td>
<td>13,615</td>
<td>19.9</td>
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<tr>
<td>Total</td>
<td>26,430</td>
<td>37.9</td>
</tr>
<tr>
<td>North Central:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>9,349</td>
<td>13.4</td>
</tr>
<tr>
<td>West</td>
<td>8,509</td>
<td>11.9</td>
</tr>
<tr>
<td>Total</td>
<td>17,858</td>
<td>25.3</td>
</tr>
<tr>
<td>West:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mountain</td>
<td>5,059</td>
<td>7.3</td>
</tr>
<tr>
<td>Pacific</td>
<td>9,855</td>
<td>13.7</td>
</tr>
<tr>
<td>Total</td>
<td>14,914</td>
<td>20.9</td>
</tr>
<tr>
<td>Grand Total</td>
<td>69,760</td>
<td>100.0</td>
</tr>
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</table>

Source: Bureau of Mines

Table 2. Cement shipments by producing regions, 1983.

<table>
<thead>
<tr>
<th>Region and subregion</th>
<th>Shipments</th>
<th>Percent of total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CaO</td>
<td>64.4 %</td>
</tr>
<tr>
<td></td>
<td>SiO₂</td>
<td>22.2</td>
</tr>
<tr>
<td></td>
<td>Al₂O₃</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>Fe₂O₃</td>
<td>2.9</td>
</tr>
<tr>
<td></td>
<td>MgO</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>SO₃</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Source: The Rotary Cement Kiln Chemical Publishing Co., Inc.

Table 3. Typical composition of cement.
Table 4. Typical composition of raw materials for cement manufacture.

<table>
<thead>
<tr>
<th>Material</th>
<th>CaO</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone (chalk)</td>
<td>52.0</td>
<td>5.7</td>
<td>0.8</td>
<td>0.3</td>
<td>0.4</td>
<td>40.4</td>
</tr>
<tr>
<td>High-Silica Limestone</td>
<td>33.6</td>
<td>36.8</td>
<td>1.8</td>
<td>0.6</td>
<td>0.5</td>
<td>26.4</td>
</tr>
<tr>
<td>Cement Rock</td>
<td>40.0</td>
<td>18.0</td>
<td>5.0</td>
<td>1.5</td>
<td>2.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Blast Furnace Slag</td>
<td>35.5</td>
<td>33.1</td>
<td>9.1</td>
<td>0.9</td>
<td>16.4</td>
<td>2.1</td>
</tr>
<tr>
<td>Shale</td>
<td>3.2</td>
<td>53.8</td>
<td>18.9</td>
<td>7.7</td>
<td>2.2</td>
<td>13.1</td>
</tr>
<tr>
<td>Sand</td>
<td>0.8</td>
<td>70.0</td>
<td>15.0</td>
<td>5.0</td>
<td>0.2</td>
<td>8.6</td>
</tr>
<tr>
<td>Clay</td>
<td>0.5</td>
<td>61.0</td>
<td>16.9</td>
<td>12.4</td>
<td>0.4</td>
<td>7.8</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>---</td>
<td>6.7</td>
<td>1.4</td>
<td>89.7</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Steel Mill Scale</td>
<td>---</td>
<td>2.5</td>
<td>1.1</td>
<td>89.9</td>
<td>---</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Source: The Rotary Cement Kiln Chemical Publishing Co., Inc.

Blast furnace slag may be utilized for its calcium carbonate, silica, and alumina contents. Fly ash is being used increasingly as an argillaceous raw material.

In addition to raw materials used to make clinker, gypsum is added during grinding of the clinker and serves to retard the setting of concrete.

Raw materials 1983

<table>
<thead>
<tr>
<th>Calcareous:</th>
<th>73,075</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limestone (includes aragonite, marble, chalk)</td>
<td></td>
</tr>
<tr>
<td>Cement rock (includes marl)</td>
<td>21,644</td>
</tr>
<tr>
<td>Oystershell and coral</td>
<td>2,030</td>
</tr>
<tr>
<td>Argillaceous:</td>
<td>5,736</td>
</tr>
<tr>
<td>Clay</td>
<td></td>
</tr>
<tr>
<td>Shale</td>
<td>3,011</td>
</tr>
<tr>
<td>Other (includes staurolite, bauxite, aluminum dross, pumice, alumina, volcanic material, other)</td>
<td>118</td>
</tr>
<tr>
<td>Siliceous:</td>
<td>1,669</td>
</tr>
<tr>
<td>Sand and calcium silicate</td>
<td></td>
</tr>
<tr>
<td>Sandstone, quartzite, other</td>
<td>691</td>
</tr>
<tr>
<td>Ferrous: Iron ore, pyrites, millscale, other iron-bearing material</td>
<td>1,058</td>
</tr>
<tr>
<td>Other: Gypsum and anhydrite</td>
<td>3,498</td>
</tr>
<tr>
<td>Blast furnace slag</td>
<td>49</td>
</tr>
<tr>
<td>Fly ash</td>
<td>870</td>
</tr>
<tr>
<td>Other, n.e.c.</td>
<td>103</td>
</tr>
<tr>
<td>Total</td>
<td>113,528</td>
</tr>
</tbody>
</table>

Source: U.S. Bureau of Mines

Table 5. Raw materials used in producing portland cement in the U.S.
production, and fifth in gypsum production.

In 1983, the U.S. cement industry consumed 119 million short tons of raw materials to produce 70 million tons of finished portland and prepared masonry cement. On a regional basis, the Middle Atlantic region consumed 15 percent of raw materials used by the industry, second highest among all regions.

Within the Middle Atlantic Region, Pennsylvania had 55 percent of the plants and consumed 50 percent of the raw material used by the industry. On a state-by-state basis, Pennsylvania ranked third among the States, consuming 8 percent of raw materials consumed nationally. Only Texas and California consumed more raw materials than Pennsylvania.

**CEMENT MARKETS**

Cement alone has limited utility; however, when combined with mineral aggregates, it can be used for a variety of products critical to the building, highway, and various other segments of the construction industry. Cement is marketed throughout the United States. The bulk of the consumption in 1983 was concentrated in the West South Central part of the country, which received 21 percent of total U.S. shipments, followed by South Atlantic, 15 percent; Middle Atlantic, 14 percent; East North Central and Pacific, 12 percent each; West North Central and Mountain, 8 percent each; East South Central, 6 percent; and New England, 4 percent (Table 6).

More than two-thirds, 69 percent, of cement consumed in 1983 was used to produce ready-mixed concrete, the most widely used construction material. There are more than 5,000 ready-mix concrete establishments in the United States serving the Nation's building and public works construction needs. The second largest user of cement, concrete product manufactures, used 12 percent, to make concrete blocks, concrete pipe, prestressed precast concrete, and other concrete products. Direct shipments to highway contractors and building material dealers accounted for 11 percent, and the remainder was shipped to government agencies and other miscellaneous users.

Construction sand and gravel is the most prevalent and economical source of aggregate material used with cement to produce ready-mixed concrete and concrete products. In 1983, approximately 666 million tons of construction sand and gravel was produced in the United States. Of this amount, 286 million tons, or 43 percent, was sold or used for production of concrete or concrete products. The Middle Atlantic States ranked sixth among geographic regions, both in total U.S. production of construction sand and gravel, and in the sale or use of this material by the building and public works construction industry to produce concrete and concrete products.

Cement and concrete are used extensively in all types of construction activity. Residential building, commercial building, and street and highways construction are primary markets. Public building, farm construction, water and waste, utilities, other public works, oil wells, mining, etc., are other final markets for cement products.
GEOLOGY AND MINING OF GYPSUM IN VIRGINIA

Roger D. Sharpe
United States Gypsum Company
Chicago, Illinois

ABSTRACT

Gypsum has been mined in southwestern Virginia since the early 1800's. Originally, gypsum was mined from quarries and shallow underground workings and was used for soil conditioning and construction plaster products. The Buena Vista Plaster Company operated a calcining plant, shallow underground mines, and quarries in Plasterco, Washington County, in the late 1800's and early 1900's. The United States Gypsum Company leased the Buena Vista operation in 1909, and purchased it in the 1920's. The underground workings were deepened as the shallow gypsum deposits became depleted. The No. 6 Mine was operated from 1911 to 1979, and was the deepest gypsum mine in the world. Gypsum was mined on 16 levels to a depth of about 1,420 feet (433 m). Exploration for additional reserves began in the late 1930's. A mineable deposit was identified in the same geologic formation and structure about 18 miles (29 km) northeast of Saltville. The Locust Cove Mine began production in 1964 to supplement the No. 6 Mine. Due to declining reserves and increasing mining costs the No. 6 Mine was closed in 1979. Since then, all production has come from the Locust Cove Mine. The gypsum is transported to the Plasterco Plant to be processed into various wallboard products. The Locust Cove Mine is the only active gypsum mine in Virginia.

The Locust Cove Mine is a multi-level, modified room and pillar, cut and fill operation producing approximately 250,000 tons (227,300 t) per year. Gypsum has been mined on five levels and several sublevels to a depth of about 450 feet (137 m). Currently, declines are being driven to reach the sixth level, 550 feet (168 m) below the surface.

The gypsum at Locust Cove occurs in the Mississippian Macracy Formation which is divisible into three units, in ascending order: (1) distal alluvial fan deposits - mudstone, siltstone, and sandstone overlying shallow marine and fluvial-deltaic clastic sediments of the Price Formation; (2) inner shelf carbonates - finely laminated algal limestone and dolomite with abundant brachiopods; and (3) tidal flat sediments and mudflow deposits (mud-rich sabkha) - conglomeratic mudstone, siltstone, and argillaceous limestone, with minor evaporites. Economic gypsum occurs only in the lower portion of the mud-rich sabkha deposits.

The depositional model for the Locust Cove deposit is a mud-rich sabkha environment, similar to that found today where the Colorado River flows into the Gulf of California. Primary nodular gypsum and anhydrite were deposited by diagenetic interstitial displacement of muddy tidal flat sediments in a hot, arid climate. Minor laminated gypsum was probably deposited in shallow salt pans on the tidal flat. Lenticular evaporite bodies, locally called "boulders", were stratigraphically separated by and interfingered with conglomeratic mudstones, representing episodic mudflows from nearby highlands.

The dominant geologic structure is the Locust Cove Syncline, an asymmetric, overturned, southwest plunging extension of the Greendale Syncline. The southeast limb is steeply dipping to overturned and modified by shearing and faulting. Most mining occurs along the southeast limb where the gypsum bodies have been compressed and stacked by plastic flow during deformation. The driving force for deformation was the development of imbricate thrust sheets in a decollement zone in
INTRODUCTION

The Saltville area, in Smyth and Washington Counties, Virginia (Figure 1) has been an important source of gypsum and salt for over 200 years. The history of gypsum production is interwoven with the history of salt production. Gypsum was discovered during exploration for salt deposits in the early 1800's.

During the Pleistocene Epoch many animals were attracted to the natural salt seeps and springs around the Saltville Valley. The broad valley is underlain by soft gypsum and salt-bearing rocks of the Mississippian Macrady Formation. Overlying these rocks are gravel beds and clay layers deposited during the Pleistocene Epoch by the ancestral Saltville River (McDonald and Bartlett, 1983). Abundant vertebrate fossils have been found at the contact between the clay and gravel layers, making the Saltville Valley one of the most important paleontological sites in the eastern United States.

Salt was produced by Indians from springs surrounding the valley as late as the 1760's (Kent, 1955). Commercial production of salt began around 1790, by sinking shallow wells and shafts into the Macrady Formation. Natural brines flowed into the wells and were evaporated in pans and kettles over wood or coal burning furnaces. The salt produced in the valley was used primarily in food preservation.

During the Civil War, Saltville was the only source of salt for the Confederate states. Salt furnaces were operated by the individual states and the salt was shipped on flatboats on the North Fork of the Holston River. Several skirmishes were fought near Saltville over control of the furnaces.

In 1893, two of the major salt operations were sold to the Mathieson Alkali Works, the forerunner of the Olin Corporation. Alkali products, such as sodium carbonate, sodium bicarbonate, and sodium hydroxide were manufactured at the Saltville plant until the early 1970's. Chlorine, carbon dioxide, and hydrazine were produced as byproducts.

Early Mining History

The first discovery of gypsum in the Saltville area is unrecorded, since few historical records exist on early gypsum production. The first exploration hole was drilled about 1818. Rogers (1836) discussed the great possibilities of gypsum in southwest Virginia as a source of fertilizer. He described the deposits as great detached masses of gypsum distributed along the Holston River for a distance of 40 miles (64 km). Several holes were drilled in the Plasterco area during the period 1847 to 1854, to depths of 400 to 600 feet (122 to 183 m).

Shafts were sunk following the discovery of gypsum bodies by drill holes. Gypsum was mined by enlarging the shaft and driving drifts when a thick section of gypsum was encountered. Old mine maps show numerous shallow shafts, some of which are believed to be the original exploration workings.

Numerous shallow gypsum deposits, known as "plaster banks", were operated on a small-scale by local farmers and land owners. The gypsum was sold to farmers for land-plaster, which was used to "sweeten" or condition the soil. Agricultural gypsum is still produced, but represents a small portion of the end-use of gypsum. Stevenson (1885) reported that in 1880, gypsum was being mined and processed by four companies in Smyth and Washington Counties.

In 1870, a water-powered gypsum mill was constructed on the Robertson property in Washington County (now the U. S. Gypsum Plasterco property), approximately one mile (1.6 km) from Saltville. The mill was operated by the Buena Vista Plaster Company, which was organized by local land owners to produce land-plaster and calcined gypsum plaster products.

The Buchanan plaster bank was located...
was mined from the Macrady Formation over a strike length of more than 12,000 feet (3,659 m) on 16 levels.

Prior to 1911, gypsum was mined from numerous quarries and shallow underground mines around Plasterco. The No. 1 to No. 4 Mines were relatively small operations. In 1921, the No. 6 Mine flooded and was subsequently abandoned. The No. 7 and No. 8 Mines were opened to supply gypsum to the newly constructed wallboard plant. In 1924, the No. 6 Mine was dewatered and refurbished.

GEOLOGY

Structure

The gypsum deposits in southwest Virginia are located in the Ridge and Valley Province of the southern Appalachians. The region is characterized by elongated belts of Paleozoic sedimentary rocks cut by numerous parallel thrust faults. The gently to steeply dipping thrust faults coalesce at depth to form a master decollement or detachment fault zone near the sediment-basement contact (Harris and Milici, 1977). The major geologic structures in the Saltville-Locust Cove area are the Saltville Fault and the Greendale-Locust Cove Syncline complex.

Saltville Fault

The Saltville Fault is a major thrust fault with stratigraphic displacement of over 16,000 feet (4,878 m). It extends for about 450 miles (720 km) from Alabama to west-central Virginia and has displaced Cambrian and Ordovician rocks over Mississippian rocks of the Greendale-Locust Cove Syncline complex. The dip of the fault plane is variable, ranging from less than 20° to 60°.

Greendale-Locust Cove Syncline

The Greendale Syncline is a doubly-plunging, asymmetric structure on the footwall of the Saltville Fault. The attitude of the axial plane is variable, from upright to overturned to the northwest. The southeast limb of the syncline is partly truncated by the Saltville Fault. At Plasterco, the Mac-
crady Formation was pinched upward between the carbonates in the core of the syncline and the hanging wall of the thrust fault. Gypsum and salt were concentrated below the fault plane by brecciation and plastic flow of the Maccrady Formation.

The Locust Cove Syncline is a smaller structure within the Greendale Syncline, extending approximately 8 miles (13 km) southwestward from Locust Cove (Muangnoicharroen, 1978). The axial plane attitude is highly variable from upright to overturned and the southeast limb has been truncated by thrust faulting. The syncline is bounded on the southeast by an anticline whose axial plane steepens and eventually becomes a thrust fault to the northeast of the current mine workings (Figure 2). Deformation within the Locust Cove Syncline was not homogeneous, but varied from ductile to brittle.

Stratigraphy

The gypsum resources of Virginia occur in the Mississippian Maccrady Formation, consisting of mudstones, carbonates, coarse clastics, and evaporitic minerals including gypsum, anhydrite, and halite. In the Saltville-Locust Cove area, the Maccrady Formation is up to 2,000 feet (610 m) thick, but thins both northeastward and southwestward. The Maccrady Formation crops out on both limbs of the Greendale Syncline. Outcrops on the northwest limb are relatively thin and poorly exposed. On the southeast limb, the Maccrady Formation has been greatly thickened by deformation associated with the Saltville Fault. At Locust Cove, the overlying Mississippian carbonates have been eroded or planed off by thrusting, and the bulk of the Maccrady Formation is exposed in the core of the Locust Cove Syncline (Figure 3).

The Maccrady Formation is underlain by the Price Formation, a thick sequence of fluvial-deltaic to shallow-marine clastics. The contact between the Price and the Maccrady Formations is gradational and represents a transition between a hot, humid climate to a hot, arid climate with the development of a mud-rich sabkha environment. To the southwest of Saltville, the Greendale Syncline contains up to 7,000 feet (2,134 m) of Upper Mississippian carbonates overlying the Maccrady Formation (Butts, 1940).

Depositional Model

The Maccrady Formation was deposited in a mud-rich sabkha environment. "Sabkha" is an Arabic term for a wide tidal flat complex developed along a coastline in a hot, arid region. Evaporites are deposited in the sabkha by diagenetic precipitation and growth within the wedge of tidal flat sediments near

Figure 2. Cross-section of the Locust Cove Syncline northeast of the present mine workings. Gypsum deposits are depicted by cross-hatching.
the water table elevation. The Maccrady Formation consists of four distinct stratigraphic units, of which only three are exposed at Locust Cove, but all four are exposed in the No. 6 Mine. The units, in ascending order are: (1) wadi plain deposits, (2) inner shelf carbonates, (3) mud-rich sabkha deposits, and (4) the footwall gypsum.

Wadi Plain Deposits

The lower portion of the Maccrady Formation consists of grayish-red and grayish-green shale, siltstone, and sandstone. The lower contact of the Maccrady is the base of the lowest red siltstone unit above the predominately gray and green shales and sandstones of the Price Formation. The elastic rocks were deposited as distal alluvial fan deposits that interfinger with the sabkha facies and the inner shelf carbonates. The sediments were deposited from ephemeral, discontinuous braided streams that flowed over the far reaches of alluvial fans. Clays were deposited in flooded interchannel depressions forming shale units. Sandstone units are thick bedded and were deposited by flooding of stream channels.

Inner Shelf Carbonates

Inner shelf carbonates were deposited as lime muds in the subtidal zone seaward of the sabkha. Two to three carbonate units are interbedded with grayish red siltstone and shale. The carbonates are medium gray, finely crystalline, finely laminated, and contain abundant brachiopods. Bedding is defined by carbonaceous laminae, representing subtidal algal mats.

The inner shelf carbonates form a major aquifer and define the lower mining limit of gypsum in the Locust Cove Syncline. The carbonates have undergone considerable post-depositional alteration and the development of secondary permeability and porosity.

Mud-rich Sabkha

The thickest part of the Maccrady Formation represents a mud-rich coastal sabkha environment. Within this unit are several thick lithologic units, with a combined thickness of up to 1,240 feet (378 m). The upper part of the mud-rich sabkha consists of soft, grayish red mudstones forming the core of the Locust Cove Syncline. The mudstones are comparable to red beds found in Permian sabkha complexes in the Texas Panhandle (Handford and Fredericks, 1980). Gypsum occurrence within the red mudstones is limited to satin spar veins. The lower part of the mud-rich sabkha contains the gypsum deposits that were mined in the "boulder zone" at the No. 6 Mine and at the Locust Cove Mine. The predominant lithologies are conglomeric mudstone, argillaceous limestone, and gypsum. Coarse clastics and anhydrite occur in minor proportions. The conglomeric mudstones are grayish green to grayish red, slightly calcareous, and contain pebbles of mudstone, siltstone, and gypsum. The mudstones represent periodic mudflows across the sabkha surface from nearby alluvial fans. Water rushing over the surface ripped up fragments of semi-consolidated mud, sand, and gypsum, then transported and deposited the material on the tidal flat surface.

Argillaceous limestone is the next most abundant lithology. The limestones are light gray, micritic to finely crystalline, poorly bedded, and slightly dolomitic. Gypsum is nearly absent except for secondary vein fillings of satin spar and poikilitic cement. One limestone unit has been identified to be a major artesian aquifer within the Locust Cove Mine.

Gypsum and anhydrite were deposited as diagenetic minerals within the tidal flat sediments. The sabkha is a wide, flat topographic surface whose elevation is controlled by the local ground water table (Kinsman, 1969). Ground water moves by capillary action through the sediments above the water table. Recharge occurs by lateral movement of seawater through the tidal flat wedge and periodic storm flooding.

Evaporation from the sabkha surface causes the interstitial pore fluid composition to change. Aragonite, gypsum, and anhydrite begin to form as the interstitial brine becomes supersaturated with respect to calcium. Gypsum is precipitated in the intertidal zone. Poikilitic gypsum may also form within supratidal sediments. Anhydrite forms in the supratidal zone near the ground water table. Primary anhydrite as well as anhydrite
pseudomorphs after gypsum are precipitated in the supratidal zone. Clastic or carbonate impurities are pushed aside during the precipitation of gypsum and anhydrite forming the characteristic "chicken wire" mosaic of nodular evaporites. Unless diluted by storm surges or increased ground water flow, the brine eventually becomes supersaturated with respect to magnesium and dolomitization of the carbonates begins to occur.

Gypsum and anhydrite underwent post-depositional alteration and deformation to form what is known as the "boulder zone". Lenticular bodies of gypsum and anhydrite were deformed, folded, and thickened by plastic flow during the formation of the Locust Cove and Greendale Synclines and the thrusting along the Saltville Fault. Economic gypsum deposits occur where the evaporite bodies were compressed and stacked during deformation. The evaporites are thoroughly mixed with the conglomeratic mudstones and limestone in a fashion similar to a marble cake. Many of the mudstones have a significant proportion of gypsum as poikilitic cement and satin spar veins. Many of the gypsum bodies have cores of anhydrite. Thrusting of Cambrian rocks over the Maccrady Formation buried the gypsum, which dehydrated to form anhydrite. Uplift and erosion of the overlying thrust sheet allowed ground water to percolate through the Maccrady Formation, re-hydrating the anhydrite to again form gypsum.

**Footwall Gypsum**

A thick bed of gypsum, known as the "footwall seam" occurs at the top of the Maccrady Formation in the No. 6 Mine. The footwall seam is up to 50 feet (15.2 m) thick and was mined to a depth of 1,420 feet (433 m) where it grades into anhydrite. The footwall seam represents a shallow subtidal gypsum deposit, overlain by a thick carbonate sequence. The footwall seam is absent at the Locust Cove Mine.

**UNITED STATES GYPSUM COMPANY**

In 1909, the mill and properties of the Buena Vista Plaster Company were leased by the U.S. Gypsum Company. Construction of a two-kettle calcining mill began in 1912, and it was in operation in 1913. A gypsum block plant was constructed in 1914. In 1923, the entire operation was purchased from the
Buena Vista Plaster Company. Construction began immediately on a wallboard plant with one board machine producing gypsum lath products. The new wallboard plant was put into operation in 1924.

A major expansion of the Plasterco Plant was completed in 1979. Products that have been manufactured at Plasterco include construction plasters, wallboard, lath, portland cement retarder (anhydrite), industrial binders, and agricultural gypsum.

The Plasterco Plant is a modern low-cost operation. The three major segments of the operation include the mine, mill, and wallboard plant.

Locust Cove Mine

Around 1940, exploration for additional reserves in the Saltville area was initiated. Deposits were examined northeast and southwest of Plasterco. A deposit was identified at the old Buchanan plaster bank in the Locust Cove area (Figure I). Development of the Locust Cove deposit did not begin until late 1960, and the mine went on-stream in April of 1964. From 1967 to 1971, the Locust Cove Mine was inoperative and all gypsum production came from the No. 6 Mine. Both mines were in operation from 1972 until 1979. In 1979, due to increasing mining cost and declining reserves, the No. 6 Mine was closed permanently. Since 1979, all gypsum production has come from the Locust Cove Mine.

The Locust Cove Mine is a multi-level operation producing approximately 250,000 tons (227,300 t) of gypsum per year. The gypsum deposit has been mined on five levels to a depth of 450 feet (137 m). Declines are currently being driven to reach the sixth level elevation, 550 feet (168 m) below the surface. The first through fourth levels are spaced at 75-foot (23 m) intervals, which was the traditional spacing used at Plasterco. Below the fourth level the levels are spaced at 100-foot (30 m) intervals. The levels are connected by declines, facilitating the movement of equipment and personnel. A service decline connects the mine to the surface.

The gypsum is mined by a modified cut and fill method. An initial cut is made into a gypsum body about 15 feet (4.6 m) high and up to 50 feet (15 m) wide. The floor of the drift is then mined to a depth of about 25 feet (7.6 m) and backfilled with mine development waste. Sublevels are developed between the main levels.

Faces are drilled for blasting with single- and double-boom auger drills. A slab round blasting pattern is used. Blast holes are pneumatically loaded with Anfo. Rounds are detonated by cap and fuse with dynamite as a primer. The broken gypsum is mucked out by four Eimco 915 load-haul-dump units (LHD) with 6-cubic yard (4.6 cubic meters) capacity. One Wagner 2-cubic yard (1.5 cubic meters) LHD is also used. The rock is hauled to two crushing facilities by LHD, two Wagner 20-ton (1.8 t) telescoping bed trucks, and one Elmac 20-ton (18.1 t) dump truck.

Gypsum is crushed underground and transported by conveyor belt to the surface for storage in a 400-ton (364 t) bin. A contract fleet of 16-ton (14.5 t) dump trucks transports the gypsum to the Plasterco Plant, 18 miles (29 km) to the southwest. A stationary McLanahan Rockmaster 30-inch (76 cm) diameter by 48-inch (122 cm) single-roll crusher is located on the fourth level. The crusher is fed by two transfer raises from the second and third levels. Until 1982, all of the gypsum had to be transported by LHD or rock truck from the lower levels up to the third level to dump into a transfer raise. However, in 1982, an Ingersoll-Rand (S & S) feeder-breaker was installed on the fourth level near the main crusher. As mining progresses downward, the feeder-breaker will be moved to lower levels to shorten the haulage distance.

Roof support is provided by 6-foot (1.8 m) resin bolts installed by a Secoma roof bolter. The mudstones of the Maccrady Formation are very soft and difficult to support when wet. When necessary, wire mesh and steel straps are used to give additional roof support. Development heading cross-sections are kept as small as possible. The gypsum is much more competent than the mudstones and much wider headings can be opened with little roof support.

Two 100,000-cubic foot/min (47 cubic meter/sec) Joy axial-vane fans located on the surface supply fresh air to the mine through
a 592-foot (180 m) deep shaft. Portable fans are used to distribute air through ventilation tubing on the various mining levels.

Gypsum bodies are located by drilling a fan-shaped pattern of exploration holes using air-track rotary drills. Recently, a Fletcher hydraulic longhole exploration drill was put into service. The method of drilling is similar to that used for many years in the No. 6 Mine. Holes are drilled on 156 azimuth intervals for up to 400 feet (122 m). The holes are drilled horizontally and at attitudes of 15° and 30° upward and downward. The cuttings are collected in a cyclone and if gypsum is identified, then a sample is collected for chemical analysis. Exploration drilling is also used to delineate the two major aquifers in the mine.

**Mill**

Mine run gypsum is stored on a stockpile. Grade control of gypsum purity is maintained by stockpile blending with a dozer, wheel loader, and a slusher dragline. The slusher feeds the secondary crusher, a 36-inch by 48-inch (91 cm by 122 cm) Jeffrey hammer mill which reduces the gypsum to minus 0.5 inch (1.3 cm). The rock is then dried in a 6-foot by 38-foot (1.8 m by 11.6 m) coal-fired, rotary dryer. The dried gypsum passes to a bank of four 50-inch (127 cm) Raymond mills, which grinds and air classifies the gypsum to what is called "landplaster". Landplaster is collected by four cyclones, stored in bins, then fed into four calcining kettles. These are 12.5-ton (11.3 t), coal-fired, continuous calcining kettles, one of which uses an experimental coal pulverizer. In the calcining process, gypsum is partially dehydrated to the hemihydrate state, producing what is known as "stucco" or Plaster of Paris. The chemical reaction during calcining is shown below:

\[
\text{CaSO}_4 \ 2\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot \text{H}_2\text{O} + \text{H}_2\text{O}
\]

Upon leaving the kettles the stucco is stored in hot pits where the dehydration process is completed and the material cools. The stucco then travels by screw conveyor more than 900 feet (274 m) to the stucco mixing machine which prepares the stucco slurry.

**Wallboard Plant**

The Plasterco Plant is one of the oldest, yet one of the most modern gypsum wallboard plants in the United States. Wallboard is made by spreading a slurry of stucco paste between two continuous sheets of paper. The paper is made by paper mills operated by U.S. Gypsum in several states. Most of the wallboard covering is made from recycled paper. The stucco paste is formulated in a mixing machine to control setting characteristics and the type of board being manufactured. The wallboard manufacturing process is controlled by a process computer and five programmable controllers located at critical points along the board line. The computer monitors stucco mixing parameters, board speed, kiln temperature, and other operational data. Each shipment of wallboard can be traced back to the original mixing data to aid in quality control of the finished product. Until the late 1960's, all products were shipped from Plasterco by rail. Today, all products are shipped by truck.

The continuous wet paper - stucco sandwich travels 800 feet (244 m) along a conveyor belt to the knife and inverter section. While traveling on this path, the stucco begins to hydrate and recrystallize to gypsum. At the knife and inverter, the continuous stream of wallboard is cut into 8- to 12-foot (2.4 to 3.7 m) lengths and the direction of travel reversed. The semi-set, but wet wallboard then travels through the kiln section to drive off excess moisture and complete the recrystallization process. The 12-deck, double-wide kiln is steam-heated and 420 feet (128 m) long. Steam for heating the kiln is produced by three coal-fired boilers. This is the only steam-heated wallboard kiln in the U.S. Gypsum system. The coal comes from a low-sulfur source approximately 30 miles (48 km) from the plant.

Wallboard exiting the kiln goes to a bundling and stacking section and then to the warehouse. The finished products can be delivered generally within 24 hours after the order is placed. The Plasterco plant serves a market radius of 350 to 400 miles (560 to 640 km). It is a specialty wallboard plant producing a number of products for both residential and commercial use. Wallboard is produced in 2- and 4-foot (0.6 and 1.2 m) widths and in lengths from 8 to 12 feet (2.4 to 3.7 m).
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MARYLAND'S CARBONATE ROCKS: ALPHA AND OMEGA

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ABSTRACT

Thick sequences of marbles, limestones, and dolostones, mainly of Paleozoic Age (570-230 million years ago), are found at or near the surface in Maryland from the Fall Line west. These rocks are quarried throughout the state for crushed stone, agricultural and hydrated lime, Portland cement, and specialty products, and were sources of building stone. From Frostburg to Frederick, limestone and dolostones almost always contain a well-preserved suite of sedimentary features including reefal bioherms, ooid shoal deposits, and mudcracked tidal-flat sequences indicative of shallow peritidal depositional environments in tropical seas. These rocks have been deformed at least once. In contrast, between Frederick and the Fall Line, metasedimentary marbles are found which contain poorly preserved sedimentary features but no fossils. These marbles have suffered polyphase deformation and their depositional settings are unknown.

Thin, discontinuous beds of semiconsolidated to unconsolidated skeletal sediment, mainly of Late Mesozoic and younger ages (65 million years to present), occur sporadically throughout the Coastal Plain lowlands. These are of historic interest.

INTRODUCTION

Limestones are sedimentary rocks composed mostly of the mineral calcite, and dolostones are sedimentary rocks dominantly composed of the mineral dolomite. In both the minerals calcite and dolomite the essential structural unit is the carbonate ion. Thus, limestones, dolostones and mixtures of the two are commonly referred to as carbonate rocks, or more simply, carbonates. Marble is a metamorphosed limestone or dolostone that has been so totally recrystallized due to elevated temperature and pressure that the original sedimentary or biologic fabrics have been destroyed. Marbles have an interlocking crystalline mosaic of calcite and/or dolomite. Although the term carbonate is usually restricted to the sedimentary limestones and dolostones, in this paper marbles are considered carbonates as well.

The limestones, dolostones and marbles of Maryland support healthy industries. A substantial portion of the 16.9 million tons of crushed stone produced last year in Maryland was crushed carbonate. Ninety million dollars worth of cement from three Portland and two masonry cement plants, and 7,000 tons of hydrated lime from one plant were produced in 1983. The Genstar Plant at Texas, Maryland, one of the largest crushed stone operations in the U.S., also produces pure calcite for industrial use.

A comprehensive review of Maryland's carbonate rocks and carbonate-rich unconsolidated sediments (shell beds, marls, etc.) is beyond the scope of this paper. For this, the reader is referred to Mathews and Grasty (1909). The purposes of this paper are: 1) to show the distribution of carbonate rocks in Maryland, 2) review the geologic setting of these deposits, and 3) to briefly consider their origin.

DISTRIBUTION

Figure 1 is a summary of the distribution of carbonate rocks at the surface today in Maryland, and some of the localities where they are extracted.
GEOLOGIC SETTING

The base map for Figure I is a simplified geologic map of the State. Maryland can be divided into four geologic terranes: sedimentary Appalachians, Mesozoic Basin, crystalline Appalachians, and Coastal Plain.

Although each terrane contains carbonate rocks or carbonate-rich unconsolidated sediments, the most widespread and important deposits are found in the sedimentary and crystalline Appalachians. These are separated by deposits of Mesozoic red shales and sandstones that contain conglomerates of limestone pebbles. The Mesozoic limestone-pebble conglomerates were used as a dimension stone known as "Potomac Marble". To the east (Fig. 1), the crystalline Appalachians are bordered by unconsolidated, flat-lying sands, gravels and muds of the Coastal Plain. Modern and ancient oyster shell beds, and some carbonate-rich marl beds have been sources of lime and aggregate here. The carbonate-pebble conglomerates of the Mesozoic Basin and the carbonate-rich unconsolidated sediments of the Coastal Plain will not be considered further.

By far the most important and widespread deposits are the carbonate rocks of the sedimentary and crystalline Appalachians (Fig. I).

The sedimentary Appalachians are composed of over 10,000 m of flat lying to moderately deformed and folded shales, sandstones, limestones and dolostones. These rocks range in age from latest Precambrian (700 million years B.P.) to Permian (230 million years B.P.). This thick pile sits upon a granitic basement that is roughly 1000 million years old and is a remnant of an earlier pre-Appalachian mountain belt, the Grenville Range. Within the sedimentary Appalachians, the degree of deformation increases from west to east and in Maryland appears to be the result of one coaxial deformation.
The crystalline Appalachians include some limestones and dolostones but are mostly low- to very high-grade metasedimentary rocks. These include phyllites, schists, gneisses, marbles, and quartzites. Metavolcanic rocks, granitic intrusive rocks, and thrust sheets of ultramafic rocks are also found. Rocks of the crystalline Appalachians are severely deformed and, as in the sedimentary Appalachians, deformation increases from west to east. These rocks also rest upon Grenville age granitic basement. Unlike the Maryland sedimentary Appalachians, the crystalline Appalachians show a multiple, complex deformational history. Ages of the metasedimentary rocks of the crystalline Appalachians are not precisely known, but probably range from about 700 to 400 million years B.P. Thus, these metasediments are equivalent to at least part of the geologic section in the sedimentary Appalachians.

Figure 2 is a restored NW-SE section of the crystalline and sedimentary Appalachians from Colton (1970), Fisher, Higgins & Zietz (1979), and Edwards (1984). This cartoon roughly depicts the pre-deformational and pre-metamorphic geometry of the rocks now exposed at the surface. Thicknesses of the rocks in the sedimentary Appalachians are relatively well known. However, the thicknesses of metasedimentary units in the crystalline Appalachians are not well known and may be in substantial error.

There are three sequences of carbonate rocks found in the sedimentary and crystalline Appalachians: 1) Lower Cambrian (560 million years B.P.) to Middle Ordovician (470 million years B.P.) sequence, 2) Upper Silurian (400 million years B.P.) to Lower Devonian (390 million years B.P.) sequence, and 3) Mississippian (330 million years B.P.) sequence (Fig. 2). Table I gives the formation names and (where known) thicknesses that comprise the various sequences. Moving up-section, the carbonate sequences become thinner and less widespread. Figure 2 illustrates the vast reserves of carbonate rocks in Maryland. Virtually all of the units listed in Table I have been quarried or mined at some point.

**ORIGIN OF MARYLAND'S CARBONATE ROCKS**

Our understanding of ancient carbonate rocks is based on the concept of Ginsburg (1974) termed "comparative sedimentology". Comparative sedimentology is using modern carbonate sediments to understand ancient carbonate rocks.

The largest and thickest areas of modern carbonate deposition are on shallow marine shelves in tropical areas. Modern marine carbonates are almost wholly biogenic, and warm shallow seas are where carbonate se-
creting organisms flourish, especially the important lime-mud producing green algae. These shallow shelves or banks are composed of (Fig. 3): an extensive shallow platform, a narrow edge or margin, and a relatively steep slope that grades out into a basin (Wilson, 1975; Ginsburg and James, 1974; James and Ginsburg, 1979; Flugel, 1982). These bank systems can be quite large. The shallow platform of the Great Bahama Banks covers over 100,000 km² and is nowhere greater than 10 m deep.

We can compare this modern system to the ancient one at three different scales. First, we can compare thin sections and hand samples of epoxy-impregnated, modern sediments directly to thin sections and hand samples of ancient rocks. Secondly, we can compare excavated trench walls or closely-spaced cores of modern sediments to ancient outcrops. Finally, we can compare the regional "big picture" of a large present day area to formations within an ancient depositional basin.

The shallow platform is divisible into two environments: the shelf lagoon environment and the tidal flat environment.

The shelf lagoon environment is wholly subtidal and is generally a few meters to 10 meters deep. A number of sub-environments make up the shelf lagoon environment. These include shoals of carbonate sand of tidal and/or wave origin, patch reefs, and uniform mud bottoms. The deposits of the shoals are well-sorted ooid, skeletal, or peloidal sands that are internally cross-stratified. The patch reefs are organically-built frameworks of encrusting organisms surrounded by sands derived from the breakdown of organisms living on the reefs. The deposits of the mud bottom are lime muds with scattered shells of infaunal organisms. Mud bottoms host a prolific burrowing infauna which totally homogenize the sediment. Organisms which produce tremendous amounts of carbonate sand and mud live in all three shelf lagoon subenvironments. James (1979a) has referred to the shallow shelf lagoon as a "carbonate sediment factory" capable of producing enough sediment to keep up with even the most rapid sea-level rises (Schlager, 1981). This ability of shallow shelf lagoons to produce vast amounts of sediment, and to stay at or near sea level accounts for the vast thicknesses of carbonate rocks in the geologic record.

The tidal flat environment contains intertidal and supratidal mudflat environments. These mudflats are commonly covered by a blue-green algal mat that imparts a distinctive stromatolitic or cryptalgal lamination to the sediment. In addition, the cryptalgal deposits of these mudflats often carry desiccation mudcracks due to subaerial exposure at low tide. The source for the lime mud that accumulates in the tidal flats is the adjacent shallow subtidal shelf lagoon. As mud is carried onto and dumped in the tidal flats, they build out (or prograde) over the adjacent shelf lagoon deposits. In ancient carbonate sequences, this progradation is recorded as a shallowing-upwards cycle in which subtidal shelf lagoon deposits are overlain by mudcracked laminites of the intertidal and supratidal mudflats.

The two environments of the shallow platform leave behind two distinct facies. The subtidal shelf lagoon facies consists of interbedded cross-stratified grainstones of ooids, peloids, or skeletal hash; massive poorly-bedded skeletal packstones or wackestones; and boundstones of skeletal framework-building organisms. The tidal-flat facies is composed of shallowing-upwards cycles. James (1979b) considers shallowing-upwards cycles as the hallmark of platform deposition.
At the shelf margin is a fringe of carbonate sand shoals or coralgal reefs. Along the edges of the Great Bahama Banks, the sands are dominantly ooids and can extend back tens of kilometers from the shelf edge into the shelf lagoon. These sand fringes can be composed of other grain types. For example, at the edge of the bank off the Florida Keys is White Bank, a skeletal shoal. Tidal flushing on and off the banks produces large sandwaves on these shoals. Waves impinging on the banks also produce wave swash bars. As a result of these two processes, these carbonate sand shoals are internally cross-stratified. The reefs at the shelf edge are frameworks of encrusted corals and red algae. Detrital skeletal sands fill the interstices between the encrusting organisms. Shelf margins are an active diagenetic site, best seen in modern reefs where the interstitial skeletal sands are often cemented.

The entire shelf margin system is subjected to episodes of organic boring, dissolution, internal sedimentation in voids, and cementation. Because it is an active site of cementation, the slopes of modern carbonate banks can be quite steep. In fact, the upper part of the slope off the Belize reefs is a vertical wall hundreds of meters high (James and Ginsburg, 1979). At the base of this wall is a talus pile composed of blocks of reef and cemented marginal shoal. Sand and mud derived from the shelf lagoon and edge mixes with pelagic mud and surrounds the blocks. This talus slope fines out laterally into the basin which may be from a few hundreds to thousands of meters or more in depth. In the basin, finely laminated pelagic muds composed of tests of planktonic organisms are punctuated by thin beds of carbonate turbidites composed of material derived from the shallow shelf.

Much of the recent work on Maryland's carbonates has involved comparative studies between the ancient rocks and the modern deposits outlined above. These studies are listed in Table I, and the following discussion is based on this work.

In the sedimentary Appalachians all three of the carbonate sequences (Fig. 2) were deposited in a shelf lagoon - tidal flat setting. This is clearly recorded by the tidal flat facies composed of meter-scale shallowing-upwards cycles that are common in these rocks. These shallowing-upwards cycles record the lateral progression of tidal flats over the shallow shelf lagoon. Cycles end in laminated lime mudstones which carry mudcracks and other evidences of subaerial exposure. An example of one such cycle is given in Figure 4. Details of other cycles for other formations are given in the references of Table I.

The tidal flat facies are interbedded with shelf lagoon facies. Formations composed dominantly of shelf lagoon facies include the Stonehenge Limestone, Helderberg Formation, and Greenbrier Formation. Cross-stratified grainstones and burrowed skeletal-rich wackestones are common rock types. In the Cambro-Ordovician sequence, patch reefs composed of skeletal algae (thrombolites) are common. The algae include Renalcis and Renalcis-like forms as well as Girvanella.

In the crystalline Appalachians, many of the carbonates are marbles in which any traces of original sedimentary features have been destroyed. However, Fisher (1978) recognized shallowing-upwards cycles in the Wakefield Marble.

The Frederick and Grove Limestones at the western edge of the crystalline Appalachians still have recognizable sedimentary fabrics (Reinhardt, 1974; Demicco, 1985). Most of the Upper Cambrian Frederick Limestone is a slope deposit composed of a number of meter-thick beds of talus debris breccias with blocks up to several meters in
These breccias are interbedded with thin beds of micritic limestone composed of debris washed off the platform. The large blocks in the breccias are composed of the skeletal algae Epiphyton and Girvanella. Geopetal fills in these blocks clearly demonstrate transport. The Lower Ordovician Grove Limestone conformably overlies the Frederick, contains shallowing upwards cycles, and is a shallow platform deposit. The Frederick-Grove Limestone sequence records the filling of a small basin that was east of the main platform in Late Cambrian time. The edge of this basin was the site of an Epiphyton-Girvanella shelf-edge reef. By the Early Ordovician, the basin had filled, and the shallow platform extended to the east. Unfortunately, the eastward equivalents of these deposits are too highly metamorphosed to allow sedimentologic analysis. Their environments of deposition must await further study and may never be known.

**SUMMARY AND CONCLUSIONS**

1) Maryland has vast amounts of carbonate rocks that were deposited, deformed, and in some cases metamorphosed during the history of the Appalachian Mountains.

2) The vast bulk of these carbonates are shallow platform deposits in which shallowing-upwards cycles are common.

3) Deeper slope facies existed for a short time in a small basin east of the main platform. This was filled by Early Ordovician time, allowing the platform to prograde eastward.

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NONFUEL MINERAL INDUSTRY IN VIRGINIA

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ABSTRACT

Mineral production in Virginia for 1982 was valued at $1.72 billion, compared to $1.79 billion in 1981. Total production was lower due to the economic slowdown that developed during the later part of 1979 and has continued through 1982. The rank of mineral commodities produced in 1982, by total sales, was coal, stone, cement, lime, sand and gravel, and natural gas. Virginia led the nation in the production of kyanite and a feldspar marketed as "Virginia Aplite", was one of three states producing vermiculite, and was the fourth leading state in production of crude iron-oxide pigments. The State ranked 24th in the Nation in nonfuel mineral production ($283 million in 1981). Other commodities produced in Virginia include miscellaneous clay materials, absorbent clay, industrial sands, gypsum, petroleum, sulfur, talc, etc. Processing plants imported and prepared lithium, magnetite, manganese, and perlite for various markets.

Resources that may become more important in the future include specialty industrial sands, raw materials suitable for fillers and extenders, raw materials suitable for rockwool, barite, and greensands for potential use of their ion-exchange properties in landfills.

INTRODUCTION

Total nonfuel mineral production in Virginia in 1982 was 263.18 million dollars, and in 1983, preliminary figures of 283.19 million dollars indicate an increase of more than 20 million dollars (Table 1). Per capita nonfuel mineral production in Virginia for 1983 was $51.68. The volume (or tonnage) of production is about four times that of the the fishing industry; and 1982 figures show that the value of production, including coal, oil and gas, is about 25 times that value for the fishing industry. As a comparison, tourism amounts to about 3 billion dollars per year.

The economic slowdown that developed during the later part of 1979 continued through 1982 but turned around in 1983, primarily due to an increase in the production of cement and clay. Value of production of clay, sand and gravel, and stone decreased during the years 1979-1982 but these commodities increased in total value in 1983 (Table 2). The State led the Nation in the production of kyanite, was the only producer of a feldspar marketed as "Virginia Aplite," and was one of three States mining vermiculite (White and Sweet, 1982). Several mineral commodities were imported into the State for further processing. These include iron oxide pigments, lithium carbonate, magnetite, manganese, mica, perlite, and, until mid-1982, vanadium pentoxide (Sweet, 1983). The major mineral resources industries in Virginia are discussed in the following pages.

CEMENT

Virginia's cement industry consists of three plants located in Warren and Botetourt Counties and in the city of Chesapeake. The slowdown of building and highway construction had depressed the cement market in Virginia until 1983, when production increased.

Riverton Corporation in Warren County produces masonry cement at their plant at Riverton. Crushed limestone from the Athens Formation is calcined, hydrated, and mixed with Portland cement purchased from out-of-state sources. Sales are to building-supply dealers in Virginia and surrounding states.
Lone Star Cement Inc. operates a plant west of Tinker Mountain in Botetourt County. This is the largest operation owned by Lone Star in the nation. The facility produces Portland cement from locally-mined limestone and shale, and utilizes scrap iron from Roanoke Electric Steel Company. In the past, waste magnetite (roasted pyrite) from Kyanite Mining Corporation in Buckingham County was used as a source of iron. Clinker is manufactured in five coal-fired kilns and ground into cement. Most of the cement is sold to ready-mix companies and approximately 75% of the plant's production is shipped by rail.

Lone Star Lafarge, Inc., operates a cement manufacturing facility in the city of Chesapeake. The company purchases crushed quicklime (93 to 96% CaCO₃) from northern Virginia and alumina on the open market from several aluminum companies in the southeast. Three types of calcium aluminate cement are produced: low Al₂O₃ (Fondu), medium Al₂O₃ (50 to 55%) and high Al₂O₃ (70 to 80%), including SECAR 71, and SECAR 80. Advantages of this cement over Portland cement are rapid setting, and resistance to high and low temperatures, corrosion, and wear.

CLAY MATERIALS

Residual and transported clay, shale, and weathered phyllite and schist are used as raw material to produce almost a half-billion bricks in Virginia annually when all plants are working at full capacity. Tazewell Clay Products Company in Tazewell County, extrudes clay to produce clay stemming used by the coal industry to tamp shot holes.

Lightweight aggregate is produced by four different companies in Amherst, Botetourt, Buckingham, and Pittsylvania Counties. Weblite Corporation in Botetourt utilizes shale from the Rome Formation to produce lightweight aggregate by the sintering process. Semi-anthracite coal waste from the Valley Coal Fields near McCoy, Montgomery County, is used to fire the kilns. Lightweight aggregate is produced from the Triassic shale in the Danville basin by the Virginia Solite Company near Cascade, Pittsylvania County. Solite Corporation near Arvonia in northern Buckingham County utilizes the Arvonia slate of Ordovician age, and Amlite Corporation, formerly Hercules, Inc., near Snowden in Amherst County mines slate of Cambrian age from the Hampton Formation.

The old Cold Spring kaolin deposit, located near Big Levels in Augusta County, was last operated in 1951. In 1912, prospecting began in a 50-foot vein of white clay near the bottom of the weathered Shady (Tomstown) Dolomite, discovered in the workings of an old iron pit. In 1918, Cold Spring Mining Company, a subsidiary of Georgia Kaolin Company took over the operation, producing clay as a paper filler. The material was marketed as "white clay" instead of kaolin because of the advantage in freight rates. From the early 1920s and extending over a ten-year period, about 100,000 tons of white clay (valued at almost $850 thousand) were produced. An old chemical analysis of the material indicates 39% alumina. Clay was mined from a 500- by 800- by 90-foot pit area by power shovels and transported in mine cars to a 2.7-mile long aerial tramway ending at the preparation plant near the railroad. In the early 1930s, several veins of clay, 5 to 20 feet thick, with some impurities were mined for use as a filler in oil paints.

Production in 1949 and 1950 averaged about 6,200 tons per year with an annual value of $85,000. The preparation plant burned during the late summer of 1951 and it was not rebuilt because of the deteriorating grade of raw material, expense of processing, and low demand for the product. About 3,300 tons of material, valued at almost $49,000 was produced in 1951. Large spoil piles of kaolinitic material, with small bits of manganese and bauxite remain on the site. In July, 1982, James River Limestone Co., Inc. applied to Augusta County for a special use permit, with plans to utilize the material for various grades of filler-extender material and possibly as an ingredient in white cement.

During early 1981, a large deposit of montmorillonite clay was discovered in the Walkerton area of King and Queen County. In 1982, Bennett Mineral Company began to mine and process the clay to produce pet litter and industrial absorbent. The facility used wood waste as fuel to dry the clay in a rotary kiln.

FELDSPAR

In 1983, Virginia was the only State that
<table>
<thead>
<tr>
<th>Mineral</th>
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<th>1983 p/ Quantity (thousands)</th>
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<td>W NA</td>
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<td>Lime</td>
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<td>654 30,525</td>
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<td>Stone:</td>
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<tr>
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<td>36,000 143,600</td>
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<tr>
<td>Dimension</td>
<td></td>
<td>4 1,130 4 1,129</td>
</tr>
<tr>
<td>Combined value of cement, feldspar, gypsum, kyanite, sand and gravel (industrial), sulfur, talc (soapstone), vermiculite, and values indicated by symbol W</td>
<td>XX 59,484</td>
<td>XX 72,483</td>
</tr>
<tr>
<td>Total</td>
<td>XX 263,183</td>
<td>XX 283,191</td>
</tr>
</tbody>
</table>

p/-Preliminary. NA-Not available. W-Witheld to avoid disclosing company proprietary data; value included with "Combined value" figure. XX-Not applicable.

Table 1. Nonfuel mineral production in Virginia. Production as measured by mine shipments, sales, or marketable production (including consumption by producers).

produced a material marketed as "Virginia ap­lite", a light-colored dike rock composed of quartz and orthoclase feldspar. It is sold to the glass industry to improve the workability of the molten material and to impart a chemical stability to the finished glassware.

The Feldspar Corporation operates a mine and plant near Montpelier in Hanover County in east-central Virginia. Feldspar is mined from an open pit and the ore is trucked to the plant adjacent to the mine for crushing, grinding, classifying, and drying. Clay minerals are removed by gravity concentration and electrostatic separation. Magnets remove the iron and other heavy minerals, which are stockpiled. The processed feldspar is shipped by truck and rail to market, which includes the southern states, New Jersey, Pennsylvania, Ohio, and Indiana.

Clay and silt with a high percentage of kaolinite and mica have accumulated in settling ponds of many mineral processing plants at rates between 75,000 and 100,000 tons per year. This material was evaluated in the mid-1960's and found suitable for face brick and drain tile. It fires dark brown to gray. Fines may have a potential as flux material for the brick industry.

The International Minerals and Chemical (IMC) Corp, mined anorthosite at Piney River in Nelson County until June 1980, when it closed because of the deteriorating grade of the feldspar. Residuum overlying this anorthosite has been examined in the past for possible use in ceramics (Figure I). Sweet (1982) noted that the residuum in several locations is suitable for medium to high duty refractories and has an alumina content of up to 35.55%. Reflectance tests indicate a brightness of 73.0.

Feldspar in Amherst County is marketed as aggregate by the Dominion Stone Plant, Inc. Fines, resulting from the crushing of anorthosite for use as road aggregate, are presently stockpiled. An attempt was made to market the fines as roofing material, but transmission of light was too great and the product was unmarketable.

Feldspar has also been mined from several pegmatite bodies in the Piedmont province including those in Amelia and Bedford Counties.

FERROVANADIUM

Chemstone Corporation, a subsidiary of Engelhard Corp., produced ferrovanadium at their Alloys Plant in Strasburg, Shenandoah
County, until mid-1982. A residue from this process is an alumina concentrate with 84 to 88% alumina, several percent magnesia, and 1.5% vanadium. This waste material has been marketed for use as an abrasive material.

**GYPSUM**

United States Gypsum Company, which operates a plant in Norfolk, receives crude gypsum from Nova Scotia. The material is ground and calcined to produce wallboard and other gypsum-based products as well as a "land plaster" for the peanut-farming industry. The Norfolk facility also receives a few shipments of anhydrite from the Nova Scotia operations for sale to local cement manufacturers. The company operates an underground mine at Locust Cove, Smyth County and a wallboard plant at Plasterco, in adjacent Washington County. Gypsum, occurring as isolated boulders in the Maccrady Shale, is mined by a modified underhand stoping system. Crude gypsum is trucked to the plant at Plasterco where it is made into wallboard. Some fine gypsum is marketed as "land plaster", a soil conditioner.

In early 1984, U.S. Gypsum Co. acquired the high-calcium lime operation of Gold Bond Building Products, Division of National Gypsum Co., in Giles Co.

**IRON OXIDE PIGMENTS**

Virginia is one of four states producing iron oxide pigments. Hoover Color Corporation in Pulaski County produces ocher, umber, and sienna, and is the only operation in the United States producing sienna. Raw pigments are mined by open pit methods and trucked to the company plant at Hiwassee where the pigments are pulverized, dried, ground, graded, blended, and packaged prior to shipping. The finished product, used as a coloring agent in a variety of products, is

![Figure 1. Residuum over anorthosite feldspar near Lowesville, Nelson County.](image-url)
Table 2. Select commodity production in Virginia.

shipped throughout the United States, Canada and Mexico.

Blue Ridge Talc Company, Inc., imports crude iron oxide pigments from a midwest supplier. The pigments are ground and calcined for use in paints, fertilizers, and cement coloring. Markets are domestic and foreign.

KYANITE

Kyanite is an aluminum silicate with a maximum of 61.8% alumina and a minimum iron content of 0.16%. The first recorded production of kyanite was in Prince Edward County during the 1920's. Currently, the State produces approximately 45% of the world's kyanite from two mines in Buckingham County. Above 3,000 degrees Fahrenheit, kyanite is converted to mullite and its expansion depends on grain size and temperature. The resulting material is a super-duty refractory with a pyrometric cone equivalent of 36 to 37 which resists cracking, warping, slagging, and deformation from high temperature. It is sold in 35-, 48-, 100-, 200- and 325-mesh sizes. These products are used in the refractory, ceramic, glass, metallurgical, and foundry industries.

Kyanite Mining Corporation operates two mines and processing plants in Buckingham County, one at Willis Mountain and one at East Ridge. Kyanite-bearing quartzite is quarried from open pits and recovered by froth flotation. Any included sulfides are oxidized and the ferric oxides are reduced to ferrous oxide which can be removed by magnetic separation.

Approximately 40% of the output is shipped through the port of Hampton Roads to worldwide customers. The company produces approximately 90,000 tons per year (Dixon, 1980). The company also sells a sand by-product which is used in masonry cement, concrete, and for landscaping golf courses.

LIME

Lime sales ranked behind cement in Virginia in 1983. Over the past 10 years, lime production has added over $200 million to the State's economy, although lime sales have been lower recently due to the slowdown in the steel industry.

The lime industry is concentrated in Frederick, Giles, and Shenandoah Counties. In northern Virginia, W.S. Frey Company, Inc., and Chemstone Corporation (Figure 2) quarry and calcine the high-calcium, New Market Limestone. Two companies in Giles County, the U.S. Gypsum Co. and the Virginia Lime Co., operate underground mines in the Five Oaks Limestone. Principal uses are in the paper and steel industries and for water purification. The paper industry uses lime for regeneration of sodium hydroxide and for the neutralization of sulfate water, a by-product of paper manufacture. Lime is used by the steel industry to control slagging, and in neutralization of acid mine water. It is also used for masonry lime, sewage treatment, and for agriculture.

LITHIUM

Foote Mineral Company processes lithium carbonate from Spruce Pine, North Carolina along with calcium hydroxide from various sources to produce lithium hydroxide at their Sunbright plant in Scott County. Lithium hydroxide is used in multipurpose grease lubricants. In the past, limestone from an underground mine at the site was used in the process, and a calcium carbonate precipitate was produced as waste. This material remains on the site and may become a valuable by-product. An approximate analysis is 43 to 50% calcium carbonate, 3 to 6% calcium hydroxide, and 40 to 80% water.

MAGNETITE

Reiss Viking Corporation in Tazewell County in southwestern Virginia processes out-of-state mill-scale magnetite for use in
coal preparation. Magnetite is mixed with water to form a heavy-media slurry into which raw coal is fed. The heavier impurities sink, but the lighter coal floats and is recovered. About 2 pounds of magnetite is consumed for every ton of coal that is cleaned. Ground magnetite is also marketed for sale to the foundry industry in Alabama, Kentucky, Tennessee and Virginia.

MANGANESE

Union Carbide Corporation, Battery Products Division, operates a manganese processing facility in the city of Newport News. Manganese ore, imported from South Africa and Gabon, is dried, crushed, ground, and shipped to other company facilities for use in the manufacture of batteries.

MICA

Asheville Mica Company and an affiliate, Mica Company of Canada, process mica at facilities in Newport News. Crude mica is purchased through New York brokerages from Madagascar and India. Asheville Mica Co. utilizes the imported mica to produce fabricated plate-mica. Mica Company of Canada uses splittings from Asheville to produce reconstituted plate-mica. Mica has been produced in the past from pegmatite bodies in several counties in Virginia, including Amelia, Henry, and Powhatan.

ORNAMENTAL AGGREGATE

Several materials have been utilized for ornamental aggregate in past years. Vein quartz has been produced in Albemarle, Buckingham, Fluvanna, Greene, and Rappahannock Counties. Quartz pebbles have been produced from Caroline County. Dolomite and quartzite are presently produced in Botetourt and Rockbridge Counties, and are marketed as exposed-aggregate materials. Rock materials for use in terrazzo include black limestone of the Edinburg Formation in the Valley and Ridge province and greenstone in the Piedmont province.

PERLITE

The Manville Corporation operates a plant at Woodstock, Shenandoah County, to expand perlite. This material is a volcanic glass with high water content and "onionskin" appearance, and is shipped by rail from Grants, New Mexico. Expanded perlite is used in the manufacture of roof insulation board marketed throughout the eastern United States. Although sales were off slightly, as compared with those of the previous year, product demand in 1982 for roofing installation and maintenance was strong.

POTASH

Potash is used mainly in the agricultural industry. The mineral sylvite contains approximately 63% potash and the mineral kainite contains almost 19% potash. Potassic silicates, such as orthoclase feldspar, that are common in igneous and metamorphic rocks release potash upon weathering. Fines from crushing operations in these types of rocks may provide a low-grade potassium source. Granite fines from mineral operations in southern Virginia have been trucked to central Virginia for low-grade fertilizer (D. Via, personal communication). Chemical analyses of granitic materials from Brunswick and Nottoway Counties in the southern Piedmont province indicate a potash percentage higher than 10%.

Greensands or glauconitic marls are located in the Coastal Plain province and are exposed along the Potomac, Rappahannock, Pamunkey, and James Rivers. The glauconite, a hydrous silicate of iron and potassium, makes the material potentially valuable for fertilizer as the potash content can range up to 10% in the purer greensands. The material may also be important in ion exchange with toxic materials in landfills and waste dumps.

SAND AND GRAVEL

More than 130 sand and gravel operations were active in Virginia during 1983. The leading regions of production are Charles City, Chesterfield, Henrico, and Prince George Counties in the vicinity of Richmond, as well as Caroline, King George, Spotsylvania and Stafford Counties around Fredericksburg. Historical cost data for sand and gravel in Virginia were compiled in a report by the Di-
vision of Mineral Resources (Sweet, 1978). Large tonnages of construction sand and gravel, produced east of Fredericksburg, are shipped by rail into the northern Virginia - Washington, D.C., market area. A large portion of the production by Sadler Materials and Lone Star Cement, Inc., is barged on the James River below Richmond to the Norfolk area. Shipments are also made by rail and truck to the western part of the State. Major uses for sand and gravel include construction, asphalt, fill, and snow and ice control.

Industrial Silica

J.C. Jones Sand Company excavates industrial sand at Virginia Beach for use in foundry-casting applications and as a traction medium. Glass sand is produced near Gore in Frederick County by Unimin Corporation from the Ridgeley Sandstone of Devonian age. CED Process Minerals Inc., also near Gore in Frederick County, recrystallizes purchased sand in a rotary kiln to produce cristobalite, which is marketed as a fine grit. Fine grained cristobalite (200- to 400-mesh) is marketed for precision metal and dental castings. Sand from the floodplain along the Appomattox River in Chesterfield County is used for filter material, and river sand from the Levisa Fork in Dickenson County is used for traction sand in the coal mines. Quartzite from the Erwin (Antietam) Formation at Lots Gap (Figure 3) in Wythe County is marketed as metallurgical flux.

STONE

Crushed Stone

Quarry operators mine and process about $1 million worth of limestone, dolomite, sandstone, quartzite, granite, gneiss, diabase, basalt, amphibolite, slate, "Virginia aplite," marble, and marl. Limestone, dolomite, and sandstone producers are located in the Valley
and Ridge Province and Plateau Province in the western and southwestern portions of the State. Principal end uses are for road construction, concrete aggregate, asphalt aggregate, and agricultural application. Glass-grade dolomite which is low in iron, sulfur, phosphorus, and carbon is produced from the Honaker Dolomite of Cambrian age by Piedmont Mining Corporation, located on the site of Tri State Lime Company, Scott County. "Rock dust" for coal mines (335,000 tons in 1980) is produced at six quarries in southwest Virginia. Dust is spread in coal mines to prevent explosions. The material should contain less than 5% silica and 100% should pass 20-mesh with 70% passing 200-mesh. Finely ground dolomite and limestone are also marketed by several operations for use as a filler material.

Tailings from the processing plant of New Jersey Zinc Company at Austinville, Wythe County, consist of five to six million tons of wet to dry, minus 180-mesh material that is approximately 20% magnesium carbonate. Lead and zinc have been mined in the area since 1755 from the Shady Dolomite of Cambrian age. Possible uses may be to market the material in slurry form as dolomititic limestone, or to dry it for use as rock dust.

Approximately 5% iron as pyrite in the original rock may be a problem. This material, along with the processing plant, was recently acquired by James River Limestone Co. of Buchanan, Virginia. A new quarry west of the old plant has been opened and agricultural lime is being produced.

Sandstone is produced for roadstone, concrete aggregate, asphalt stone, and manufactured fine aggregate. Quartzite from the Antietam Formation is quarried by Locher Silica Company in Wythe County and marketed as metallurgical flux. Similar material has been produced in Rockbridge County in the past.

Granite, gneiss, diabase, basalt, amphibolite, slate, and marble are produced in the Piedmont and Blue Ridge Provinces which include much of the central portion of Virginia (Figure 4). Major end-uses are for roadstone, asphalt stone, and concrete aggregate.

Slate is mined and crushed by three companies in Buckingham County and one in Amherst County. Two of the companies, Amlite Corporation and Solite Corporation, also expand slate for lightweight aggregate production. Crushed slate production, utilizing the waste material from former dimension slate operations, has increased as a result of local highway construction.

Appomattox Lime Company, Inc., quarries a Precambrian marble (Mt. Athos Formation) near Oakville in Appomattox County for agricultural lime. Sales are principally to the eastern coastal areas of Virginia and North Carolina.

One company near Winchester in Frederick County mines marl for agricultural applications. The material is excavated with a front-end loader, disked, and dried before it is sold.

**Dimension Stone**

Dimension stone production ($1.1 million in 1982) of diabase, slate, granite, quartzite, and soapstone was reported from quarries in the Valley and Ridge and Piedmont Provinces. Slate is the leading stone produced in terms of cubic feet and value. Two companies, Arvonia-Buckingham Slate Corporation, Inc., and LeSueur-Richmond Slate Corporation, quarry slate in the Arvonia area of Buckingham County. Arvonia slate production dates from the late 1700's when slate was quarried for the roof of the State Capitol in Richmond. Slate producers supply the building trade with a variety of products ranging from material for exterior applications such as
roofing and flooring to interior uses such as hearths and sills.

Diabase is produced for use as monument stone at Virginia Granite Company in southern Culpeper County. Granite is presently produced from one quarry in Hanover County, while quartzite is produced for flagstone at three quarries: two are producing from the Weverton Formation of Cambrian age in the Bull Run Mountains in Fauquier County (Figure 5), and one is in Campbell County.

SOAPSTONE

Alberene Stone Company produces soapstone for speciality laboratory materials and for panels used in conjunction with woodstoves. Flagstone is a by-product. Intermittently active quarries are in Albemarle and Nelson Counties.

Figure 4. Quarry of Luck Stone Corp., Boscobel Plant in Petersburg Granite at Manakin, Goochland County.

Figure 5. Dimension stone quarry in quartzite of Weverton Formation in Bull Run Mts., Fauquier County (circa mid-1960's).
SULFUR

Elemental sulfur is recovered by the Claus process from hydrogen sulfide gas during crude oil refining by Amoco Oil Company. The refinery is near Yorktown on the York River. About 50 tons of sulfur is produced per day and is marketed for eventual use in fertilizer.

TALC

Blue Ridge Talc Company, Inc., in Franklin and Henry Counties produces talc for foundry applications. Talc, occurring in talc-chlorite-dolomite schist is mined by open-pit methods, trucked to the company's mill on the Franklin-Henry County border and ground for foundry use as releasing agent in mold coatings. Much of the ground talc is shipped to foundries in the western Pennsylvania area. Sales have recently been down because of the depressed state of the steel industry.

VERMICULITE

Virginia is one of three States that mines vermiculite, a hydrated magnesium-iron-aluminum silicate. Virginia Vermiculite, Ltd., operates an open-pit mine and processing facility near Boswells Tavern, in Louisa County northwest of Richmond. Material is excavated with a backhoe and front-end loader, and trucked to the adjacent plant where desliming, flotation, drying, and screening produce materials in four basic sizes. Most of the crude vermiculite is shipped by rail in unexfoliated form to North Carolina, West Virginia, Ohio, and other eastern states. Uses for the exfoliated material include packing, insulation, lightweight concrete, and potting material.

REFERENCES


THE CHROMITE INDUSTRY OF MARYLAND, PAST AND FUTURE

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Baltimore, Maryland

ABSTRACT

Chromite, the only ore of chromium and one of our strategic metals, is found nearly worldwide. However, 98% of the known reserves are concentrated in only four countries. The United States has some chromite resources, but no significant reserves. The Maryland podiform deposits were discovered about 1810 by Isaac Tyson Jr. and his discoveries supplied most of the world's chromite demand for over twenty years.

Maryland's chromite deposits are concentrated in a belt 12 to 13 miles wide running from the Pennsylvania State Line in Cecil County to the Potomac River in Montgomery County. Three types of occurrences have been exploited: massive pods, disseminated lenses, and placers. Maryland production was minimal, probably not in excess of 120,000 tons, and it is unlikely that these deposits could compete economically with foreign imports in normal times. Should a national emergency arise, the Maryland deposits are ideally located with respect to today's consumers.

Future exploration will probably uncover additional reserves in the old districts similar in size and grade to that already found. The search for chromite should be concentrated in the serpentine zones using geochemistry, gravity and some of the newer electrical techniques.

Chromium was discovered in 1797 by Louis Vauquelin, a French Chemist. The name comes from the Greek word chroma, meaning color, and refers to the brilliantly colored red, orange, yellow, and green compounds of chromium. With the possible exception of iron it is one of the most versatile elements in modern technology. In addition, because of its scarcity in the United States, it is one of our nation's most important strategic materials. Chromium is used in ferrous alloys, as a plating material, in pigments, leather processing, refractory materials, and in many other diverse applications. Chromium therefore transects the line between industrial minerals and metallic ores. Chromite is the only ore of chromium, and while chromite is found nearly worldwide, 98% of the known reserves are concentrated in five countries: the Republic of South Africa 67.6%, Zimbabwe 29.7%, Finland 0.8%, USSR 0.5%, and Turkey 0.1%. Other important localities are the Philippine Islands, Brazil, and Iran.

The United States has no significant reserves. However, some resources do exist primarily in Montana, Oregon, California, Washington, Alaska, Maryland, and Pennsylvania. Chromite deposits occur both as stratiform deposits such as the Bushveld Complex of Africa and the Stillwater Complex in Montana, and as podiform deposits such as our local ones characterized by lenticular or pod-shaped masses within serpentine and peridotite rocks. The world's largest podiform deposits are located in the Ural Mountains of the USSR which produces about 2 million tons of chromite annually.

The Maryland podiform deposits were discovered about 1810 by Isaac Tyson Jr. on the Tyson Farm at Bare Hills located north of the city of Baltimore. Tyson soon recognized that chromite was associated with serpentine which forms barren soils making a marked contrast with the normal fertile soils of the Piedmont. Using this method, Tyson was able...
to locate both the Soldiers Delight region 10 miles west of Bare Hills in Baltimore County, and the Reed Mine near Jarrettsville in Harford County by about 1827. Discoveries in Cecil County and in adjoining portions of Lancaster Co., Pennsylvania, soon followed and by 1828 most of the world's supply of chromite came from the Maryland-Pennsylvania area. Maryland and Pennsylvania continued to be the principal producers of chromite until 1848, when the rich podiform deposits in Turkey were discovered and gradually replaced the sources in the United States.

The Tysons were not content to have a monopoly on the chromite mining but also attempted to capture the chemical industry as well, and for 40 years dominated the manufacture of chromium compounds in the United States. Isaac Tyson's death in 1861 marked the decline of chromite mining in Maryland, and after 1882, production except for a period during World War I was sporadic. The production of chromium products, however, remains a viable industry in Baltimore today.

Maryland chromite deposits are concentrated in a belt 12 to 13 miles wide running from the Maryland-Pennsylvania line in Cecil County to the Potomac River in Montgomery County. Three types of occurrences have been exploited: massive pods and lenses, disseminated lenses, and placers of chromite sands. In general, Maryland chromite tends to be high in iron (in other words, a portion of the chromic oxide is replaced by iron oxide). It is therefore not considered to be good metallurgical grade ore although it would more than satisfy modern requirements for chemical grade chromite. Production records for the various deposits are sketchy to nonexistent but it is estimated that the total Maryland production exceeded 120,000 tons, which with the adjoining Pennsylvania production accounts for 25% of the total chromite produced in the United States. Although the United States was the principal chromite producer during the 1800's, domestic production has seldom exceeded 1000 tons per year since that time. The exceptions were those times of emergency during World Wars I and II, and the Korean conflict of the 1950's. Domestic

Figure 1. View of serpentine barrens at Soldiers Delight, Baltimore County.
production of chromite ceased entirely following the termination of the last defense production act contract in 1961. While some chromite was produced for export in California during 1976, the United States has been totally dependent on foreign sources for the past 22 years.

South Africa has with its huge reserves dominated both our chromite and ferrochromium imports (See Figure 2). It is unlikely that Maryland's deposits could ever compete with these sources in normal times. However, it can also be seen that our chromium sources are to a great extent located in countries where political problems and changes can occur rapidly. Should a national emergency arise, the Maryland deposits are ideally located with regard to today's consumers, most of whom are located in the eastern United States, and three of these in the Baltimore area.

Maryland chromite deposits historically have been small and spotty making both mining and exploration costs high. Some dissem-
inated chromite exists, but these deposits are also small, and there is no reason to believe that future exploration will uncover reserves much different in either size or grade from those already exploited. Practically all of Maryland's discoveries have been exposed or near-surface finds. It can be assumed therefore that at least as much or more chromite remains as has already been found. The search for buried deposits has not been very successful in the past. Several attempts have been made to locate additional deposits in the vicinity of the old mines using various geophysical techniques such as magnetics, resistivity and gravity. Concentrations of titaniferous magnetite tend to mask any anomaly caused by the weakly magnetic chromite, and difficulty with both terrain corrections and instrumentation complicated the gravity results. Modern computer techniques should make gravity a viable exploration option today. In addition, careful geochemical studies accompanied by some of the newer electrical methods such as induced polarization may prove to be successful as well as economical methods of exploration.

The search for chromite, as Tyson surmised many years ago, should be confined to the serpentine zones, and probably only to those portions which show anomalous geochemical values for chromium. Those districts which had the greater production such as the State Line, Soldiers Delight, and Jarrettsville areas, most likely hold the greatest potential for future discoveries, but many of the lesser-explored serpentine areas such as the Etchison district in Montgomery County may also contain hidden chromite deposits (See Figure 3). An aeromagnetic anomaly near Port Herman in Cecil County is suggestive of an un-exposed ultramafic which could further widen the exploration possibilities. Maryland's future for chromite production is rather dim, but it has the potential for making a small contribution in the unlikely event the United States would be unable to obtain all its chromite needs from abroad.

REFERENCES


Williams G.H. (1893) Mines and minerals, in Maryland, its resources, industries, and institutions: Sun Job Press, Baltimore, Maryland p. 120-122.
From 1978 to 1983 a study was made to arrive at a realistic appraisal of Maryland's mineral resources. The approach used combined geologic data with socio-economic and political factors to remove land areas from potential mineral resource development. The results of this study, completed in several phases, can be divided into two categories. The first product was a series of 11 maps for Maryland's Western Shore Counties. The second product of this study was a sequence of maps on a single county for a specific mineral resource over a given time span. Anne Arundel County, located between Baltimore and Washington, D.C., was chosen a "typical" suburban county. Sand and gravel deposits were the resource evaluated. Data similar to that gathered for the Lands For Potential Mineral Resource Development maps mentioned above were generated for the years 1938, 1952, 1964, 1978, and 1980. Total available acreages were calculated for these years and a rate of preemption established.

This rate reflects the impact of developmental trends and historical events through the years. The ultimate purpose of this study, beyond determining whether a rate of preemption could be established, was to set an inspirational example for other political subdivisions endowed with unencumbered mineral resources.

ACKNOWLEDGEMENTS

The Lands Information and Analysis Office of the U.S. Geological Survey funded this study. Andrew Wulff compiled the data on the rates of preemption and drafted the results. The Coastal Resources Division of the Tidewater Administration of the State of Maryland also funded portions of the project.

INITIAL STUDY

The initial study "Lands for Potential Mineral Resource Development" began in 1978 in reaction to a crisis. A major sand and gravel producer complained that there was no place left to mine his product. In response, we set out to determine exactly where deposits of sand and gravel were still potentially available for mining. Figure 1 shows the en-
Figure 1. Location of sand and gravel resources, by county, in Maryland, and Anne Arundel County, where the current study was focused.

The information in each Phase I category was graphically compiled and superimposed on geologic maps depicting sand and gravel deposits. Acreages of remaining deposits of sand and gravel were calculated from the resulting maps, and volumetric estimates followed. Even when recovery, quality, accessibility, and other probability factors were considered, resource estimates seemed high. Phase II information, consisting of less absolute, less permanent factors controlling site selection, was then added. We could not include such factors as denial of access by property owners, public attitude, high cost of purchase, economic constraints, unuseable areas of a deposit, and changes which occur over time.

CURRENT STUDY

After the initial study, Anne Arundel County was chosen for a detailed analysis of its resources, largely because it lies entirely within the Coastal Plain where sand and gravel is the primary resource being extracted today. The State Capital is located along the Chesapeake Bay in Anne Arundel County, which is a suburban county, close to both Baltimore and Washington, D.C. (Figure 1). There is a significant demand for sand and gravel in the County that roughly coexists with a generally negative attitude toward mining. Other than zoning, there are no organized land-use controls on mining. Production of sand and gravel has fluctuated in recent years in the County, and there is at present a downward trend in the number of acres available for mining.

Anne Arundel County contains over 260,000 acres of land, 75% of which was farmland or undeveloped as recently as the 1960's. About 109,000 of these acres were originally underlain by sand and gravel deposits of variable origin and quality. The initial studies showed that only 15,000 acres were
still potentially available in 1978. These acres shown in Figure 2 are clustered along the environmentally sensitive Patuxent River, once a proposed "wild and scenic river." The map reveals there has been no coordination between the location of mineral resources on the one hand and the zoning controls and other factors that limit site selection for mining on the other. After this initial analysis, the next step was to determine the trend leading up to the situation as it existed in 1978. Using the methods established for the original study, data were compiled for specific time intervals. These intervals were defined on the basis of availability and concentration of necessary data. Four time segments were selected: prior to 1938, 1938 to 1952, 1952 to 1963, and 1963 to 1978. Prior to 1938, it is assumed that all deposits of sand and gravel were available for mining. The results provided an historical perspective and established the rate of preemption of sand and gravel deposits in this urban area.

Figure 2 depicts the lands for potential mineral resource development in 1978. The grey area shows the distribution of sand and gravel deposits in the County. Black indicates where mining could not occur because of the factors listed in Table I. Phase II factors were not a consideration in 1938. Land use was difficult to establish; road patterns were just becoming permanent, and there were few densely developed areas in the County, excluding Annapolis. There were also fewer operations for sand and gravel since demand was low. Government ownership was determined from maps of non-taxable property. It is notable that these holdings were greater in 1938 than at any later date.

In 1952, zoning was first established in the County. The comprehensive ordinance prohibited mining in over 45% of the County. Zoning became at once the influential factor in site selection. This trend has continued.
Land use and zoning again were major factors in site selection for mining. Areas restricted by zoning regulations have incrementally risen to prohibit access to over 50% of the sand and gravel deposits in the County.

**SUMMARY**

Shown in Figure 6 is a summary impact of each factor on the availability of sand and gravel in Anne Arundel County. The line across the top represents the total acreage underlain by sand and gravel, before man had any significant demand for the material (pre-1900). As is evident in Figure 6, the acreage remaining had diminished dramatically by 1963. Areas of prior mining (heavy stipple) show a steady increase. The preemptive land use category, however, sharply increased, reflecting the large population growth in the County. Government ownership or acquisition...
PHASE I: STATUTES (LEGAL RESTRICTIONS)

GOVERNMENT OWNERSHIP
PRIOR MINING
LAND USE
ZONING
MINERAL RESOURCES

PHASE II: SECONDARY LIMITING FACTORS

ENVIRONMENTAL REGULATIONS
DNR ACQUISITION SITES
HISTORIC SITES AND DISTRICTS
EASEMENTS
COSTS

Table 1. Factors affecting mining site selection.

(open dots) had stabilized by 1963, but the advent of zoning (vertical lines) had a remarkably restrictive effect on potential mining areas.

Tabulations on the impact of each category on sand and gravel availability were not made for 1978. It can be assumed that preemptive land use increased, as the population rose considerably. Government lands had probably grown due to open space allocations, new park acquisitions, and the establishment of recreational areas. Environmental actions such as flood plain and wetland regulations, as well as negative attitudes regarding surface mining, may possibly have had the greatest unquantifiable impact in that the acres remaining for mining may no longer be accessible.

The total acres underlain by sand and gravel remaining in 1978 were planimetered. Approximately 14% of the initial, pre-1900 resource acreage remained. Table 2 lists the percentages of acres of sand and gravel remaining for the time intervals studied. Figure 7 graphically shows the rate of preemption of sand and gravel deposits between 1900 and 1978. It is based on the arbitrary assumption that all resources were free of restrictions in 1900. The graph shows a dramatic decrease in available acreage in the years since 1938. The trend after 1978 is problematical, and it is doubtful whether at this time the trend can be reversed. Rather, it is likely that the acreages available for sand and gravel extraction will continue to decrease. Environmental actions and regulations, continuation of mining activities, inflexible zoning practices, public attitude, and population trends all give basis to this statement. For example, there are currently over 18,000 acres in the County involved in the subdivision approval process. Another area of concern is how much of the remaining 15,000 acres contain economically viable deposits of sand and gravel.

<table>
<thead>
<tr>
<th>Year</th>
<th>Percentage</th>
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<td>1938</td>
<td>71%</td>
</tr>
<tr>
<td>1952</td>
<td>47%</td>
</tr>
<tr>
<td>1963</td>
<td>31%</td>
</tr>
<tr>
<td>1978</td>
<td>14%</td>
</tr>
</tbody>
</table>

Table 2. Original sand and gravel acreage remaining in selected years.
Figure 7. Rate of preemption of sand and gravel deposits in Anne Arundel County between 1900 and 1978.
The main purpose of this study was to determine if there was a trend in the availability of sand and gravel resources over the years. The obvious answer is yes. The amounts of sand and gravel are diminishing rapidly. Land use and land use controls in existence seem to have no regard for mineral resources and their location. If the trend continues at the same rate of preemption, there will soon be no place left to mine.

To reverse the trend at this point, or even to maintain the status quo, would require a serious mineral resource management program as well as other changes, including a release of zoning prohibitions on mining. If sequential land use practices were encouraged, preemption could be reduced and zoning regulations could be altered for more flexibility. It is hoped that this latest study of sand and gravel in an urban area will enable planners in similar areas or those in rapidly developing communities to be aware of the impact of regulations and land use controls on the availability of mineral resources. It is my hope that something can be done to alter the trends indicated. After all, an ounce of foresight is worth tons of sand and gravel.

SELECTED REFERENCES


ABSTRACT

Industrial minerals produced in New York State include cement, clay, emery, garnet, gypsum, peat, salt, stone, sand and gravel, talc and wollastonite. Leading commodities in order of decreasing value are stone, salt and cement. Approximately 100 quarries produced more than 32 million tons of stone statewide. Crushed stone production was dominated by limestone for concrete but included sandstone, trap and slate for bituminous aggregate and road base. Granite, sandstone and slate were produced for cut stone and flagging. New York continues to rank third nationally in the production of salt at about 5 million tons. Rock salt from underground mines is used principally for ice and snow control. Salt also is produced from brines for use by the chemical industry. New York ranked 8th in shipments of portland cement and 17th in masonry cement. Cement production increased slightly over 1982 levels. The entire U.S. production of emery came from two mines in Westchester County. The material is used as non-slip additive for floors and pavements. Small amounts are used for coated abrasives and tumbling media. Clay production increased to 350 thousand tons, up slightly because of increased activity in the cement industry. Other major users of clay are brick and pottery manufacturers. Two companies produced garnet for abrasives from mines in the Adirondacks. The Barton Company has completed its move to a new garnet mine on Ruby Mountain and is back in production. Nationally, New York garnet ranks second in output and first in value. Gypsum production held steady but was down in value. Output of calcined gypsum was about 840 thousand tons. Peat production has been stable in the past two years, up about 9 percent since 1980. Approximately 39 thousand tons of peat were produced for soil improvement. Producers of sand and gravel shipped 19 million tons last year, down in volume but up slightly in value from the recent past. One firm produced industrial sand. All talc production came from two mines in St. Lawrence County. Production and value are increasing. Talc is used for ceramics and as a mineral filler in paint, floor tile, rubber and paper. New York was one of only two states producing wollastonite last year; two producers have mines in the Adirondacks. NYCO, a division of Processed Minerals, Inc., has ceased mining operations at Willsboro and begun a new open-pit mine at Lewis.

INTRODUCTION

Industrial minerals have long played an important role in the economy of New York State. In the past, as many as twenty-four mineral products have been mined for uses as varied as chicken grit, mill stones and lamp chimneys. At present, eleven minerals form the industrial minerals of New York. Of these, stone, salt and cement are the leading commodities by value. Sand and gravel, clay, peat, gypsum, garnet, emery, talc and wollastonite also are produced. Estimated value of non-fuel minerals produced in New York in 1983 was $508.8 million (Harrison, 1984). Most of this value was derived from the production of industrial mineral commodities. Value of mineral production overall has been increasing since 1981 although some construction related industries, e.g. sand and gravel, exhibited a decrease in production during the most recent economic recession.
Many types of stone are present in New York, although all are not actively quarried at present. The value of stone has been approximately one quarter of the total mineral value over the last ten years. Carbonate rock, i.e. limestone, dolostone, and marble lacking ornamental qualities, make up the bulk of crushed stone production. The material is used as bituminous aggregate, road base and as a component in the manufacture of cement.

Approximately seventy companies with eighty to one hundred operative quarries produce in thirty-six of New York's sixty-two counties. The six largest producers: Allied Chemical Inc., Atlantic Cement Inc., Fitzgerald Brothers Construction Company, General Crushed Stone, Lone Star Industries, Inc., and Tilcon Inc., produce roughly one half of the total amount from nineteen quarries. Production declined in 1980 and 1981 but has increased during the past year (Table I).

Production of crushed carbonate rock occurs statewide. The counties leading in production are Onondaga, Albany, Rockland, Dutchess, Erie and Green. These are near to or contain large population centers, as would be expected for a low-value, high-bulk product.

Crushed trap rock is produced in Rockland County from the lower Jurassic basaltic rocks (Palisades diabase) which crop out there. The New York Trap Rock Company, a subsidiary of Lone Star Industries Inc., is the leading producer. Taconic slates, mainly Ordovician in age, are quarried in northern Washington County by about twelve firms. The slate occurs in various shades of red, green and black. It is crushed for use as roofing granules and also split for flagging.

Dimension stone is produced from granite and sandstone in New York. The term "granite" denotes igneous, metamorphic and metasedimentary rocks of the Adirondack and Hudson Highland regions. The stone occurs in white, shades of red, green, blue-gray, and yellow, and exhibits a variety of igneous and metamorphic textures. It is quarried for curbing, stair treads, paving blocks and similar uses.

Sandstone is produced for flagging and architectural work. Rocks often quarried are the Cambrian Potsdam sandstones of the circum-Adirondack region, the Devonian Oriskany sandstone of the Helderberg Escarpment, and the Devonian subgraywacke of the Catskill Mountains. "Lenrock" stone, trade name of marine turbidite rocks quarried in Tompkins County, contains abundant sole markings which make the rock attractive for building veneer.

Salt has had a prominent place in the mineral industry of New York. It is widespread (Figure I) and is the most easterly extractable salt in the United States. The salt underlies an area of at least 10,000 square miles with an aggregate thickness from 75 to 250 feet. Individual beds vary from 10 to 75 feet thick. Reserves are estimated at 4.3 trillion tons. New York ranks third in salt production in the United States.

A complete history of the early development of the salt industry can be found in Newland (1921) from which the following account is extracted. The first mention of salt in New York occurs in the records of Jesuit missionaries who visited the Onondaga region in the mid-17th century. It is known that native Americans and occasional traders ob-

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**Table I. Stone and salt production, and value in New York, 1979-1983.**

<table>
<thead>
<tr>
<th></th>
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<tr>
<td></td>
<td>$77,751</td>
<td>$99,395</td>
<td>$103,668</td>
<td>$117,718</td>
<td>$102,735</td>
</tr>
</tbody>
</table>

1 - Preliminary
2 - Thousand short tons
$ - Thousands of dollars

Figure 1. Mineral resources of New York State.

The industry began in 1788 when New York State obtained title to land on the shore of Onondaga Lake for the purpose of making salt. The State took control of the entire industry in 1797. Brine, derived from the Silurian Salina Formation, was pumped from glacial till in buried valleys. Wood-fired evaporators were employed before solar evaporation was introduced in 1821. The State relinquished control of the wells in 1908 when brine concentration had fallen to an uneconomic 14 to 15 percent (theoretical maximum is 25 percent).

Rock salt was discovered in 1865 and first exploited in 1881. Fresh water was pumped into 1,000- to 1,200-foot deep wells. Brine was extracted and evaporated. The first shaft was begun in 1884 at Retsof in Livingston County and reached the first production level at 1,000 feet in 1885. The Retsof mine, currently operated by International Salt Company, is the largest underground salt mine in the non-communist world. The present shaft, completed in 1922, is 1,152 feet deep. Working faces are nearly five miles from the production shaft. Since 1885, the Retsof mine has produced more than 100 million tons of rock salt.

In addition to the Retsof mine, rock salt currently is produced by the Cargill Corporation from a mine in Tompkins County. The International and Cargill mines account for fifty percent of the state's salt production. It is used for snow and ice abatement.
Salt is produced from brine wells by Allied Chemical Corporation in Onondaga County, International Salt Company in Schuyler County, and Hooker Chemical Corporation and Morton Salt Company in Wyoming County (Figure I). Salt from these brines is used to produce soda ash, chlorine and other chemicals. Production statistics for the salt industry are included in Table I.

CEMENT

Raw material for the manufacture of cement, both natural and portland, is abundant and widespread in the state. Nationally, New York ranks eighth in portland and seventeenth in masonry cement shipments.

Like salt, cement production has a long history in the state. In the early 1800's it was found that a certain calcined limestone would not slake but, when ground, developed "hydraulic properties" (Newland, 1921). Production of this natural cement began in Madison County; it was used in construction of the Erie Canal. The first natural cement plants were established in the 1820's in Ulster and Onondaga Counties. These used impure dolostones or limestones containing 20 to 40 percent silica, iron oxides and considerable clay. The mines began as open pits, but soon became underground room and pillar excavations which extended up to 1,000 feet along strike and 800 to 1,000 feet down dip. Manufacture of natural or hydraulic cement ceased in 1966 with the closure of the last remaining operation at Rosendale in Ulster County.

The first Portland cement plant was established in 1881 in the Hudson River Valley where the industry is centered today (Figure I). Active Portland cement plants are located in Albany, Greene and Warren Counties. Atlantic Cement Company, Inc., a subsidiary of Newmont Mining Corporation, is the leading producer accompanied by Glens Falls Portland Cement Company, a subsidiary of Moore McCormack Resources Inc., Lehigh Portland Cement Company and Lone Star Industries, Inc.

SAND AND GRAVEL

Because it is a glaciated state, New York has abundant sand and gravel deposits. Production declined during the recent recession but has begun to recover (Table 2). The total number of operators statewide exceeds one thousand. Principal producers are Colonial Sand and Stone Company in Dutchess County, Roanoke Marboro Sand and Gravel Corporation in Suffolk County, and Valente Gravel Inc. in Albany and Rensselaer Counties. The material is used for road base, fill and concrete or bituminous aggregate. One firm produced industrial sand.

CLAY

Also as a result of the most recent glacial period, New York State contains many large and small clay deposits. The largest are in the Hudson River Valley where a series of post-glacial lakes provided an ideal depositional environment for the formation of thick clay layers. Other, smaller deposits occur in the area occupied by glacial Lake Erie, in the Ontario Lowlands, and in river valleys and small glacial lakes scattered across the state. Clays of Cretaceous age are exposed on Long Island. In contrast to other Atlantic seaboard states, New York possesses only small amounts of high grade kaolinite suitable for porcelain and white ware (Department of Commerce, 1951).

Eight producers are active in New York State. Albany County accounts for 55 percent of the total production, followed in decreasing order by Ulster, Broome, Onondaga, Orange and Erie Counties. The clay is used in cement manufacture, brick, pottery, and slips for glazing and bonding. The decrease in production shown in Table 2 resulted from the recent decline in construction activity.

PEAT

New York ranks seventh among twenty peat producing states. Peat bogs are present throughout the state; however, the most extensive are in the Finger Lakes region, the St. Lawrence lowlands, and the "Drowned Lands" of the Walkill Valley in Orange County. Six producers in Dutchess, Westchester, Broome, Seneca and Cattaraugus Counties mine peat bogs for agricultural uses. Production figures are given in Table 2.
### Table 2. Sand and gravel, peat and clay production, and value in New York, 1979-1983.

<table>
<thead>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>*</td>
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<td>21,918</td>
<td>21,255</td>
<td>17,569</td>
<td>19,050</td>
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<td>48,311</td>
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<tr>
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<td>597</td>
<td>312</td>
<td>352</td>
</tr>
<tr>
<td>$</td>
<td>3,027</td>
<td>2,479</td>
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<tr>
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<td>43</td>
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<td>$</td>
<td>630</td>
<td>917</td>
<td>811</td>
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</tr>
</tbody>
</table>

- Preliminary
- Thousand short tons
- Thousands of dollars
- Withheld to avoid disclosure of company proprietary data


In the 1920's attempts were made to mine peat in the Finger Lakes region for fuel, but these proved to be uneconomic. The New York State Energy Research and Development Authority is currently conducting a study in the northwest Adirondacks on the environmental effects of mining and burning peat.

**Gypsum**

Extensive deposits of gypsum which have been exploited since the 1820's occur along the outcrop belt of the Silurian Salina Formation (Figure 1). The gypsum occurs in beds six to sixty feet thick and is mined to within a few hundred feet of the surface. Deeper, the gypsum grades into anhydrite.

The United States Gypsum Company entered New York in 1903 and currently operates a mine in Genesee County (Figure 1). The gypsum is calcined in company-owned plants in Genesee and Rockland Counties. In 1982, output was up to 13 percent and value increased 18 percent. The product is used in wallboard and plaster. Out-of-state gypsum is imported by National Gypsum Company to Rensselaer County and by Georgia-Pacific Corporation to Westchester County for calcination. Total output of calcined gypsum was about 840 thousand tons.

**Emery**

The entire United States production of emery comes from two mines in Westchester County (Figure 1). The emery occurs in the upper Ordovician Cortland complex, a suite of mafic to ultramafic intrusive rocks (Friedman, 1956). Production from these small open-pit mines was down in 1981 but held steady in 1982. The product is used as a non-slip additive for stair treads and floors. Minor amounts are used for abrasives and tumbling media.

**Garnet**

Nationally, New York garnet production ranks second in volume and first in value. The leading producer, Barton Mines Corporation, is the oldest, continuously-operating, family owned mine in the United States (Figure 1). Recently, Barton Mines ceased operations at their historic Gore Mountain site and commenced mining on Ruby Mountain, a few miles to the northwest. The old Gore Mountain pit, with its spectacular exposures of garnet ore, remains open to academic groups and the public.

NYCO, a division of Processed Minerals Inc., also produces garnet as a by-product of wollastonite production. Garnet is used in coated and bonded abrasives, glass grinding and polishing, metal lapping and sand blasting.

**Talc**

New York ranks fourth nationally in the production of industrial talc. The talc occurs in metasedimentary rocks in the northwest Adirondack lowlands (Figure 1) and is interbedded with marble and various calc-silicates. Gouverneur Talc Company Inc., a subsidiary of R.T. Vanderbilt Company Inc., operates two mines, underground and open pit, in St. Lawrence County. Production was up 8 percent in volume and 22 percent in value in 1981, then down 19 percent in volume and 15 percent in value in 1982. The product is used mainly in ceramics and paint.

Clark Minerals Inc., a subsidiary of Whittaker, Clarke and Daniels Inc., grinds imported talc for use by the cosmetic and rubber industry at a mill located in St. Lawrence County.
WOLLASTONITE

Virtually all of the wollastonite produced in the United States comes from New York. The mineral is mined from metasedimentary rocks in the northeast and northwest Adirondack Mountains. NYCO has ceased mining operations at Willsboro in Essex County and opened a new pit at Lewis. Milling continues at Willsboro.

Gouverneur Talc Company operates an open-pit and an underground mine at Harrisville in Lewis County for wollastonite. The product of both the NYCO and Gouverneur Talc Company mines is used in ceramics, plastics, refractories, flux and insulating board.

ACKNOWLEDGMENTS

Contribution number 442 of the New York State Science Service.

REFERENCES


LIMESTONE RESOURCES FOR THE COAL INDUSTRY:
AN EVALUATION OF THE NEWMAN LIMESTONE (MISSISSIPPIAN)
ON THE CUMBERLAND OVERTHRUST BLOCK, SOUTHEASTERN KENTUCKY

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ABSTRACT

The Eastern Kentucky Coal Field is one of the major coal-producing regions of the world. With 1,240 underground mines and 1,800 surface mines active in 1982, the region is a large market for limestone products: rock dust for explosion abatement in underground coal mines; agricultural stone for surface-mine reclamation; construction stone for haulage roads; and, to a lesser extent, high-calcium limestone for acid-drainage control.

Movement of the Cumberland Overthrust Block has brought the Newman Limestone (Mississippian) to the surface on Pine Mountain in the southeastern part of the coal field, a region otherwise generally devoid of operable limestone deposits. To evaluate the Newman as a potential source of low-silica stone (less than 4% silica) for rock dust, 2,736 foot-by-foot samples for major-element analysis have been taken at 10 sites along the 125-mile length of Pine Mountain.

Analytical results show that thick deposits (41-64 feet) of low-silica stone are present in the lower Newman of Harlan and Letcher Counties. These deposits in the central part of the outcrop belt may be sufficiently thick to produce by selective quarrying or underground mining. Production, however, will be complicated by the steep dip of the beds and by displacement along small-scale faults within the Newman. In the northeastern and southwestern parts of Pine Mountain, low-silica zones range from 10 to 28 feet in thickness, but probably are too thin to produce economically from the dipping beds.

INTRODUCTION

The Eastern Kentucky Coal Field in the western part of the Appalachian Basin is one of the major coal-producing regions of the world. In the 1982 calendar year, 112,055,615 tons of coal were produced from 3,040 mines (Stanley, 1983). With its 1,240 underground mines and 1,800 surface mines, the region is a large market for limestone products: rock dust for explosion abatement in underground coal mines; agricultural stone for surface-mine reclamation; construction stone for haulage roads; and, to a lesser extent, high-calcium limestone for acid-drainage control. The coal-bearing rocks (Pennsylvanian) of eastern Kentucky, however, generally are devoid of operable limestone deposits, and a major part of the coal-industry requirements is met by haulage into the region from limestone operations west of the coal field and from adjoining states.

Movement of the Cumberland Overthrust Block along the Pine Mountain Overthrust Fault has brought the Newman Limestone...
(Mississippian) to the surface in the southeastern part of the coal field where it crops out in a narrow belt along Pine Mountain (Figs. 1 and 2). Five quarries operating in the Newman outcrop belt furnish part of the coal-industry requirements for construction and agricultural stone (Fig. 3). However, no rock dust has been produced from the Newman, and most, if not all, of the rock dust used by the more than 300 underground coal mines of southeastern Kentucky currently is obtained from sources outside the State. The availability of rock dust from a source within the coal field should contribute to a more economical operation for coal producers by lowering transportation charges, a major factor in determining the cost of limestone products. To evaluate the Newman as a potential source of low-silica stone (less than 4% silica) for rock dust, 2,736 foot-by-foot samples for major-element analyses have been taken at 10 sites along the 125-mile length of Pine Mountain. Two terms are used in this report for carbonate rocks with chemical characteristics suitable for the special requirements of coal producers and other industries. Low-silica stone designates carbonate rocks with a total (free and combined) silicon dioxide ($\text{SiO}_2$) content of 4 percent or less. High-calcium limestone designates carbonate rocks composed of 95 percent or more calcium carbonate ($\text{CaCO}_3$).

**Figure 1.** Regional geologic setting of Newman Limestone on Pine Mountain, southeastern Kentucky.

**Figure 2.** Generalized cross section showing structural setting of Newman Limestone on Pine Mountain. Adapted from Csejtey (1971).

**NEWMAN LIMESTONE**

The Newman Limestone of southeastern Kentucky is divided into two informal units, designated as the lower member and upper member. The lower member of the Newman is composed principally of limestone, with lesser amounts of dolomite and shale, and minor amounts of siltstone and sandstone (Fig. 4). The upper member consists of shale with various amounts of interbedded limestone, dolomite, siltstone, and sandstone. Operable deposits of limestone are restricted to the lower member.

The thickness of the Newman along Pine Mountain, as reported on the eighteen geologic quadrangle maps covering the outcrop belt, ranges from 350 feet (Rice and Maughan, 1978) to 800 feet (Rice and Wolcott, 1973). For the lower member, reported thicknesses range from 250 feet (Rice and Newell, 1975) to 520 feet (Rice and Wolcott, 1973).

The carbonate rocks in the lower member of the Newman can be described in general terms as consisting of four lithologic subunits. The combined thickness of the lower three subunits averages about 125 feet; the fourth (uppermost) subunit generally is more than 200 feet thick.

The basal subunit is composed of calcilutite and dolomite; chert is common. The overlying, or second subunit, which is the best potential source of low-silica stone, consists of bioclastic and oolitic calcarenite with
The third subunit, designated as the Taggard Red Member by Wilpolt and Marden (1959), is a useful stratigraphic marker in the central and northeastern parts of the outcrop belt. In the southwestern part of Pine Mountain, identification of the position of the Taggard presently is uncertain. The Taggard has an average thickness of about 15 feet and is composed of bioclastic calcarenite with interbedded green and red calcilutite, and red and green shale in the lower and upper parts. The distinctive red and green coloration, contrasting with the dominantly gray and greenish-gray limestones in the other subunits, facilitates its identification. However, zones of argillaceous limestone and dolomite with similar red and green coloration occur at other positions within the lower member; their occurrences are indicated as "reddish limestone" in Figures 4 and 5.

The fourth, or uppermost subunit consists of bioclastic calcarenite (in part oolitic) alternating with greenish-gray and dark-gray, argillaceous, silty calcisiltite and calcarenite. Zones of calcilutite, dolomitic limestone, dolomite, sandy limestone, chert, and shale occur in the subunit. Detrital quartz and clay content of the limestones generally increases upward in the unit, reflecting the gradation from the limestone-dominated lower member to the shale-dominated upper member of the Newman.

LOW-SILICA STONE FOR ROCK DUST

Pulverized limestone, dolomite, and other inert materials used as rock dust for explosion abatement in underground coal mines must meet specifications for silica content. Public Law 91-173, the Federal Coal Mine Health and Safety Act of 1969, specifies that these materials are not to contain more than a total of 4 percent free and combined silica (Federal Register Office, 1970).

Analysis of the foot-by-foot samples taken from the lower member of the Newman shows that potentially operable deposits of low-silica stone are present on Pine Mountain (Fig. 6; Table 2). The thickest deposits, 64 feet at the Harlan quarry (H) in Harlan County and 41 feet at the Hurricane Gap roadcut (HG) in Letcher County, are in the central part of the outcrop belt. They may be sufficiently thick to produce by selective
Table I. Key to sampled sections shown in report.

<table>
<thead>
<tr>
<th></th>
<th>Adams Stone Corporation Burdine quarry, Letcher County</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>Elkhorn Stone Company Elkhorn City quarry, Pike County</td>
</tr>
<tr>
<td>H</td>
<td>Nally &amp; Haydon, Inc. Harlan quarry, Harlan County</td>
</tr>
<tr>
<td>HG</td>
<td>Hurricane Gap roadcut, Letcher County</td>
</tr>
<tr>
<td>LB</td>
<td>Limestone Branch quarry (inactive), Whitley County</td>
</tr>
<tr>
<td>MB</td>
<td>Mountain Branch Limestone Company quarry, Pike County</td>
</tr>
<tr>
<td>P</td>
<td>Pineville quarry (abandoned), Bell County</td>
</tr>
<tr>
<td>W</td>
<td>Whitesburg quarry and mine (abandoned), Letcher County</td>
</tr>
</tbody>
</table>

Quarrying or underground mining. In the northeastern and southwestern parts of the outcrop belt, low-silica zones range in thickness from 10 to 28 feet, but probably are too thin to produce economically from the dipping beds. The rocks on Pine Mountain dip steeply, commonly 25° to 35° SE, into the Middleboro Syncline (Froelich, 1973).

Production from an interval encompassing two low-silica zones and an intervening ledge partly composed of low-silica stone may be feasible locally. At the Harlan quarry (H), Harlan County, two low-silica zones are present in the lower part of the member: 64 feet (av. 0.82% silica) and 25 feet (av. 1.01% silica) (Fig. 6). The two zones are separated by a 7-foot ledge in which two of the 1-foot samples have a silica content greater than 4 percent (4.08% and 4.90%). For the 96-foot interval encompassing the two low-silica zones and intervening 7-foot ledge, the average silica content is 0.97 percent.

The thickest deposits of low-silica stone in the Newman occur in the calcarenitic interval below the Taggard (Figs. 5 and 6). The calcarenite is bioclastic (mainly micrite-enveloped grains) and oolitic. Zones of secondary dolomite occur in the thick calcarenites in the central part of Pine Mountain. Northeastward along the outcrop belt, varied amounts of calcilutite (in part low-silica stone) and argillaceous "reddish limestone" are interbedded with the calcarenite below the Taggard, resulting in thinner low-silica zones.

Table 2. Average values for foot-by-foot analyses of selected low-silica deposits in lower member of Newman Limestone on Pine Mountain. (See Table I for key to sampled sections.)

<table>
<thead>
<tr>
<th></th>
<th>Thickness (Feet)</th>
<th>CaCO₃</th>
<th>MgCO₃</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>CaO</th>
</tr>
</thead>
<tbody>
<tr>
<td>LB</td>
<td>27.5</td>
<td>94.76</td>
<td>4.18</td>
<td>0.30</td>
<td>0.18</td>
<td>0.10</td>
<td>0.03</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>H</td>
<td>64.0</td>
<td>91.37</td>
<td>6.82</td>
<td>0.82</td>
<td>0.12</td>
<td>0.14</td>
<td>0.04</td>
<td>0.06</td>
<td>0.04</td>
</tr>
<tr>
<td>HG</td>
<td>41.0</td>
<td>89.2</td>
<td>8.2</td>
<td>1.65</td>
<td>0.19</td>
<td>0.15</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>MB</td>
<td>22.0</td>
<td>95.51</td>
<td>1.47</td>
<td>1.85</td>
<td>0.18</td>
<td>0.09</td>
<td>0.06</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>

The increased amount of low-silica calcarenite in the southwestern part of Pine Mountain, as indicated by the Limestone Branch quarry (LB), Whitley County, suggests that the area warrants exploration for exploitable deposits (Fig. 4). Common sources of silica in Newman calcarenites are detrital clay and quartz, chert bodies, and selectively silicified fossil grains and fragments.

A large market for rock dust exists in the coal-producing areas northwest and southeast of Pine Mountain. In the 1982 calendar year, 50,717,754 tons of coal were produced by 987 underground mines in 11 southeastern Kentucky counties (Fig. 3; Stanley, 1983). Rock-dust requirements in the face area of underground coal mines average about 10 pounds of rock dust per ton of mined coal (Ralph Perry, Kentucky Department of Mines and Minerals, oral communication, 1983). In
terms of 1982 coal-production figures, a minimum of about 250,000 tons of rock dust would be required by underground coal mines in 11 southeastern Kentucky counties.

Additional quantities of rock dust are needed during mining to maintain the incombustible content of the total amount of dust in the mine, particularly along conveyor-belt haulageways. The incombustible content of the combined coal dust, rock dust, and other dust is to be not less than 65 percent; in the return aircourses, the incombustible content is to be not less than 80 percent (Federal Register Office, 1970). A higher incombustible content is required where methane is present in any ventilating current.

Figure 6. Distribution and thickness of low-silica deposits in lower member of Newman Limestone on Pine Mountain. Datum is top of Taggard. (See Table I for key to sampled sections.)

**HIGH-CALCIUM LIMESTONE FOR ACID-DRAINAGE CONTROL**

Limestone is used to neutralize acid drainage from coal mines and refuse piles. The most effective limestones have a high calcium carbonate content and low magnesium carbonate content (Bituminous Coal Research, 1970, 1971; Ford, 1974; Hill, 1974; Hill and Wilmuth, 1971). Dolomite and dolomitic limestone, which contain appreciable amounts of magnesium carbonate, react very slowly with acidic waters and are not effective neutralizing agents. The limestone should have a low percentage of inert constituents, such as silica and alumina; their presence means less available alkalinity per ton of stone.

Nine zones of high-calcium limestone are present in the sampled sections on Pine Mountain, occurring within nine of the low-silica zones. The high-calcium deposits range from 10 to 37 feet in thickness, but mainly are less than 20 feet thick. Individual deposits probably are too thin to produced economically from the steeply dipping beds. A potentially operable thickness of high-calcium limestone, encompassing two high-calcium zones and an intervening ledge partly composed of high-calcium stone, is present at the Harlan quarry (H), Harlan County. The 69-foot section of limestone (principally calc-
arenite) immediately underlying the Taggard at the quarry (Figs. 5 and 6) averages 96.35 percent calcium carbonate; six of the 1-foot samples in the interval have a calcium carbonate content of less than 95 percent.

**EXPLOITATION**

Limestone operations on Pine Mountain mainly have produced stone from steep-walled trenches or pits which have faces commonly as much as 200 feet high. The trenches essentially are oriented along the strike of the steeply dipping limestone. One open-pit operation in Pike county currently employs a series of benches oriented along strike. Stone has been produced by underground mining at a site in Letcher County.

The production of low-silica stone or high-calcium stone from the Newman on Pine Mountain will require either selective quarrying or underground mining. Potentially exploitable deposits are overlain by a thick sequence of limestones that contain a relatively high percentage of silica and other noncarbonate constituents. Both open-pit benching, either on or within the deposit, and underground mining will permit the production of chemically pure stone without contamination from overlying limestones which do not meet specifications for maximum silica or minimum calcium carbonate content. Underground mining also offers the potential for year-round operation and avoids costs of overburden removal and reclamation.

Production will be complicated by the steep dip of the beds, commonly 25° to 35° (Froelich, 1973), and by faulting within the Newman. Small-scale thrust faults are relatively common in the Newman and may displace a deposit of chemically pure stone. Repetition of beds by thrust faulting may result in a deposit locally having an apparent thickness greater than its true thickness. Faults and associated fractures are avenues for the movement of water, soil, and other materials into the limestone body.

Coring will be required to determine the thickness and extent of a deposit of chemically pure stone and to establish the presence of sufficient reserves to support economic exploitation. Cores will provide samples for chemical analysis and physical testing.

**ACKNOWLEDGMENTS**

Investigation of limestone and dolomite resources in eastern Kentucky for coal-related industries has been supported by the Kentucky Energy Cabinet, principally through grants from the University of Kentucky Institute for Mining and Minerals Research. Major-element analyses were performed by Catherine M. Poole, Mary E. Barron, and Charles Jones at the Kentucky Center for Energy Research Laboratory. The Hurricane Gap section (HG), sampled during an earlier investigation by Frank H. Walker and Robert E. Hauser, was analyzed at the Mining Engineering Laboratory, University of Kentucky, under the supervision of Thomas A. Kendall.

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NON-METALLIC MINERAL DEPOSITS
OF ALPINE PERIDOTITE-SERPENTINITE BODIES

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The University of Michigan
Ann Arbor, Michigan

ABSTRACT

Alpine-type peridotite-serpentinite bodies, which, by the plate-tectonic hypothesis, represent fragments of oceanic crust and mantle tectonically elevated into continental blocks above a subduction zone in the environment of an oceanic plate-continental plate collision, are important sources for an extremely varied assemblage of non-metallic mineral products. The general nature of these non-metallic deposits depends upon 1) the extent and type of the serpentinization process, and 2) the extent and type of post-serpentinization deformation and/or metasomatism. Thus the complete roster of these deposits falls into three genetic categories:

1. Minerals that are essential ingredients of the unaltered peridotites.
2. Minerals whose formation was part of the serpentinization process.
3. Minerals formed as the result of post-serpentinization deformation or post-serpentinization metasomatism.

The complete list of non-metallic mineral and rock products that have been obtained from Alpine bodies includes: dunite (olivine); chromite (refractory grade); serpentine asbestos - both vein-type (Quebec) and massive (California) types; amphibole asbestos (anthophyllite); corundum - both vein-type in hydrothermal albitites and disseminated ruby in hornblendeite; talc and steatite; magnesite; verde antique; sepiolite; vermiculite; and a variety of gemstones, e.g., jadeite, nephrite, California jade (vesuvianite) and chrysoprase. Potential products are sodic plagioclase from contact-metasomatic albitite bodies and brucite disseminated in serpentinites. In addition, several metallic elements have been produced from Alpine peridotites-serpentinites; Cr from metallurgical grade chromite, Ni from garnierite-group minerals, and native platinum.

The two North American Alpine peridotite belts (the Appalachian belt from Newfoundland to Alabama, and the west-coast belt from Alaska to California) differ significantly in their tectonics, geologic age, and degrees of serpentinization and post-serpentinization alterations - hence also in the nature of their non-metallic mineral products.

ALPINE-TYPE PERIDOTITES

Alpine-type peridotite-serpentinite bodies occur in folded and faulted geosynclinal (meta-) sediments of orogenic belts. Many were involved to varying degrees in the orogeny resulting in the metamorphic and metasomatic transformation of peridotite, wholly or in part to serpentinites. In places these are accompanied by varied assemblages of such species as talc, carbonates, amphiboles, chlorites, albite, among others. Individual bodies, small as compared with stratiform lopoliths, may be petrologically either homogeneous or variable, in irregular (non-layered) patterns. In addition to various peridotites (dunite, pyroxenites), gabbros also appear in the complexes, and in some areas dioritic and
granophyric rocks also are comagmatic.

The unaltered bodies may show discontinuous layering. This, plus strong preferred orientations of the lattices of the olivines, has been interpreted as the result of plastic flow during intrusion of largely solid material. Contact metamorphic effects are generally absent. Tectonic flowage of serpentinite masses along faults is clearly established, in some cases all the way to the surface where they were extruded as breccias, including melanges. Serpentinization results from low-temperature reactions between the cooling peridotite bodies and waters encountered during their upward journey, and the degree of serpentinization is governed by the length of the journey and the temperatures and the amount of water encountered.

GEOLOGY

The Appalachian belt of ultramafic rocks stretches along a sinuous southwest-trending line from Newfoundland to Alabama, some 1800 miles. The bodies, which occur in highly deformed rocks of Precambrian to lower Paleozoic age, are probably mainly of Taconic age (Ordovician) (Hess, 1937). The emplacement of the ultramafic Mt. Albert, Quebec, intrusion is dated at 495 my. (Lower Ordovician). The belt of Quebec Appalachian ophiolites and their associated melanges defines the Brompton lineament marking the early Paleozoic margin of northeastern North America. In central western Maine an ophiolite sequence is early Paleozoic in age, probably Cambrian. In Vermont the serpentinites are regarded as Devonian in age (Jahns, 1967).

The double nature of the belt was documented by Hess (1937), in which he recognized a western well-populated arm separated by about 100 miles from a discontinuous, sparsely represented eastern zone. The arms of the belt are about 10 miles wide. Individual bodies range from sills or sheets through thick pods to irregularly tabular masses, some up to several miles across. Hess (1937) regarded the location of the belt as marking the position of the zone of maximum orogeny. Modern plate-tectonic models visualize the peridotite-serpentinites as components of ophiolite belts that represent remnants of ancient oceanic lithosphere generated at mid-oceanic ridges and subsequently incorporated into continental margins or within zones of convergence.

During Devonian time, the ultramafic bodies of Quebec underwent further deformation (Acadian orogeny) which thoroughly fractured the serpentinites, allowing entry of solutions possibly in part derived from nearby granitoid plutons. Serpentinites of Pennsylvania also exhibit the results of multiple deformations, but it is uncertain whether the multiplicity occurred within the framework of the Taconic orogeny or whether the younger Acadian orogeny participated (Lapham, 1967). The Alpine bodies of the Blue Ridge belt of the southern Appalachians have a multiphase deformational history. Raymond and Swanson (1981) correlate five deformational events: D<sub>1</sub> and D<sub>2</sub> with Precambrian mantle sea-floor spreading, and/or accretion events; D<sub>3</sub> with the Taconic orogeny; D<sub>4</sub> with the Acadian orogeny; and D<sub>5</sub> with Appalachian/Hercynian events.

In general the ultramafic bodies in the southern part (North Carolina and Georgia) of the Appalachian belt show lesser serpentinization and other alteration than do those from Virginia northward (Table I). The forsterite deposits of North Carolina and Georgia have been described by Hunter (1941), who recorded 275 peridotite bodies in the Blue Ridge of these two states, many of them dunite. He calculated that they contain a minimum reserve of 230,000,000 tons of dunite, averaging 48.07% MgO. Most of this reserve is in about 25 large dunite bodies that are relatively free of serpentinization and other alterations. The famous Webster-Addie ultramafic "ring", the largest in the Blue Ridge, in which several dunite quarries have been operated, was a concordant sheet that was subsequently domed and deformed and later erodionally decapitated (Miller, 1953).

The Pacific Coast ultramafic zone stretches from Baja California into Alaska. Like its Appalachian counterpart it is multiple, and its development has been an extremely complex and lengthy process. In California two belts are recognized: 1) A Coast Range belt, the younger, intruded in Late Cretaceous time and extensively modified by Tertiary high-angle, strike-slip faults of the San Andreas system; 2) A Sierra
Nevada - Klamath Mountain belt, the older, intruded during Late Jurassic (Nevadan) time. The ultramafic bodies formed huge sheets floored by regional thrust faults. The Coast Range bodies are integral components of ophiolite complexes which are interpreted as exposed Mesozoic oceanic crust (Bailey et al., 1970).

In middle and northern Washington the Cascade belt of peridotite and serpentinite trends N 30° W along the range. Some ultramafic bodies are older than the regional metamorphism; others are involved with the Cretaceous thrusts, and still others are post-

<table>
<thead>
<tr>
<th>Location</th>
<th>Minerals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newfoundland</td>
<td>Serpentinite, some fresh dunite</td>
</tr>
<tr>
<td>Quebec</td>
<td>Serpentinite, asbestos, steatite</td>
</tr>
<tr>
<td>Maine</td>
<td>Serpentinite, steatite, carbonatite</td>
</tr>
<tr>
<td>Vermont</td>
<td>Serpentinite, asbestos, talc, verde antique</td>
</tr>
<tr>
<td>New York, New Jersey</td>
<td>Serpentinite, chromite</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>minor talc and corundum</td>
</tr>
<tr>
<td>Maryland</td>
<td>Serpentinite, talc (soapstone), peridotites less altered</td>
</tr>
<tr>
<td>Virginia</td>
<td>Serpentinite, considerable unaltered</td>
</tr>
<tr>
<td>North Carolina</td>
<td>peridotite, dunite, corundum, minor</td>
</tr>
<tr>
<td>Georgia</td>
<td>chromite, asbestos, talc, Ni-serpentine</td>
</tr>
<tr>
<td>Alabama</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Alterations and economic mineral products in ultramafites of the Appalachian belt (North to South).

Early Tertiary. Thus pre-, syn- and post-orogenic types are present (Ragan, 1967). Some of the Cascade peridotites are entirely metamorphic, formed by deserpentinization under middle amphibolite-facies conditions (Vance and Dungan, 1977).

In the Rocky Mountain Cordillera of British Columbia and the Yukon Territory the ultramafic intrusions are spread in age from Devonian to Early Jurassic but are mainly either Devonian to Early Mississippian, or Pennsylvanian to late Middle Triassic. Some of the serpentinites were re-intruded tectonically during younger orogenies.

In southeastern Alaska, 35 ultramafic bodies intruded during early Middle Cretaceous time (100 - 110 my.) are in a belt 350 miles long and 35 miles wide (Taylor, 1967). An older, four-unit belt lies 60 to 70 miles to the west. These complexes resemble classic Alpine ultramafites in their restriction to eugeosynclinal orogenic belts but differ in the presence of concentric zoning and pronounced contact metamorphic and metasomatic effects ("Alaskan type").

A relatively large percentage of the California ultramafic bodies have been serpentinized, many completely, particularly those of the southern and central part of the state (Table 2).

Relatively fresh dunite occurs in some of the Washington ultramafic bodies, and some of these have been explored. Noteworthy are the Twin Sisters body of the Twin Sisters Range, 20 miles east of Bellingham, and Olivine Hill on the southeast corner of Cypress Island, 80 miles northwest of Seattle. The Twin Sisters body is the largest single peridotite mass in the Cascade belt, with an elliptical outcrop area of about 90 square kilometers (Ragan, 1967). It intrudes Shuksan thrust plates and overlying Paleocene sediments; hence it is post-orogenic and Tertiary in age. Reserves at Olivine Hill are calculated as 50 million tons; small amounts have been mined.

**ALTERATIONS AND MINERAL DEPOSITS**

The secondary rocks and minerals deposits formed in Alpine ultramafites involve mainly:

1. The reassignment of Mg from high-temperature silicates (olivine, pyroxene), with the addition of water into low-temperature hydrous Mg-silicates such as serpentine minerals, chlorite and talc; or, with the addition of CO₂, into magnesite.

2. The partial oxidation of Fe²⁺ from these silicates to form secondary magnetite.

3. The reassignment of Ca from pyroxenes and anorthite, with the addition of water, to form low-temperature hydrous Ca-silicates such as prehnite, zoisite, hydrogarnet, tremolite and xonolite (rodingite). With the addition of CO₂, calcite is formed.

4. The release of "excess" Al from
plagioclase with hydration to form amphiboles or zoisite, and to generate corundum.

5. The introduction of Na (and some released from calcic plagioclase) to form albite, jadeite and nephrite.

The general nature of the non-metallic deposits depends upon 1) the extent and type of the serpentinization process and 2) the extent and type of post-serpentinization deformation and/or metasomatism. Thus the complete roster of these deposits falls into three genetic categories:

1. Minerals that are essential ingredients of the unaltered peridotites.

2. Minerals whose formation was part of the serpentinization process.

3. Minerals formed as the result of post-serpentinization deformation or post-serpentinization metasomatism.

The complete list of non-metallic mineral and rock products that have been obtained from Alpine bodies includes: dunite (olivine); chromite (refractory grade); serpentine as aggregate; serpentine asbestos - both vein (Quebec) and massive (California) types; amphibole asbestos (anthophyllite); corundum - both vein type in albitites and disseminated ruby in hornblendite; talc and steatite; magnesite; jadeite, nephrite, California jade (vesuvianite) and chrysoprase. Potential products are sodic plagioclase from contact-metasomatic albitite bodies and brucite disseminated in serpentinites. In addition, several metallic elements have been produced from Alpine peridotites-serpentinites: chromium from metallurgical grade chromite, nickel from garnierite-group minerals, native platinum, and josephinite.

**ASBESTOS**

Asbestos deposits of Alpine peridotites occur as veins, disseminations and total replacements of dunite and harzburgite. The asbestos is chiefly chrysotile; much less abundant are asbestiform anthophyllite and tremolite; asbestiform soda-tremolite is exceptional.

The action of water on forsterite below 400°C can produce serpentine and brucite:

\[
2\text{Mg}_2\text{Si}_3\overset{3}{\text{O}}_6 + 3\text{H}_2\text{O} \rightarrow \text{Mg}_3\text{Si}_2\overset{5}{\text{O}}_5(\text{OH})_4 + \text{Mg(OH)}_2
\]

Olivine + Water \rightarrow Serpentine + Brucite

Brucite probably occurs in less than one-third of all serpentinites (Thayer, 1966), but was long overlooked owing to its superficial optical similarity to antigorite.

Enstatite may also be serpentinized:

\[
6\text{MgSiO}_3 + 3\text{H}_2\text{O} \rightarrow \text{Mg}_3\text{Si}_2\overset{5}{\text{O}}_5(\text{OH})_4 + \text{Mg}_3\text{Si}_4\overset{10}{\text{O}}_10(\text{OH})_2
\]

Enstatite + Water \rightarrow Serpentine + Talc

A mixture of olivine and enstatite reacting with water yields serpentine:

\[
\text{Mg}_2\text{SiO}_4 + \text{MgSiO}_3 + 2\text{H}_2\text{O} \rightarrow \text{Mg}_3\text{Si}_2\overset{5}{\text{O}}_5(\text{OH})_4
\]

Olivine + Enstatite + Water \rightarrow Serpentine

In the equal-volume serpentinization process a major obstacle has always been the requirement of removing MgO and SiO₂ in large amounts. At low temperatures, SiO₂ has a large solubility, but MgO does not. If saline solutions are the main agents in serpentinization instead of relatively pure water solutions, the equilibrium becomes (Leonardos and Fyfe, 1967):
The sodium chloride solutions are obtainable from modified seawater or from seawater-saturated sediments, both available in ophiolite-eugeosynclinal environments. The sodium silicate solutions derived via the above reaction are postulated as the main genetic agent for the manifold manifestations of associated albite rocks. If CO$_2$ is present in solution, so that excess magnesium is removed as carbonate, serpentine and magnesite are formed up to 500°C.

Serpentinites are rocks consisting of mixtures of various serpentine species and subordinate other minerals. All three polymorphs, chrysotile, antigorite and lizardite, can occur together in serpentinites. Accessory minerals include chlorite, talc, carbonates, brucite, anthophyllite, tremolite-actinolite, and magnetite. Residual species are olivine, enstatite, chromite and other spinels.

Many serpentinites display cataclastic effects, such as fractures, shear zones and faults, which in many cases are strongly intensified in the marginal parts of the serpentinite bodies. Major faults and mega-shear zones in serpentinite generally are devoid of asbestos, but intricately fractured rock masses bordering such fundamental structures may be occupied by stockworks of asbestos veins. Optimum open-fracturing conditions are developed in zones between rocks of contrasting competency. For example, completely serpentinized bodies tend to fail by flow or shear, whereas only partly altered adjacent peridotites can sustain complex open-fracture systems serving to localize asbestiform serpentine (Shride, 1973).

Most chrysotile asbestos deposits are of the vein type. Individual veins tend to be discontinuous and short, branching and pinching abruptly. Ore deposits usually consist of a more-or-less rectilinear stockwork of veins with enclosed blocks of barren serpentinite. These deposits are irregular in shape, and erratic in grade. Less common are "ribbon veins" - narrow zones of subparallel, closely-spaced veins divided by thin serpentinite slabs. Although usually not more than a few inches to a few feet wide, such zones may be high-grade and extensive. Slip-fiber veins are localized along faults or minor slip planes.

Tremolite asbestos, the most common type of amphibole asbestos, usually occurs as slip-fiber veins along fault zones. Such veins occur chiefly in serpentinite but also are known in various other wall rocks, both metamorphic and igneous. Anthophyllite asbestos also occurs chiefly in altered peridotites in pods of mass-fiber as much as 200 feet long and 50 feet thick (Georgia and North Carolina). Both of these types of deposits are very minor sources of asbestos.

A non-vein type of deposit is represented by that at Coalinga, California, where an intensely sheared serpentinite body, 14 by 4 miles in size, consists chiefly of flaky serpentine minerals. In the southeastern half of the mass, minute chrysotile fibers occur disseminated among their micaceous relatives in amounts locally over 50 percent. The rock is considered ore if it yields 20 to 25 percent fiber (group 7 only) upon milling (Shride, 1973).

In the Pacific serpentinite belt asbestos deposits are categorized as follows (Shride, 1973):

1. Some 90+ deposits in California, over half of which are chrysotile, the rest tremolite and anthophyllite. Two deposits, Copperopolis and Coalinga, have been significant producers.

2. A few prospects in Oregon, of chrysotile.

3. A number of prospects and one important deposit (Cassiar) in British Columbia.

4. Various prospects near the Kobuk River in northwestern Alaska.

In the Appalachian belt commercial asbestos deposits are confined to short segments:

1. North coast of Newfoundland, e.g., the Advocate deposit.

2. Eastern Townships of Quebec,
the world's largest district, yielding about 70 percent of the world's production.


4. Western North Carolina and northeastern Georgia - solely anthophyllite.

The requisite idealized sequence of events leading to the maximum development of asbestiform serpentine deposits is:

1. Intrusion of Alpine-type ultramafites and their subsequent pervasive but incomplete serpentinization.

2. A second period of deformation involving tensional and torsional stresses. Solutions, hydrothermal, connate-metamorphic, or both, extended the serpentinization, remobilized chrysotile and deposited it as cross-fiber veinlets developed in partly altered rocks of competency sufficient to sustain fractures rather than fail by flowage.

CORUNDUM

In Alpine-type ultramafic bodies corundum occurs:

1. In plumasites; sodic plagioclase-corundum-biotite rocks, in veins or "dikes". Marundites are similar feldspar-corundum-margarite rocks.

2. As disseminations in uralitized ultramafic rocks.

Plumasites have been controversial rocks ever since they were first described by Lawson (1901) from the lower slopes of Spanish Peak, Plumas County, California, where the rocks occur in a 45-foot "dike" cutting an amphibolite peridotite. Similar rocks were found in Natal, Transvaal, Pennsylvania, North Carolina and Georgia, the Urals, and Finland. Variously interpreted as syenitic pegmatites oversaturated in $\text{Al}_2\text{O}_3$, as desilicated granite pegmatites and aplites, as hybrid pegmatites "contaminated" by ingestion of $\text{Al}_2\text{O}_3$-rich minerals, and as hydrothermal veins, they still present some enigmatic features.

Their general characteristics have been summarized by Larsen (1928):

1. All are irregular, dike-like, or vein-like in form.

2. All cut Alpine-type peridotites or serpentinites.

3. Quartz is rare; feldspar is usually sodic, rarely calcic, plagioclase. Variable amounts of corundum are present; locally it is the chief mineral. Biotite (or vermiculite) is abundant in feldspar-poor veins. Secondary muscovite, margarite and diasporic may be abundant. Other constituents are garnet, tourmaline, hornblende, zoisite, chlorite, scapolite, apatite and spinel.

4. Some bodies are zoned with a core of granitic pegmatite or aplite and have albitic outer zones. Most are petrologically irregular.

5. Between the veins of their ultramafic hosts are a series of zones which are anchimonominal. From the vein outward the complete idealized sequence is:

a) Albitite or corundum albitite (vein)

b) Vermiculite (from phlogopite or biotite), some chlorite

c) Chlorite-talc

d) Actinolite

e) Anthophyllite

f) Ultramafic rock (host)

Together these zones range from a few inches to about two feet in width, with little correlation between their thicknesses and that of the central plumasite or albitite. They are fracture-
controlled replacement bodies in which $K_2O$, $Al_2O_3$, $SiO_2$, $H_2O$ and in some cases $CaO$ have been added to the peridotite.

The problem of albitite and plumasite veins is only one facet of the general problem of the association of albitite-sodium-silicate rocks with Alpine-type serpentinites. The other variations include:

1. Discontinuous zones of albitite metacrysts in country-rock schist outside the chloritic "blackwall" zone around some Vermont serpentinites.

2. Jadeite bodies and jadeite-albite veins cutting albite-crossite schists, (New Idria district, California; Coleman, 1961).

3. Contact-metasomatic albitites replacing sediments and volcanic rocks along serpentinite contacts (Mocassin Quadrangle, California; Leonardos and Fyfe, 1967).

Sedimentary and volcanic rocks that occur along serpentinite contacts or as tectonic inclusions in serpentinite commonly display alterations involving relative enrichment in sodium accompanied by Ca-Mg invasion (rodingite) from the serpentinite (Coleman, 1963).

At Buck Creek, North Carolina, in addition to plumasite veins, ruby corundum occurs disseminated in a hornblende formed by replacement of amphibole troctolite (Hadley, 1949). The rock consists chiefly of bright green (chromian) edenite ("smaragdite"), minor calcic plagioclase, and scattered ruby and chromite grains. The ruby forms tiny basal plates 0.03 to 2.0 mm across. The formation of the corundum is envisaged as a two-stage process by Hadley (1949):

1. Formation of coronas around olivine grains along plagioclase contacts; the coronas consists of amphibole and spinel.

2. Formation of the aluminous edenite and destruction of the spinel, the excess alumina deposited around and replacing chromite as corundum.

**MISCELLANEOUS MINERALS**

Both jadeite, a pyroxene of ideal composition $NaAlSi_2O_6$, and nephrite, a megascopically similar amphibole of the tremolite-actinolite series, occur in altered peridotites of the Alpine type. Jadeite is the principal constituent of jade, a semi-precious gemstone. Nephrite is of similar value. Some "jades" are jadeite-nephrite intergrowths. Both occur in or near serpentinites as pods, lenses and veins a few feet to 200 feet long. Jade ranges in color from white to green; only a small percentage normally is of good gem quality. Some is banded. Jadeite masses may contain natrolite, pectolite and albite as "impurities". Contact zones between jadeite bodies and serpentinite contain hydrogrossularite, lawsonite, pumpellyite and amphibole (Yoder and Chesterman, 1951).

In the Pacific serpentinite belt jade and nephrite have been found in:

1. California (see Wright, 1957), including beach boulders in the Cape San Martin region. Both jadeite and nephrite.

2. Oregon, Curry County, nephrite in serpentinite.

3. British Columbia, serpentinite in the Fraser River Valley. Both nephrite and jadeite as alluvial cobbles and boulders.

4. Alaska, Jade Mountain on the Kobuk River Valley. As nephrite both in stream boulders and in serpentinite.


"Californite", a massive variety of vesuvianite found at several localities in northern California, also is a semi-precious gemstone. The green to gray, highly fractured material which resembles jade occurs in veins and lenses in serpentinite.
Although some talc deposits are formed as part of the general consequences of the alteration of Alpine-type peridotites to serpentinites, most commercial talc deposits are of metamorphic origin. Magnesite deposits also are of several genetic types; most are replacements in various carbonate rocks. Minor vein occurrences of magnesite occur in some serpentinites.

REFERENCES


Larsen, E.S. (1928) A hydrothermal origin of corundum and albitite bodies: Econ. Geol., v. 23, p. 398-433.


Sodium sulfate (Glauber's salt) is required in the pulp and paper industry and is also widely used in detergents as a replacement for phosphates. Future uses of this industrial mineral include solar energy storage and as an ingredient in glassmaking.

Worldwide, there are few commercial deposits of sodium sulfate. North America has major accumulations of this commodity located primarily in Montana, North Dakota, Saskatchewan and Alberta. These northern Great Plains deposits form in shallow ephemeral lakes that range in area from less than one square kilometer to more than 300 square kilometers. There is a wide variety of basin shapes from small kettles to large riverine channels. The basin morphology is controlled primarily by the immediate postglacial history of the area.

The postglacial sediment column within these deposits generally consists primarily of thickly-bedded mirabilite crystal with variable amounts of other evaporite minerals (bloedite, epsomite, natron), organic debris, and clay- to sand-sized clastic material. The mirabilite is both endogenic and authigenic in origin, precipitating from supersaturated intermittent surface brines as well as from pore waters. Variations in mineralogy and brine chemistry occur between basins and through time within a single basin.

The stratigraphic sequence within a deposit is usually complex. Lateral facies changes and post-depositional processes, including solution/reprecipitation of the crystal bed and salt karsting, may modify the sedimentary record considerably.

The origin and evolution of these deposits is still problematic. Their chemistry is likely due to a complex series of reactions including cation exchange and dissolution of subsurface evaporite and carbonate bedrock by circulating groundwater. These playa basins, however, are just one stage in an evolutionary spectrum which also includes the deeper saline lakes of the region.

INTRODUCTION

Sodium sulfate has been produced commercially from playa lake deposits and brines in the northern Great Plains for over 65 years. Some of man's earliest industrial efforts in the northern Plains region were centered on salt extraction from alkaline sloughs and lakes of southern Saskatchewan. Total composite reserves for this region (North Dakota, Montana, Saskatchewan, and Alberta) are among the largest in the world (Weisman and Tandy, 1975). Presently, about 500,000 tonnes of sodium sulfate are produced per year from ten "active" deposits. The total annual value of this product normally exceeds $40,000,000 making this region the world's leading producer.

Despite their economic importance, until recently there has been very little modern sedimentological or geochemical data collected and essentially no stratigraphic information on these deposits. A knowledge of the
sedimentary processes, mineralogy, and post depositional alterations of the sediment is essential not only to assess the potential of the resource, but also to evaluate both the short-term changes and long-term evolution of the depositional system.

In addition to developing the required knowledge base for exploitation of this resource, investigation of these deposits is important for several other reasons. Saline and hypersaline lacustrine environments are one of the least understood depositional regimes in sedimentary geology. A study of the evaporite mineralogy and its relation to basin morphology, hydrochemistry, and brine evolution will do much to advance our knowledge of terrestrial evaporite sequences. Theoretical models of these sequences are becoming increasingly important in both the petroleum and mineral exploration industries. Similarly, diagenetic reactions involving the precipitated evaporite minerals and clastic grains are very important in the generation of other saline minerals as well as authigenic silicates (such as zeolites and clay minerals) and carbonates. Details of these reactions, however, are poorly known and infrequently studied.

These lakes are also useful for paleoclimatic studies. The sediments in the playas are a sensitive indicator of any changes in the hydrologic budget within each drainage basin. Thus, the stratigraphic record in the lakes should be a good reflection of both short-term as well as long-term climatic fluctuations.

Finally, elevated levels of heavy metals such as copper, zinc, and lead are present in the sediments of several of these deposits. Mining and extraction of the salts can mobilize these elements, thereby creating a potential environmental problem.

The purposes of this paper are to: (a) review the general geologic and hydrologic setting of the sodium sulfate deposits, (b) briefly discuss the modern sedimentary processes operating in the basins, and (c) examine the evolution of the deposits as suggested by the sedimentary fill in representative basins.

REGIONAL SETTING

Topography, Climate, and Hydrology

The sulfate deposits discussed in this paper are found in the Great Plains physiographic province of North America (Fig. 1). This region is characterized by hummocky to gently rolling topography interspersed with numerous deep, often terraced valleys that have been cut by glacial meltwater. The Missouri Coteau, a distinct 50- to 100-km wide band of knob and kettle topography, is the dominant geomorphic feature of the area.

In general, the northern Great Plains experience a cold, continental, semi-arid climate. Stable, high-pressure continental and Arctic air masses dominate during the winter months giving the region its characteristic cold, clear weather. Continental and Polar air masses also dominate the summer weather resulting in warm and dry conditions. The region is south of the main paths of winter and summer low-pressure systems, but pressure and temperature gradients associated with these systems often lead to the area being influenced by high winds. Mean daily temperature during January over most of the region is about -17°C; during July it is +20°C. However, the most important characteristic of the region in terms of temperature is its extreme variability. There are wide...
variations in temperature between seasons, between years, and between day and night. This temperature variability has a significant impact on many chemical and physical aspects and processes of the salt lakes of the region.

In addition to temperature, another important climatic factor influencing the region is the high evaporation/precipitation ratio. The mean annual precipitation is about 30 cm; however, more than 125 cm of water can be lost per year through evaporation from open water bodies (CNC/IHD, 1978).

Large areas of the northern Great Plains are characterized by internal drainage. Because of its lack of integrated drainage, the Missouri Coteau contains many individual closed basins which often contain salt lakes. Other large areas of internal drainage also exist in central and western Saskatchewan and eastern Alberta. Together, these basins comprise one of the largest areas of closed drainage in North America.

Bedrock and Glacial Geology

The northern Plains are underlain by nearly horizontal Phanerozoic sedimentary rocks of thicknesses up to 5,000 m (Fig. 2). The Paleozoic section consists mainly of a series of stacked carbonate-evaporite cycles, whereas the overlying Mesozoic and Cenozoic bedrock is dominantly sand-shale sequences. Dissolution of the highly soluble Paleozoic evaporites by groundwater has modified the relatively simple structural relationships of the flat-lying formations and has created collapse structures over much of the area (Christiansen, 1967a, 1971). Grossman (1968) maintains that this evaporite dissolution has provided a source of ions for the many salt lakes of the region.

The bedrock surface has also been strongly modified by preglacial erosion (Whitaker and Pearson, 1972). By the start of the Quaternary Period a mature, dendritic drainage pattern had been established over much of the northern Plains (Stalker, 1961; Christiansen, 1967b). In general, this ancestral pattern is reflected by today's streams, except that much of the upper Missouri River actually flowed northeast into Hudson Bay rather than into the Mississippi River basin (Meneley et al, 1957).

The bedrock of the region is mantled by up to 300 m of unconsolidated Quaternary sediment, mainly till and glaciofluvial sands and gravels. During deglaciation, meltwater from the retreating glacier carved numerous ice-marginal channels and spillways in this sediment (Christiansen, 1979). Although now abandoned, or buried under more recent sediment, these valleys are often sites of salt lakes. The hydrodynamic properties of the Quaternary sediments influence, to a major degree, the location and development of the playas by controlling the direction of flow and the quantity of groundwater discharge (Last, 1984).

Origin of the Basins

Unlike many other playas and salt lakes of the world, the origin of the sodium sulfate-rich basins in the Northern Great Plains cannot be attributed primarily to tectonism or deflation. Rather, these lakes occupy closed depressions that were created in association with glacial activity in the region during the past 20,000 years. There are three basic types of basins with combinations and gradations existing between each type: (a) channel/riverine basins, (b) roughly circular "sinkhole" basins or doughnuts, and (c) broad,
flat depressions with no distinctive morphological character.

Most of the sodium sulfate deposits of the region occupy basins that are distinctly riverine in nature (Fig. 3). These basins were created by meltwater cutting a channel into the surrounding glacial material during or immediately after recession of the Wisconsinan ice sheet between 17,000 and 13,000 years ago. The basin is usually floored by well sorted gravels and sands, whereas the channel banks are normally composed of till. Closure of the basin is usually due to a debris slide or an incipient alluvial fan which has prograded across the channel. In channel basins that have a north-south orientation, isostatic crustal rebound has also provided closure by differentially raising the southern end of the basin more than the northern end.

In areas of glacial ice stagnation, such as the Missouri Coteau, the ice sinkholes form the dominant basin type. These sinkhole basins tend to be small and circular, but sometimes can have great thicknesses of postglacial clastics and salt. For example, the Ingebright deposit in southwestern Saskatchewan contains up to 50 m of salt in an area less than 0.5 square kilometer (Rueffel, 1968).

Finally, some of the lakes are remnants of much larger postglacial or ice marginal lakes. These basins are simply low spots in the morainic debris and are usually surrounded by old strandlines and lacustrine sediments. The basins can be very large (greater than 300 square kilometers), with most of the reserve in the form of dissolved salts in the brine.

ECONOMIC GEOLOGY

Commercial exploitation of the saline lakes in the region began in 1918 with the extraction of both magnesium and sodium sulfates and carbonates from Muskiki Lake, near Saskatoon, Canada. Production of anhydrous sodium sulfate (salt cake) from some 20 different lakes in the United States and Canada (Fig. 4) gradually increased over the next five decades to a high of approximately 700,000 tonnes in 1973 (Fig. 5). Today, this region supplies nearly 50% of the total North American demand for sodium sulfate with the rest coming from deposits in southwestern United States, and as byproducts of various manufacturing processes. A tremendous increase in the price of salt cake during 1973-75 (from $15 to $48/tonne) and again during 1980-83 (from $62 to $108/tonne) saw a renewed interest in leasing and mining activities in the region during these periods.

Historically, the two largest uses of sodium sulfate have been in producing kraft paper and allied products, and in the manufacture of detergents. More recently, however, the energy industry has been consuming larger amounts of the salt by its use as a conditioner to facilitate fly ash suppression in coal-burning power plants (Tremblay, 1984). Another new use of salt cake is in the manufacture of potassium sulfate by the reaction of sodium sulfate with potassium chloride. Other potentially significant applications include use in glass, ceramic, and paint manufacture, and in solar energy collectors.

The sodium sulfate industry in this region is based on reserves of three basic
Figure 4. Map showing the sodium sulfate deposits of the northern Great Plains.
types: (a) the sodium sulfate that is dissolved in brines that fill the saline lake basins, (b) the hydrated sodium sulfate mineral mirabilite which occurs seasonally on the floor of the salt lakes due to precipitation within the overlying water column, and (c) the bedded salts composed mainly of mirabilite and thenardite that make up the postglacial sedimentary fill in some basins.

Although each of these three sources has been exploited during the past, most production today is from the hypersaline lake waters which are pumped from the basin into holding reservoirs. Upon further concentration by evaporation during summer and then cooling during the fall season, relatively pure mirabilite (Glauber's salt) is precipitated from the solution (Fig. 7). The overlying brine is then drained back into the lake basin, and the salt is removed to stockpiles. Solution mining using hot water (MacWilliams and Reynolds, 1973) and dredge mining of the permanent salt beds are also used.

This harvested Glauber's salt must be dehydrated prior to marketing. The methods for this processing vary considerably and are reviewed in detail by Weisman and Tandy (1975), and Rueffel (1968). Most producers simply raise the temperature of the salt to above its fusion point (about 32 °C), and then either continue heating to evaporate the water of crystallization or remove the solid anhydrous precipitate from the slurry.

Table 1. Mineralogy of saline playas of the northern Great Plains (taken, in part, from Egan, 1984). Minerals in uppercase indicate common occurrence.

<table>
<thead>
<tr>
<th>CARBONATES</th>
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<tbody>
<tr>
<td>Aragonite CaCO₃</td>
</tr>
<tr>
<td>Calcite CaCO₃</td>
</tr>
<tr>
<td>Magnesian Calcite CaCO₃</td>
</tr>
<tr>
<td>Dolomite CaMg(CO₃)₂</td>
</tr>
<tr>
<td>Prehnite Mg₄Si₂O₇(OH)₂</td>
</tr>
<tr>
<td>Hornfels Ca₂Mg(NH₄)₂CO₃</td>
</tr>
<tr>
<td>Li Hornfels Mg₁₂CO₃</td>
</tr>
<tr>
<td>Siderite Fe₂CO₃</td>
</tr>
<tr>
<td>Glauberite Al₂(CO₃)₃·3Na₃(OH)₆</td>
</tr>
<tr>
<td>Dawsonite Na₃(CO₃)₃(OH)₆</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>SULFATES, SULFIDES, AND CHLORIDES</th>
</tr>
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<tbody>
<tr>
<td>Gypsum CaSO₄ · 2H₂O</td>
</tr>
<tr>
<td>Thenardite Na₂SO₄</td>
</tr>
<tr>
<td>Bloedite Na₂₃(SO₄)₂ · 11H₂O</td>
</tr>
<tr>
<td>Sodium Na₂SO₄</td>
</tr>
<tr>
<td>Potassium K₂SO₄</td>
</tr>
<tr>
<td>Barium BaSO₄</td>
</tr>
<tr>
<td>Magnesium MgSO₄</td>
</tr>
<tr>
<td>Hydrated MgSO₄ · H₂O</td>
</tr>
<tr>
<td>D'Anastase Mg₉(SO₄)₁₀(OH)₁₁</td>
</tr>
<tr>
<td>Hydrocalcite Mg₆(C₂O₄)₃ · 6H₂O</td>
</tr>
<tr>
<td>Xonotlite Mg₆(SO₄)₅(C₂O₄)₃ · 12H₂O</td>
</tr>
<tr>
<td>Pyrites FeS₂</td>
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<table>
<thead>
<tr>
<th>SULFATES AND OXIDES</th>
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</thead>
<tbody>
<tr>
<td>Quartz SiO₂</td>
</tr>
<tr>
<td>Feldspar K₂Al₂Si₃O₈</td>
</tr>
<tr>
<td>Diaspore Al₂O₃</td>
</tr>
<tr>
<td>Biotite Mg₃(C₂O₄)₃(OH)</td>
</tr>
<tr>
<td>Hornblende Ca₂Mg₃Si₃O₁₀(OH)₂</td>
</tr>
<tr>
<td>Riebeckite Al₃Si₃O₁₀(OH)</td>
</tr>
<tr>
<td>Talc Mg₃Si₂O₅(OH)</td>
</tr>
<tr>
<td>Mixed-layer clay variable</td>
</tr>
<tr>
<td>Chlorite (Fe, Mg)₂Al₃Si₂O₁₀(OH)</td>
</tr>
<tr>
<td>Mucope Al₃Si₂O₅(OH)</td>
</tr>
<tr>
<td>Noradumite Al₃Si₂O₅(OH)</td>
</tr>
<tr>
<td>Goldschmidt Fe₃(OH)</td>
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<tr>
<td>Diaspor A(Al, Fe)</td>
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</tbody>
</table>

Figure 5. Annual production and value of sodium sulfate mined from salt lakes in the northern Great Plains.
brine or as permanent salt within the sedimentary fill, to be considered economically viable for extraction. Despite some differences, these latter "minable" accumulations simply represent one end-member of a continuum of saline lakes and basins in the Great Plains. It is important to recognize not only the unique features that give rise to a specific deposit, but also the similarities between all deposits in terms of common physical and chemical processes and evolutionary sequence.

**Description of Modern Sediments**

In their natural state the near-surface (modern) sediment of these sodium sulfate-rich lakes usually consists of a mixture of very soluble evaporite minerals, sparingly soluble precipitates, clastic detrital material, and organic matter (Table 1). The soluble salts, often making up nearly the entire near-surface sediment mass, are composed of mainly mirabilite, thenardite, and bloedite, with secondary abundances of kieserite, epsomite, burkeite, hexahydrate, and halite. These salts are clear to white, often coarsely crystalline, and occur in a wide variety of habits and morphologies.

The sparingly soluble component, usually amounting to less than 25% of the modern sediment, is composed mainly of gypsum and a wide variety of authigenic carbonates and silicates including: protodolomite, nesquehonite, huntite, natron, trona, and mixed-layer clays. These sparingly soluble precipitates are usually very fine grained and often detectable only by x-ray diffractometry and scanning electron microscopy.

The detrital component of the modern sediment closely reflects the composition of the surrounding glacial materials: clay minerals (mainly illite and smectite), dolomite, calcite, quartz, and feldspars (Egan, 1984). In deposits that are actively being mined, this clastic material usually comprises the bulk of the modern sediment. As the soluble sodium sulfate is extracted in mining operations, a layer of this insoluble residue blankets the deposit, thereby greatly decreasing the efficiency of the "brining" extraction process.

The organic matter component of the near-surface sediment is generally quite low (less than 10%), except near the margins of the lake where sheetwash can supply abundant allogetic organics.

**Distribution of Modern Sediments**

Understanding the occurrence and genesis of the near-surface sediment in these saline lakes is greatly aided by the recognition of distinctive sedimentary facies within the basin. These facies belts are, in general, similar to those identified in saline playa environment elsewhere (e.g., Hardie et al., 1978). Because most of the lakes occupy relatively steep-sided, riverine troughs, the basin margin areas are dominated by poorly sorted colluvium and sheetwash sediments that slope...
and only rarely is there any development of strandline features such as beaches or dunes.

Basinward, the mudflat/sandflat grades down to meet broad mudflats and sandflats (Fig. 7). Classic alluvial fans are not found, and only rarely is there any development of strandline features such as beaches or dunes. The mudflats and sandflats are periodically exposed mudflats often become encrusted crusts formed by the evaporation of brine salts from these dried crusts. The mudflats are also areas of massive intrasedimentary crystallization of salts resulting in destruction of lamination.

Basinward, the mudflat/sandflat grades into the salt pan (Fig. 7). This is the most dynamic zone of the basin in terms of sedimentary processes. As a result of surface runoff and groundwater contribution, water is ponded in this area for several weeks to several months. The concentration of the brine is raised by dissolution of previously deposited salts and by evaporation throughout the season, thereby eventually causing supersaturation and precipitation of a variety of evaporite minerals. Nucleation and precipitation of salts can occur in several forms and at several sites in the brine: (a) at the surface of the brine in form of hopper-shaped crystals (Fig. 8) which can coalesce to form large floating crystal rafts, and (b) at the sediment-water interface in the form of either rounded accretionary grains (termed "mirabilites") or large, euhedral, bladed to tabular crystals and massive crystalline aggregates (Fig. 8).

### STRATIGRAPHIC RELATIONSHIPS AND INTERPRETATIONS

Considering the broad geographic area, it is not surprising that no two playa basins in this region are exactly alike in terms of stratigraphy and evolutionary sequence. Certain stratigraphic associations are recurrent, however, and a generalized evolutionary pattern can be deduced from the deposits investigated to date.

On the basis of preliminary core descriptions and analyses, five lithostratigraphic units have been identified in basins in which there is a full postglacial sequence preserved. In basins that are being altered by mining operations or by other postdepositional destructive phenomena (such as salt dissolution), one or more of these units may be missing. The stratigraphic units observed consist of: (a) a basal coarse clastic (sand and gravel) unit which directly overlies glacial debris, (b) a grey-colored calcareous clay and silt unit, (c) a black, reducing clay with abundant intrasedimentary salt crystals, (d) a massive salt unit, and (e) an uppermost, laminated salt-mud unit. The main characteristics of these units are described in Table 2.

Although detailed interpretations of this lithostratigraphy are not yet complete, the sequence of units suggests the following series of events: immediately after or possibly concurrent with the formation of the basin by meltwater from the retreating glacier or creation of a sinkhole by melting of buried ice, the coarse clastics of Unit A were deposited by fluvial or sheetwash processes. Ponding of water in the basins occurred as the downslope end of a fluvial channel was dammed or by simply accumulation of runoff and meltwater in a topographically low area. Deposition of Unit B and part of Unit C occurred during this time probably in lakes that were considerably larger and fresher than those of today.

### Table 2. Summary of lithostratigraphic units.

<table>
<thead>
<tr>
<th>Unit A</th>
<th>Coarse sands and gravels; well sorted; oxidized colours; very low organic and moisture contents; sands can be lime- or clay-sized; lamination; mainly quartz, feldspars and detrital carbonates; very sharp lower contact with fir, pebbly clay (till).</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit B</td>
<td>Silty clay and sand; black to greenish grey; usually highly reducing; medium grey to greenish grey; generally no observable bedding except for indistinct wispy laminations and occasional thin calcareous zones; low organic content; high moisture content; very soft to friable but with depth.</td>
</tr>
<tr>
<td>Unit C</td>
<td>Silty clay; black to dark green; highly reducing; medium grey to greenish grey; generally no observable bedding except for indistinct wispy laminations and occasional thin calcareous zones; low organic content; moisture content higher than Unit A but lower than Unit C; firm; calcareous with occasional to abundant sandstone, fragmentized bivalves, and cladoeceran remains identified; sharp lower contact; 0.5-3 m thick.</td>
</tr>
<tr>
<td>Unit D</td>
<td>Coarse sands and gravels; well sorted; oxidized colours; very low organic and moisture contents; sands can be lime- or clay-sized; lamination; mainly quartz, feldspars and detrital carbonates; very sharp lower contact with fir, pebbly clay (till).</td>
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</table>

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Figure 7. Diagrammatic cross section showing principal sedimentary facies in a typical salt playa of the northern Great Plains.

Gradually, however, in response to the drier and warmer climatic conditions that prevailed over the prairies beginning about 8,000 years B.P., water levels in the basins declined and concentration of the brines increased. Although initially relatively deep, chemically-stratified water bodies may have existed in selected basins as suggested by Grossman (1968), it is very likely that climatic conditions soon deteriorated to support only very shallow, playa types of lakes during most of the deposition of Unit D. That is, rather than envisioning a water column several tens of meters deep from which precipitation of the soluble salts is occurring, it is more likely that the thick sequence of massive salt in these basins is due to precipitation in a shallow salt pan/ephemeral lake environment. Prolonged intervals of warm-dry years may have resulted in dry lake conditions, desiccation, and possible erosion of the upper sediments of the salt pan. Wind- and sheetwash-transported clastics periodically blanketed the basin, effectively decreasing the amount of salt dissolution during the next wet phase. Eventually, about 3,500 years ago, as the climate moderated and a more favorable hydrologic budget existed, shallow (and in some cases relatively deep) water conditions returned to the basins.

**ORIGIN OF THE SALTS**

The origin and ultimate source of the salts in these lakes has been the subject of considerable discussion in the scientific literature. As summarized by Sloan (1972, p. C22): "Many observations about the occurrence of the salts are valid, but interpretations of their genesis have generally been needlessly complex and unsubstantiated by the observed facts." Certainly much of the high salinity of the seasonally ponded brines is derived from dissolution of previously precipitated salts by the relatively dilute inflow (Last, 1984). Groundwater also likely plays a major role in supplying ions to the basins; however, to-date this groundwater contribution has not been adequately documented.
Figure 8. Examples of salt crystals from playas of the region. All crystals shown are mirabilite:
(a) hopper-shaped crystal (scale bar = 2 cm)
(b) dog-tooth crystals (scale bar = 2 cm)
(c) finely radiating and dendritic crystals (scale bar = 10 cm)
(d) massive crystal aggregate (scale bar = 10 cm)

Many researchers (e.g., Rueffel, 1968; Grossman, 1968; Freeze, 1969) have stressed the close association of major sodium sulfate and magnesium sulfate deposits with buried preglacial valleys, and conclude that these buried valleys act as conduits for groundwater which supplies dissolved components to the lakes. The ultimate source of the ions still remains problematic. It is questionable whether the Paleozoic evaporites, which are known to have undergone extensive dissolution by circulating groundwater, can be a likely source because of an incompatible brine chemistry (Fig. 9). While such factors as oxidation of pyrite in the Cretaceous shales and dissolution of gypsum in the till and bedrock to provide a source of sulfate are likely possibilities (Wallick and Krouse, 1977), the complicated fractionation characteristics of the sulfur in sedimentary sulfates and sulfides and the presence of sulfate-reducing bacteria make documentation difficult.

ACKNOWLEDGEMENTS

Our continuing work on the sodium sulfate deposits of the northern Great Plains is supported by grants from Energy, Mines and Resources Canada, the Natural Sciences and Engineering Research Council of Canada, and the Canadian Plains Research Center.

REFERENCES CITED

(1967b) Preglacial valleys in southern Saskatchewan: Saskatchewan Research Council, Map No. 3


REFRACTORY DOLOMITE PRODUCTION IN A GEOLOGICALLY COMPLEX AREA

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ABSTRACT

The J.E. Baker Company is an established producer of dolomite refractory products, agricultural materials, and mineral fillers. Over the years, the company has operated many quarries throughout the northeastern United States. At the present operating plant, deep exploratory diamond core drilling has recently proven its value by helping to clarify what had been previously thought to be extremely complex geology. This exploratory drilling has determined the presence of a marker lithology which not only defines the base of the usable stone, but also establishes the position of the quarry stone within the regional stratigraphy. Even with a better understanding of the general geology of the deposit, an intensive quality control program is still required due to the highly variable nature of the carbonates above the newly established marker bed. This quality control program begins with close-spaced core drilling and progresses through extensive raw material and finished product sampling, in order to insure that all materials meet their established specifications.

INTRODUCTION

The J.E. Baker Company produces a full range of dolomite refractories, agricultural materials, and mineral fillers from a single quarry located just west of the city of York in southeastern Pennsylvania (Figure I). The Baker Company is also a fully integrated producer of refractory dolomite brick, used extensively in the steel, cement, and lime industries.

The company had its beginnings in 1889 as the Wrightsville Lime Company, producing lime in an upright shaft kiln for use in plaster, whitewashing, and agriculture. In 1896, the company acquired its first quarry containing dolomite. This was the beginning of the company's long association with dolomite, and in particular with one dolomite formation. This first dolomite quarry became known as the Billmeyer plant, and was located on the east side of the Susquehanna River in Lancaster County, Pennsylvania. In the early 1900's, the company became the first to produce a "roasted dolomite" for use by the steel industry. In 1904, the name of the company was changed from the Wrightsville Lime Company to the J.E. Baker Company.

The first dead-or double-burned dolomite was also produced at this plant in 1910 from the company's first rotary kiln.

Through the years, other quarries were opened in this same dolomite formation. The Union Stone Company which was acquired by the J. E. Baker Company in 1923, but which had been controlled by Mr. John E. Baker since 1902, was located across the Susquehanna River from the Billmeyer plant at Saginaw in York County. Two quarries were eventually opened on this property. Another site in Lancaster County known as the Chickies plant was operated briefly from 1914 until 1918 mainly to supply the increased demand for roasted dolomite during the First World War.

The farms on which the current operation is located were first acquired in 1946, and stripping for the main quarry was started in mid-1950. In August 1952, the plant with one rotary kiln was officially commissioned. A second rotary kiln was added in 1959. This dolomite deposit was discovered more by accident than by good geologic work. It just so happened that a friend of the Baker family had a farm for sale, and asked Mr. William
H. Baker if he would be interested in looking at it. More as a courtesy than anything else, Mr. Baker sent a man out to inspect the property and collect some outcrop samples. Much to everyone's surprise, the samples indicated the potential of a deposit of high quality dolomite, so the property was optioned, drilled, and purchased.

Through the years, the Baker Company has developed many additional quarries that were not in this dolomite formation. Most of these quarries have been located in Pennsylvania, but the company has operated pits in Maryland, Virginia, West Virginia, New York, Indiana, and Ohio. These quarries have produced various materials such as dolomite, high-calcium limestone, granite, serpentinite, and coal.

**GENERAL GEOLOGY**

The dolomite formation that has been so critical to the existence of the J.E. Baker Company is the Ledger Dolomite of Cambrian age. This formation is named for the exposures found near the small hamlet of Ledger in the Amish area of Lancaster County. The Ledger Dolomite is part of a sequence of Cambrian and Lower Ordovician carbonates that underlie the York section of the Conestoga Valley. In York County, the Conestoga Valley is a long, narrow northeast-trending structure that is bounded to the south by Lower Cambrian clastics, and to the north by both Lower Cambrian clastics and overlapping Triassic sediments.

The high purity Ledger Dolomite at the Baker deposit is usually composed of massive gray to light gray dolomite with dark gray mottling. It is typically medium to coarse crystalline and highly fractured. It is estimated that along the north side of the Conestoga Valley, the formation is approximately 1,000 feet thick. Recently, extensive areas of very high purity oolitic dolomite have been encountered. These oolites are commonly concentrated in dark gray bands that give the only good indication of bedding. This discovery has given insight into the environment of deposition of this formation, and indicates it is probably a shelf-derived carbonate. The lower purity dolomites are generally gray with a light pink to purple tint, and are more...
finely crystalline. Bedding, with the exception of the oolitic bands, can rarely be seen in the quarry. When noted, it is commonly disrupted by numerous closely-spaced faults that usually show small to moderate offsets. No fossils have been found in this formation, and it is assigned a Middle Cambrian age based strictly on its stratigraphic position.

A generalized stratigraphic section of the York-Hanover portion of the Conestoga Valley is found in Table I.

It is becoming apparent from recently acquired data that the geology in the York section of the valley may be fairly simple in a general view, but is very complex when observed in detail. Work by other company and consulting geologists in the valley tends to bear this out. Work that has been completed by K. Weaver, R. Ganis, R. Cathcart, L. Meade, and D. Hopkins indicates that once a marker bed has been established, the geologic structure is usually easily identified. Problems arise when units between marker beds are investigated in detail. Some of the problems are caused by the difficulty in distinguishing rocks from different formations. Dolomite from the normally high-calcium Kinzers Limestone can be physically identical to dolomite from the Ledger Formation, and white marble occasionally found in the Ledger Formation is physically and chemically identical to high-calcium white marble found in the Kinzers Formation. (As a note of interest, this white marble is extensively quarried in the York-Hanover valley for whiting material.) To compound the problem, there are areas where limestones and dolomites are intimately interbedded making formation identification extremely difficult. Based on these problems, it is easy to understand how the structure and stratigraphy can be misinterpreted when dealing only with scattered outcrops, small quarries, or even shallow drill holes.

A review of this information has led to the belief that much of the structural complexity which has been attributed to this valley in the literature may not exist in quite the degree previously thought. The problem instead lies in frequent facies changes within the carbonates, and formations that were misidentified due to the similarity of rock types.

**DEEP EXPLORATORY DRILLING**

It was this complexity in detail and the lack of an established marker horizon that led the Baker Company to develop a program for locating the quarry within the local stratigraphic section. The only way to do this was to complete some deep exploratory drill holes. This drilling would also have the added benefit of determining what the ultimate quarry depth could be. Prior to this, it had been a company practice to limit all drilling to a depth of 100 feet. In the last ten years, deeper drilling was completed, but nothing exceeded 200 feet in depth. This more-or-less shallow drilling, even though very closely spaced, did not yet allow the big picture to be seen.

Four years ago, permission was granted to drill one deep hole during a scheduled core drilling program. (Here is should be noted that better communication with management was important in convincing them of the potential rewards of deep drilling.) This first hole was targeted for a depth of 400 feet from the floor of the second level of the quarry. Due to equipment limitations, the hole was only completed to a depth of 286 feet. Even so, the results were of great interest. At a depth of 165 feet, a 20-foot zone of black, pyritic shaly dolomite was encountered. Much of the remainder of the hole contained high-silica dolomite with minor black shaly dolomite.

It appeared that this first deep hole had given everything that had been hoped for.
had intersected what appeared to be a potential marker bed, and had also determined the ultimate thickness of the high quality dolomite. However, joy with the results from this hole was tempered by the knowledge that correlation between 200-foot deep holes on a close spacing had proven to be nearly impossible.

After the success of this first deep hole, management allowed the inclusion of three additional deep holes in the 1981 diamond core drilling project, and three more holes in the 1983 project. These holes have given valuable insight into the geometry of the deposit, and will allow much greater flexibility in planning for the future development of the pit.

From the results of this deep drilling, it is now interpreted that the marker bed that has been consistently encountered, is actually the upper member of the Kinzers Formation. This member has recently been informally designated the Longs Park Member (Gohn, 1976). The physical characteristics of this unit fit well with Gohn's description. This same contact between the high purity Ledger Dolomite, and the black, pyritic shaly material of the Longs Park Member of the Kinzers Formation is clearly visible in Pit No. 2 of the York Stone and Supply Company, located 2.5 miles to the northeast.

If the interpretation is correct, what is noted is a geologic structure that is fairly simple. Visible is an approximate 20° to 25° southward dip, occasionally disrupted by faulting. This is in contrast to the seemingly impossible geological relationship that appeared to exist when analyzing the close-spaced shallow drilling alone. The deep drilling has also indicated that the great complexity previously noted could usually be ascribed to rapid facies changes within the formation, both laterally and down-dip.

The value of a well planned deep drilling project in an area of seemingly complex geology should be readily apparent. Many questions that have remained unanswered for years may be quickly solved with the drilling of only a few well placed holes. In some cases, it may be difficult to convince management or a client of the value of drilling rock that will never be quarried or mined. However, after the facts are presented and the potential benefits made known, the value of such a project in a complex area should be evident.
QUALITY CONTROL

The desire of management to maintain very close quality control, as well as the need to have an exact knowledge of the high purity dolomite reserves coupled with the complex nature of the more detailed geology, has led to the evolution of an intensive quality control program in order to insure that only the proper quality dolomite is used in the various products manufactured.

This program begins with extensive, close-spaced diamond core drilling. The property has been laid out on a 75-foot square grid pattern. Core drill holes are located at the intersection of the grid lines. Initially, drilling in undeveloped areas was completed on a 300-foot spacing. This spacing was reduced to 75 feet as the quarry advanced and rock quality indicated that further investigation was warranted. In the past, some drilling in this valley has been completed on a 50-foot spacing in order to keep a close control on stone chemistry.

Core from this drilling is logged, sampled, and delivered to the in-house laboratory for analyses by X-ray fluorescence. Lithologic breaks are based on sampling intervals which do not exceed ten feet in length in order to maintain a close control. Sample intervals normally average approximately five feet. The core is analyzed for its silica, iron, alumina, calcium carbonate, and magnesium carbonate content. The chemical results from the drilling are then delivered to the Data Processing group, where weighted averages of all components are tabulated for the different quarry lifts. This information is then transferred to color coded operational maps which indicate dolomite quality for each level. From these maps, yearly extraction plans, based on updated sales forecasts, are formulated. These maps are also used to develop accurate determinations of the reserves of different dolomite content, and to govern daily operations of the quarry.

This close-spaced drilling also allows the identification of some of the common operational problems that are encountered during pit development. These problems include isolated zones of high-calcium white marble (Figure 4), similar to that found in the Kinzers Formation, zones of very friable...
dolomite sand, blocks or isolated pockets of black, pyritic shaly dolomite or dolomitic shale, zones of hematite veining, and areas of red shale and red shale-cemented breccia (Figure 5) resulting from Triassic (?) solution collapse. Close-spaced drilling allows almost all of these potential problem areas to be identified well in advance of quarry development, and allows the area to be avoided entirely, or, if that is not possible, to develop an extraction plan for the material so as not to interfere with normal quarry operation. Much less than 10% of the total available stone will be waste.

This extensive drilling has also enabled certain trends in the chemistry of the dolomite to be defined. Generally, the east section of the quarry can be divided into three east-west trending bands that conform to the chemical specifications assigned to the three qualities of dolomite produced from the quarry. The highest quality dolomite, called brick stone, used for the production of refractory dolomite bricks and refractory specialties, forms the north band. The intermediate quality of dolomite, fettling stone, used to produce dead-burned dolomite for various applications, forms the second band. Lastly, the lowest quality dolomite, called agstone or roadstone, forms the south band.

By consulting with the operational map, an area of the quarry is selected where the desired quality of dolomite is projected to occur. After an area is identified, a percussion hole shot is laid out and drilled. The shots will consist of five to ten holes in a single row. Single rows are used in order to maintain a close control on stone chemistry. The holes are generally on a 16-foot burden and a 17-foot spacing on the first levels. The first level height typically varies from 45 to 65 feet depending on topography, and both of the lower levels are limited to a 50-foot face height. The location of each blast hole is surveyed and plotted on a base map. Blast hole cuttings are collected continuously, with one sample bagged for every ten feet drilled. One composite sample for each hole is made in the laboratory. Each hole is then analyzed for silica, iron, and alumina. After a shot is blasted down, two quarry shot samples are collected and analyzed, one from each side of the shot.

This procedure allows three checks to determine the quality of dolomite within a shot. The first check is the core drilling which gives a general idea of the dolomite quality. The second and most important check is the blast hole analysis, and the third is the quarry shot samples. Only when blast
hole and quarry shot analyses agree on dolomite chemistry, will the shot be run for its intended purpose. If the chemistry does not agree, the shot will typically be run for the next lower quality dolomite.

At the shot, the dolomite is loaded into 35-ton Euclid haulers by a 12-cubic yard Clark loader. The dolomite is then transported to either the primary crusher, or to the proper quality surge pile.

When the highest quality dolomite is processed, additional samples are taken after primary and secondary crushing and screening, and prior to the dolomite being placed into the kiln raw feed bins. At the conveyor feeding the bins, a one pint jar of raw feed is collected for every 50 tons of material binned. After four pint jars are collected, representing 200 tons of binned stone, they are combined, split down, and delivered to the laboratory for analysis. If the material in the bin is found to be not to specifications, the bin will be emptied.

An additional composite sample of raw feed is also taken as it exits the raw feed bins, and before it enters the rotary kilns. As the processed grain exits the kiln, hourly samples are taken to insure that the material meets both chemical and density specifications.

Many additional samples are taken and checked in the process of manufacturing various refractory products such as dolomite bricks, gunning materials, ramming products, etc. If a product does not meet its stated specifications, it will be used to manufacture a product that requires lower specifications, or if that is not possible, it will be discarded.

It was the evolution of this program of close-spaced diamond core drilling, through selective quarrying to extremely detailed sampling of raw material and finished products, that has allowed the company to continue to manufacture high quality products from a deposit that is structurally (on a small scale) and chemically complex.

Figure 5. Triassic shale-cemented breccia.
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ABSTRACT

Of the more than 40 million tons of crushed stone produced in Illinois in 1981, more than 30 percent came from just 3 quarries in Cook County. More than 43 percent of all the stone came from just 4 counties in the Chicago Metropolitan region. Most existing quarries in the Chicago region are surrounded by industries, businesses, and residences that make expansion impossible. Urban growth also has covered many potential quarry sites.

The highest quality aggregate in the Chicago region is mined from reefal dolomites in the Silurian Racine Formation. The largest reefs are confined to the upper parts of the Racine near the Lake Michigan shore where urbanization is greatest. To the west, where the region is less urbanized, reef structures are rare, but the underlying Joliet, and Kankakee through Wilhelmi Formations (Silurian) are exposed at the bedrock surface. The upper parts of these units contain some fairly pure dolomite.

West of Chicago, high-quality aggregate is produced from uppermost units of the Ordovician Galena Group exposed near the crest of the Wisconsin Arch. The amount of chert in these rocks decreases eastward in the subsurface, and test drilling has shown the Galena to be a nearly pure dolomite beneath Chicago.

Underground mining of the rocks of the Galena Group may become a large-scale source of aggregate for the Chicago market. Elmhurst-Chicago Stone Company has driven an incline through the Maquoketa Shale (Ordovician) that forms the floor of its Elmhurst quarry and is producing stone from the underlying Galena.

Potential quarry sites in reefal dolomites of the Racine may be present in Kankakee County south of Chicago. These quarries are almost twice as far from Chicago as are the large quarries that currently supply that market.

INTRODUCTION

Urban encroachment on aggregate resources is a major problem facing many metropolitan areas. In Chicago, for example, favorable geologic conditions and conveniently situated quarries have so far allowed local producers to meet demands for increasing quantities of high-quality aggregate, while keeping the costs of transportation and production low. However, as local surface resources become exhausted and potential sites for new quarries are swallowed up by expanding suburbs and industrial development, the future has begun to look cloudy for both producers and consumers of aggregates in the Chicago area.

Over the past 150 years more than 100 sites have been quarried in the Chicago area. Most of these have closed because of economic fluctuations, exhaustion of high-quality stone, buy-outs by competitors, or other considerations, and the demand for stone in the Chicago area has been met by fewer but larger quarries. More than 43 percent of the 40 million tons of crushed stone produced in Illinois in 1981 came from the Chicago area. The value of stone products from this area in 1981 was 64.7 million dollars. Three quarries
accounted for nearly 70 percent of the stone produced in the Chicago area. By the time the reserves of high-quality stone are exhausted at these few remaining sites, urban growth will have blocked many potential quarry sites, and it will be almost impossible to open new quarries in the local area.

If new sources of high-quality aggregate cannot be found in northeastern Illinois jobs and local tax revenues will be lost, particularly if stone must be imported from nearby Indiana, Wisconsin, or Michigan. Costs of aggregate will certainly increase when material must either be shipped to the metropolitan area from greater distances or produced by more costly mining methods.

This paper discusses the geology of the Chicago area as related to the stone industry, describes some problems of stone production in an urban environment, and suggests possible new sources for stone in the Chicago region (Figure 1).

**GEOLOGY OF CHICAGO AREA**

**DOLOMITE RESOURCES**

Nearly all the crushed stone produced in the Chicago region is derived from dolomite of Silurian age. Although this dolomite underlies all but the western edge of the region, only a few sites contain large reserves of high-quality stone suitable for use in concrete highway pavement.

Several geologic factors affect the availability of suitable stone resources in the region: thickness and composition of overburden, bedrock topography, bedrock structure, and lithology of the bedrock.

**Overburden Composition and Thickness**

Unconsolidated Quaternary glacial moraines, other drift deposits, and lake sediments cover nearly the entire region (Figure 2). These deposits reach 350 feet (106 m) in thickness, but average about 100 feet (30 m) (Willman, 1973). Moraines generally form the thickest overburden and are most common in the western part of the study region. Where drift is thickest, bedrock outcrops typically are confined to a few areas where Pleistocene rivers eroded deep channels. Glacial outwash deposits are significant sources of high-quality aggregate in Lake and McHenry Counties, where bedrock outcrops are almost nonexistent.

Glacial lake sediments are confined mainly to eastern and southern Cook County, but also occur in Kankakee, Kendall and western Will Counties (Figure 2). Lake sediments typically are thinner than morainal deposits.

**Bedrock Topography**

In eastern and southern Cook County, Silurian rocks form scattered, low hills that project above the general bedrock surface and through the surrounding Pleistocene lake sediments to form outcrops. These bedrock hills also are present to the east in Lake Michigan (Bretz, 1939). Many quarries have been developed on these bedrock highs, primarily because these hills are associated with reef deposits, which are the best raw material for aggregate production.
Bedrock Structure

The availability of quarry sites in the Chicago area is related to regional bedrock structure as well as to bedrock topography. The bedrock generally dips gently toward the east (Figure 3), away from the crest of the Wisconsin Arch and toward the Michigan Basin (Buschbach et al., 1982; Willman, 1973). Erosion of the eastward-dipping rocks exposes progressively older rocks at the bedrock surface in a westward direction across the region. Ordovician rocks are exposed near the western edge of the study area.

Some minor faults offset the Silurian rocks in a few areas (Buschbach et al., 1982), but have relatively little effect on the availability of quarryable stone in the study area. The Sandwich Fault Zone in the southwestern part of the area (Figure 3) also affects the distribution of Paleozoic rocks at the bedrock surface (Willman and Kolata, 1978).

Bedrock Lithology

Although Silurian dolomite occurs at the bedrock surface throughout the study area, high-quality stone is not evenly distributed. The lithology of the Silurian and older Paleozoic bedrock in the Chicago region varies stratigraphically and geographically. Characteristics that affect the quality and cost of production of aggregate include the thickness of individual lithologic units, clay and chert content of the rocks, abundance of horizontal clay seams and partings, and presence of vertical clay-filled fissures and pockets.

The thickness of the entire Silurian section ranges from 500 feet (151 m) along the Lake Michigan shoreline to zero in the western part of the study area (Figure 3). This variation in thickness is due primarily to erosion and to the general eastward dip of all Paleozoic rocks in the area. Variations in depositional features of the Silurian rocks, particularly in the Racine Formation, also affect thickness.

The Racine Formation crops out throughout Cook County and the eastern portions of Will, Du Page, and Kankakee Counties (Figure 3), and is the youngest Silurian rock unit in the area. Because of its composition and outcrop distribution, it is the major source of high-quality stone in the Chicago area.

Most of the Racine Formation consists of nonreefal, highly argillaceous, thin-bedded dolomite that is cherty in places. The basal third of the unit is less argillaceous. The Racine Formation (Figure 4) reaches a thickness of 300 feet (100 m), but reef structures in the formation cause significant local variations in the thickness that are independent of the general westward thinning of the Silurian rocks. The reefs have an upward-expanding
shape like inverted cones and may extend up through the entire Racine Formation. The Thornton reef, the largest known reef in the area, has a diameter of 1.5 km, but reefs having a diameter as small as 6 feet (2 m) also occur.

The reefs consist of high-purity dolomite and may be massive or have steeply-dipping thick or thin beds. The larger reef structures have been planed off by erosion or glaciation and may once have been much thicker than they are now. Because of their hardness and massive bedding, the reefs are more resistant to erosion than the rest of the Racine Formation. Most of the bedrock hills projecting through Quaternary lake deposits in eastern Cook County are controlled by large reefs or groups of smaller reefs in the Racine Formation.

The Sugar Run Formation (Figure 4) underlies the Racine Formation and ranges in thickness from 9 feet (3 m) to 30 feet (10 m) (Willman, 1973). The Sugar Run Formation is difficult to identify in many areas because of its gradational upper and lower contacts. Although generally a prominently bedded, slightly argillaceous dolomite, the Sugar Run varies locally in composition. Certain beds within the Sugar Run Formation make a fine building stone; during the latter half of the 19th century the Sugar Run was quarried extensively along the Des Plaines River between Joliet and Lemont for that purpose. A few very small flagstone quarries still operate in that area. The Sugar Run also is extracted for use as aggregate at many quarries.

The Joliet Formation (Figure 4) underlies the Sugar Run Formation throughout the Chicago area and ranges in thickness from 40 to 80 feet (12-24 m). Its three members (in descending order) are the Romeo, Markgraf, and Brandon Bridge. The Romeo Member is a massive, exceptionally pure dolomite ranging in thickness from 18 to 34 feet (5.5-10 m). The Markgraf Member is a cherty, argillaceous dolomite, 12 to 28 feet (3.5-8.5 m) thick. The Brandon Bridge Member ranges from 11 to 25 feet (3.3-7.5 m) thick and consists of thick-bedded, highly argillaceous dolomite (Willman, 1973). All three members of the Joliet vary in thickness and in clay and chert content. The Romeo and Markgraf Members of the Joliet, the Sugar Run Formation, and the basal Racine Formation have all been quarried successfully and can supply high-quality aggregate.

High-quality coarse aggregate generally cannot be economically produced from the Silurian rocks that underlie the Joliet. The Kankakee Formation (Figure 4) ranges in thickness from 20 to 50 feet (6-15 m) (Willman, 1973) and is the oldest Silurian unit normally quarried in the Chicago area. Carbonate rocks in the Kankakee commonly are pure dolomite, but the formation is thin-bedded, contains numerous clay beds and partings, and may contain chert nodules.

The Elwood and Wilhelmi Formations (Figure 4) that underlie the Kankakee Formation were deposited and preserved only in valleys or low spots in the eroded surface of the underlying Ordovician rocks. Near the end of the Ordovician, this region was emergent and the nonresistant shaly rocks of the Ordovician Maquoketa Group were extensively weathered. The large valleys that formed were filled with the highly argillaceous Wilhelmi and Elwood Formations during the
Silurian transgression. In areas where the Elwood and Wilhelmi are not preserved, the Kankakee Formation rests directly on the Ordovician. The Elwood Formation ranges from 0 to 30 feet (0-10 m) in thickness and consists of thin, rubbly beds of very cherty, argillaceous dolomite (Willman, 1973). The Wilhelmi Formation consists of 0 to 100 feet (0-30 m) of very argillaceous dolomite (Willman, 1973; Buschbach et al., 1982).

Overall clay content of the rocks decreases upward through the Wilhelmi, Elwood, and Kankakee Formations. As the valleys were filled and the shales of the Maquoketa Group were buried, the argillaceous content of the Silurian rocks decreased.

Much of Kane, Kendall, and the western parts of Will, Kankakee, and Du Page Counties are underlain by the Brandon Bridge Member of the Joliet, and by older Silurian rocks (Figure 3). Although potential quarry sites exist in these areas, high-quality crushed stone aggregate probably could not be economically produced on a large scale because of the high clay and chert contents of these rocks.

The Ordovician Maquoketa Shale Group (Figure 4) consists predominantly of shale, but contains minor amounts of interbedded dolomite. The uppermost Neda Formation and Brainard Shale are thinnest where the overlying Silurian Elwood and Wilhelmi Formations are thickest. The Fort Atkinson Limestone that underlies the Brainard Shale ranges from 0 to 40 feet (0-12 m) in thickness and consists of interbedded dolomite and limestone (Kolata and Graese, 1983). At a few localities (e.g., National Quarry, Joliet), the Brainard Shale or Neda Formation have been largely eroded away and the Fort Atkinson Limestone is quarried with the overlying Silurian rocks. The Fort Atkinson also has been quarried alone near Channahon and other places where it crops out, but it grades laterally into shale and dolomitic shale and is not present throughout the study area. The Scales Shale, which is the lowest unit in the Maquoketa Group, ranges from 40 to 135 feet (12-41 m) in thickness and consists entirely of shale.

The Galena and Platteville Groups (Figure 4) that underlie the Maquoketa Group are a significant potential source of aggregate for the Chicago region. The rocks are quarried throughout most of northwestern and north-central Illinois, but many of these quarries are small operations that do not attempt to produce high-quality aggregate suitable for use in concrete highway pavements (Goodwin, 1983). In the Chicago region (Figure 3), Galena Group rocks crop out in Kendall County and have been quarried there. Although the main outcrop area of the Galena Group in north-central Illinois is some 80 miles west of Chicago, some stone quarried there has been imported into the western suburbs. Rocks of the Galena and Platteville Groups underlie all of the Chicago region and underground mining of these resources may be an economical alternative to long-distance imports.

The Galena Group (Willman and Kolata, 1978) (Figure 4) consists predominantly of vuggy to vesicular, tan to brown dolomite and minor amounts of limestone. The Wise Lake Formation is generally considered to be the source of the highest quality aggregate in the outcrop area in north-central Illinois (Goodwin, 1983). The formation consists of about 75 feet (22.9 m) of pure, light brown, vesicular to vuggy dolomite. The Dunleith Formation (Figure 4) underlying the Wise Lake consists of about 125 feet (38 m) of slightly argillaceous, somewhat cherty dolomite. In most of the outcrop area, the chert content of the Dunleith is about 5 percent. The amount of chert in the formation decreases to the east, and chert is largely absent in the subsurface east of the outcrop area (Willman and Kolata, 1978). The Guttenberg Formation (Figure 4) consists of only 1 to 2 feet (0.3-0.6 m) of brown, vesicular, fossiliferous dolomite in most of the Chicago region, and the Spechts Ferry Formation is entirely absent. Therefore, the base of the Dunleith Formation essentially lies directly on the top of the Platteville Group.

The Platteville Group (Figure 4) has a total thickness of about 120 feet (36 m) in the Chicago region, about half that of the overlying Galena. Rocks of the Platteville Group commonly are thinner-bedded, finer-grained, and grayish than those of the Galena Group. Although some quarries produce from the Platteville in northwestern and north-central Illinois, those quarries generally do not produce high-quality concrete aggregate. Because the Platteville Group is so deeply buried in the Chicago region, and because it
is unlikely to produce aggregate of higher quality than the overlying Galena Group, it will not be considered further here.

For a number of reasons, underground mining seems to offer many advantages in the Chicago region (Baxter, 1980):

The high costs of land in urban areas and development of nearby housing or industry may make outward expansion of a quarry site too costly.

Underground mining and crushing operations can help to control dust and noise associated with most quarries.

Underground blasting may be less noticeable than above ground blasting because of the greatly reduced air pressure wave at the ground surface.

Lower transportation costs for sites nearer the Chicago market may partially compensate for the higher cost of underground operations.

Reclamation costs should be low because the underground openings in these strong rocks should be able to stand unsupported for hundreds of years. Subsidence is unlikely as long as the pillars are not robbed.

Leasing of mined-out areas for warehouse space may provide substantial opportunities for long-term recovery of the higher mining costs. In the long run, the underground space is potentially more valuable than the stone that came out of it.

CONCLUSIONS

The geology of the Chicago region and urban encroachment limit the options of producers seeking new stone reserves to supply the Chicago market. Growth of the Chicago metropolitan area is responsible both for increased demand for high-quality stone products and for increasingly severe restrictions of opportunities for expansion of quarries.

Dolomitized reef structures of the Silurian Racine Formation are recognized as the best aggregate resources, but such reefs are most common near Lake Michigan where the population density of the Chicago metropolitan region is greatest. Away from Lake Michigan, where the population density is lower, increasingly older, more argillaceous Silurian rocks are exposed at the bedrock surface, and the thickness of surficial overburden increases sharply. The best exploration area for new surface minable aggregate resources in the Silurian is in eastern Kankakee County. Here surficial deposits are thin in places and quarries are already operating in Silurian rocks. Because these potential quarry sites are almost twice as far from the Chicago markets as are present quarries, transportation costs will be higher.

Another potential source of high-quality aggregate may be developed by underground mining of rocks of the upper part of the Ordovician Galena Group. Although underground mining methods are more costly, these costs may be balanced by lower cost for reclamation and transportation, and longer-term investment recovery through secondary use of mined out space.

REFERENCES


POTENTIAL MARKETS FOR LIME AND LIMESTONE IN SULFUR CONTROL

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ABSTRACT

Markets for lime and limestone grew appreciably more slowly in the 1970's than in the 1960's. Consumption of lime/limestone for desulfurization of flue gases from coal combustion increased rapidly between 1971 and 1981; however, the total demand for lime/limestone was moderate, never exceeding about 0.1 percent of total demand for crushed stone and about 5.0 percent of the total demand for lime in the United States.

The New Stationary Source Performance Standards released in 1979 require a 70-90 percent reduction in potential sulfur dioxide emissions from coal-burning facilities, chiefly from the electric utilities. As old plants are closed and new ones built, more units will be using Flue Gas Desulfurization (FGD) techniques. If proposed acid rain legislation is enacted and additional lowering of sulfur dioxide emissions are required, even the older utility plants will be affected. Some plants will burn coals with lower sulfur content, but some may be retrofitted with FGD systems. The use of lime/limestone is thus expected to increase significantly over the next decade.

This paper includes a review of the present lime/limestone markets in the United States and projections for patterns of coal consumption by electric utilities. This in turn will determine demand for lime/limestone in FGD systems. Factors considered in the projections will include: (1) estimated growth of coal-based generation of electricity (2) market shares of low, medium and high sulfur coals, (3) applicability of clean air requirements and (4) possible compliance strategies for the utilities.

On the basis of such projections, estimates will be made regarding future markets for lime/limestone in the abatement of sulfur dioxide emissions from coal-burning utilities in the United States. An attempt will be made to identify quantitative differences in future regional markets.

BACKGROUND

Crushed stone production and employment in that industry declined by about 16 percent between 1974 and 1983. At the same time the real dollar unit value of crushed stone declined about 7.5 percent (Figure 1). Lime production and employment fell by about one-third, although its real dollar unit value increased nearly 15 percent (Figure 2). Despite this general downward trend a small market niche developed and grew rapidly as a result of the Clean Air Act passed in 1970. The consumption of limestone and lime in sulfur removal, virtually non-existent in 1974, amounted to 563,000 tons and 996,000 tons, respectively, in 1983 (Figure 3). Despite rapid growth rates, actual consumption of limestone/lime for SO$_2$ removal fell far short of the potential projected in the early 1970s.

The reasons for these developments were technical as well as demographic. Partly as a consequence of clean air regulations, the production of low-sulfur western coal increased rapidly in the latter part of the 1970s; eastern high-sulfur coal showed virtually no increases in the entire decade (Figure 4). At
the same time western coals cut into the markets traditionally served by high-sulfur coals. Competitive sources of energy such as nuclear and oil also contributed to slowing demand for high-sulfur coals. Nuclear power generation increased from just 1.5 percent of the national total in 1970 to 12.6 percent in 1980, about 85 percent of nuclear and 90 percent of the nation's oil-based electricity generation is concentrated in states east of the Mississippi River. Further setbacks were experienced by the high-sulfur coal industry through a shift in U.S. population toward states west of the Mississippi River, 37 percent of total in 1980 vs. 33 percent in 1970, and a 40 percent growth in per capita energy consumption in ten years in the west compared with an increase of 28 percent in the east.

**IMPORTANT FACTORS IN THE FUTURE**

Developments of the past decade such as the nuclear competition and the population shift to the west are expected to continue in the 1980s. In addition, the annual growth rates in consumption of electricity are expected to be 2 to 3 percent, thus much lower than in the 1970s. However, a number of positive factors will help increase the use of limestone/lime in sulfur dioxide removal:

1. The New Source Performance Standards (NSPS) released in 1979 require a 70 to 90 percent reduction in potential sulfur dioxide emissions from stationary sources constructed after September 1979.

2. The 1980 deregulation of railroads resulted in significant increases in the cost of transporting low-sulfur western coals. Transportation costs are likely to continue to increase for some time in the future as railroads try to increase their share of the delivered cost of coal. As a result, demand for high-sulfur coal is expected to stabilize in the 1980s and early 1990s.

3. Technological progress in Flue Gas Desulfurization (FGD) made it possible to produce marketable by-products such as gypsum, which...
will help reduce the total cost of FGD.

4. A number of legislative proposals are presently being considered in Congress to reduce future sulfur dioxide emissions. These so-called "acid rain" regulations would require a reduction in sulfur dioxide emissions by 8 to 12 million tons below the present national levels and would affect all the existing sources of pollution in addition to the new sources already regulated under the NSPS.

EASTERN AND WESTERN U.S.
COAL PRODUCTION, 1960 TO 1982

![Graph showing coal production](image)

Figure 4. U.S. Coal production.

BASIS FOR PROJECTIONS OF DEMAND FOR LIME/LIMESTONE

The most important basis for the projection of demand for lime/limestone in sulfur dioxide control has to be the quantities and sulfur contents of fuels expected to be used by electric utilities in the future. For this investigation the projections of fuel use by electric utilities in 1992 made by the North American Electric Reliability Council (NERC) have been used. For 1992, NERC projects a total use of about 862 million tons of coal and 32 million tons of oil by electric utilities. By comparison the 1982 consumption amounted to about 600 million tons of coal and 35.5 million tons of oil. Using the 1982 state-by-state consumption patterns and shares of fuels by state of origin, basic estimates for 1982 sulfur dioxide emissions by NERC Regions were prepared. The 1982 shares of fuels by state of origin were assumed to remain unchanged to the year 1992 and served as a basis for breaking down the 1992 fuel consumption by their state of origin in each of the NERC Regions. Average sulfur contents of coal by state of origin were then used to project future SO₂ emission potential.

A review of FGD systems in operation, under construction, or planned indicated that about 85 percent of all FGD systems used either limestone or lime. Although wet systems accounted for over 90 percent of the FGD capacity, the use of dry systems was expected to increase, especially for low sulfur fuels. The stoichiometric ratios indicate that about 0.875 ton of lime or 1.565 tons of limestone are needed to absorb 1 ton of SO₂. However, up to 20 percent more lime or 20 to 50 percent more limestone is required in the actual commercial operations. In this report multiples of 1.0 and 1.2 for lime and 1.2 and 1.5 for limestone requirements are used. Experience with fine grinding of limestone indicates that the multiples are probably closer to the lower values, so that the lower projections of demand seem more realistic.

INDEX OF ENERGY CONSUMPTION IN U.S. ELECTRIC POWER GENERATION

![Graph showing energy consumption growth](image)

Figure 5. Growth of energy consumption in U.S. electricity generation.
IMPORTANCE OF COMPLIANCE STRATEGY BY UTILITIES

Given the need for compliance with the NSPS regulations, new coal burning utilities have virtually no alternative to installing FGD systems. Thus, if the present set of regulatory constraints continues to apply in the future, only new power plants can be looked upon as a market for lime/limestone in sulfur removal. This represents the first model for future projections.

The proposed acid rain legislation necessitates another projection (Model 2) because it would require drastic reduction in SO₂ emissions from existing coal burning utilities. What strategies the existing utilities will use to comply with the acid rain regulations will be crucial in future projections of demand for limestone/lime. The two most important considerations in determining this strategy are the delivered prices of low- and high-sulfur coals and the expected remaining economic life of the plant, which determines the feasibility of retrofitting FGD installations or switching to lower sulfur fuels.

The retrofitting of existing utility plants with FGD systems involves large investments that can only be justified if the price difference between high- and low-sulfur coals is large, interest rates are acceptable, and the remaining economic life of the plant is long enough to recover the investments. This study assumes that investments in retrofitting FGD systems will only be made if at least half of the 30 year expected life of the plant is still remaining. Figure 5, which depicts the growth of energy consumption in electricity generation in the United States between 1950 and 1980, is used to estimate annual additions to generating capacity and the age of the plants. As seen there, the growth rates in successive decades have declined. However, the bases from which the growth rates are determined have grown. Thus, at present only about 35 to 40 percent of all existing plants are estimated to be older than 15 years. The remaining 60 percent of the existing electric utilities can be expected to retrofit with FGD systems under the acid rain model and will affect the demand for limestone/lime. It is assumed that all the high-sulfur oil (+1 percent sulfur) burned by utilities will be subject to FGD. Past experience in implementation of clean air regula-

tions indicates that utilities for which retrofitting with FGD systems is not economically feasible may be permitted to follow an extended time schedule for compliance and may not have a significant impact on consumption of limestone/lime.

1982 AND PROJECTED POTENTIAL 1992 LEVELS OF SULFUR DIOXIDE EMISSIONS

The potential for sulfur dioxide emission from coal- and oil-burning electric utilities in 1982 was estimated to be about 18 million tons. Actual emissions were about 17 million tons because existing sulfur dioxide abatement equipment removed about one million tons (Table 1). More than 80 percent of the emissions in 1982 were from coals produced and burned in states east of the Mississippi River.

In 1992 the potential sulfur dioxide emissions from coal-burning electric utilities are estimated to reach about 21.5 million tons (Table 2). Emissions from oil-burning utilities in 1992 will be about the same as in 1982, but are not included in Table 2 because existing sulfur dioxide removal nearly balanced that amount. Thus, if no further steps are taken to reduce sulfur dioxide emissions, actual emissions will also be about 21.5 million tons in 1992. Due to the expected growth in western coal consumption, the proportion of total sulfur dioxide emissions coming from eastern states will decline to about 75 percent.

PROJECTED SULFUR DIOXIDE REMOVAL IN 1992

As stated earlier two regulatory models have to be considered. Under the first model it is assumed that present regulations concerning the Clean Air Act will continue to be applied. Therefore, newly constructed utility plants will be equipped with FGD systems; old ones will continue to operate as before under the State Implementation Plans (SIP). Under these conditions, about 4.2 million tons of sulfur dioxide will have to be removed annually by 1992, about 60 percent of which is derived from eastern coals (Table 2).

Model 2 considers the proposed acid rain
Estimated 1982 emissions from coal and oil burning electric utilities in the United States.

<table>
<thead>
<tr>
<th>NERC census region</th>
<th>Eastern Coal</th>
<th>Western Coal</th>
<th>Oil</th>
<th>Overall total (95% of census consumption)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Consumption (10^6 tons)</td>
<td>Average sulfur (%)</td>
<td>Total S02 content (10^6 tons)</td>
<td>Consumption (10^6 tons)</td>
</tr>
<tr>
<td>ECAR</td>
<td>149</td>
<td>2.1</td>
<td>6.258</td>
<td>0.638</td>
</tr>
<tr>
<td>ERCOT</td>
<td>13</td>
<td></td>
<td>0.758</td>
<td>0.237</td>
</tr>
<tr>
<td>MAAC</td>
<td>53</td>
<td>2.1</td>
<td>2.226</td>
<td>4.834</td>
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<tr>
<td>MAIN</td>
<td>41</td>
<td>3.0</td>
<td>2.460</td>
<td>1.237</td>
</tr>
<tr>
<td>MAPP</td>
<td>3</td>
<td>2.0</td>
<td>0.120</td>
<td>0.106</td>
</tr>
<tr>
<td>NPPC</td>
<td>10</td>
<td>1.5</td>
<td>0.300</td>
<td>16.660</td>
</tr>
<tr>
<td>SERC</td>
<td>102</td>
<td>1.6</td>
<td>3.264</td>
<td>8.094</td>
</tr>
<tr>
<td>SPP</td>
<td>0.5</td>
<td>2.0</td>
<td>0.020</td>
<td>0.449</td>
</tr>
<tr>
<td>WCC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>359</td>
<td>14.648</td>
<td>249</td>
<td>3.323</td>
</tr>
</tbody>
</table>

1 Sulfur content averages estimated from NERC and DOE data. NERC census regions do not exactly match state boundaries; DOE data are reported by states. Averages are estimated by including complete states into NERC regions if major portions of the state are included in the region.

2 About 47 million tons of eastern coal and 23 million tons of western coal are being subjected to FGD. Estimated S02 removal in 1982 amounted to 1.08 million tons. Actual 1982 S02 emissions are estimated to be about 16.87 million tons.

Table 1. Emissions from coal and oil burning electric utilities in the U.S.

Table 2. Sulfur dioxide emissions reduction under the New Source Performance Standards.

legislation, which if enacted and implemented by 1992, will require drastic reductions in sulfur dioxide emissions from existing electric utilities. Assuming that 60 percent of these reductions will be attained by retrofitting the plants with FGD systems it is projected that about 11.3 million tons of sulfur dioxide will have to be removed annually by 1992 (Table 3). Note that most of these reductions will have to be in areas using eastern coals and high-sulfur oil as fuels.

PROJECTED DEMAND FOR LIMESTONE/LIME IN 1992

On the basis of the estimated sulfur dioxide removal needs and the ratios of lime-
stone and lime required for the removal, the demand for limestone/lime in sulfur dioxide removal in 1992 is projected in Table 4.

Under the first Model (continued application of present regulations), the demand for limestone is expected to be between 7.9 and 9.9 million tons, depending upon the ratio used and assuming that only limestone will be used for the purpose. Alternatively, 3.7 to 4.4 million tons of lime would be required.

Under Model 2 (acid rain regulations), 21.3 to 26.6 million tons of limestone or 9.9 to 11.9 million tons of lime will be needed in 1992.

In comparison with the above forecasts about 560,000 tons of limestone and 908,000 tons of lime were used for sulfur dioxide removal in 1982. It should be noted that the largest demand levels are expected to be in the ECAR and SERC Regions of the North American Electric Reliability Council, followed by the regions MAIN, MAAC, NPCC and SPP (Figure 6).

Technological changes such as fine-grinding are reducing the amount of limestone needed for sulfur dioxide removal, and neither limestone nor lime is exclusively used for the purpose. Therefore, actual demand levels for each of these two materials is expected to be on the lower end of the projections. Although the projected demand levels may appear insignificant in comparison with the

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**Figure 6. Regions of the North American Electric Reliability Council.**

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**Table 3. Sulfur dioxide emissions reduction by Flue Gas Desulfurization under proposed acid-rain legislation.**

<table>
<thead>
<tr>
<th>NERC census region</th>
<th>Tonnage subject to FGD in plants existing in 1982$^1$ (10^6 tons)</th>
<th>SO₂ removed in 1992 from plants existing in 1982$^2$ (10^6 tons)</th>
<th>SO₂ removed from new plants$^3$ (10^6 tons)</th>
<th>Consumption of oil with ≤1% SO₂ content$^4$ (10^6 tons)</th>
<th>SO₂ removed in 1992 (10^6 tons)</th>
<th>Total SO₂ removed by FGD in 1992$^5$ (10^6 tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAR</td>
<td>89.4</td>
<td>2.853</td>
<td>0.723</td>
<td></td>
<td></td>
<td>3.576</td>
</tr>
<tr>
<td>ERCOT</td>
<td></td>
<td></td>
<td>0.392</td>
<td></td>
<td></td>
<td>0.392</td>
</tr>
<tr>
<td>MAAC</td>
<td>23.4</td>
<td>0.747</td>
<td>0.009</td>
<td></td>
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<td>0.747</td>
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<td>MAIN</td>
<td>22.8</td>
<td>1.041</td>
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<tr>
<td>MAPP</td>
<td>1.8</td>
<td>0.548</td>
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<td>NPCC</td>
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<td>4.56</td>
<td>0.152</td>
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<tr>
<td>SERC</td>
<td>61.2</td>
<td>1.490</td>
<td>1.372</td>
<td>4.85</td>
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<td>SPP</td>
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<td>0.009</td>
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<td>0.617</td>
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<td>WCC</td>
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<td></td>
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<td></td>
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<td>0.415</td>
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<tr>
<td>Total</td>
<td>204.9</td>
<td>6.825</td>
<td>4.209</td>
<td>9.41</td>
<td>0.310</td>
<td>11.344</td>
</tr>
</tbody>
</table>

$^1$ Assuming 60% of coal burning utilities existing in 1982 will use FGD systems by 1992.

$^2$ Assuming average sulfur contents same as in 1982, 95% potential emissions, and 80% SO₂ removal rate.

$^3$ From last column of exhibit 7.

$^4$ 1 ton of oil = 6.667 bbl; average sulfur content NPCC = 2.2% and SERC = 2.15%.

$^5$ Sum of columns 2, 3, and 5.

<table>
<thead>
<tr>
<th>NERC region</th>
<th>Model 1</th>
<th></th>
<th>Model 2</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>10⁶ tons</td>
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<td>10⁶ tons</td>
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<td></td>
<td>of lime</td>
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<tr>
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<td>1.0¹</td>
<td>1.2²</td>
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<td>MAIN</td>
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</table>

1982 demand 0.908 0.560 Included in above totals

¹ Stoichiometric ratio
² Required excess ratio


The total size of the crushed stone industry in the United States, it could be significant for producers of the quality stone required for sulfur control.

REFERENCES


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THE ENVIRONMENTAL GEOLOGY OF GLASGOW, SCOTLAND -
A LEGACY OF URBAN SURFACE AND SUBSURFACE MINING

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ABSTRACT

The Mississippian and Pennsylvanian rocks and Quaternary sediments which underlie the City of Glasgow are described briefly. The succession contains a range of industrial, energy and other mineral resources which provided the raw materials necessary for the remarkable industrial growth of the City from the eighteenth century onwards. Throughout the past 200 years, various minerals have been extracted in quantity by open pit, strip or subsurface mining, often with some beds being re-entered and re-worked by different methods. The combination of mineral type, extractive method, and geological setting has resulted in environmental problems, which include damage to existing properties and constraints on the possible and most cost-effective options for re-development. To assist land-use planners in the design of an urban renewal programme, the British Geological Survey is being commissioned to undertake an appropriate exercise in Environmental Geology Mapping. The first phase of the study has been completed and the second is in progress with funds from the United Kingdom's Department of Environment and Glasgow District Council; the results so far obtained are presented in this paper.

INTRODUCTION

The techniques of environmental geology mapping are now employed routinely worldwide and are practiced in various forms, although the fundamental concepts of thematic (element), derived, and summary maps may still be recognized. Early leaders in this field include workers in the USA, Canada, West Germany, and more recently, the United Kingdom; their work is referenced elsewhere in review publications (Nichols, 1982; Hull, 1982). In Britain the need for environmental geology maps (EGMs) is recognized by land-use planners who are concerned to produce integrated development and other plans at strategic and local level. Consequently, Central Government has commissioned the British Geological Survey to undertake several research studies in different parts of the country to determine the relevance of the EGM concept to land-use planning. Additionally, local authorities (Regional and District) with more specific planning problems have contributed financially to these surveys. This mixed funding and differing planning requirements has resulted in each survey having distinctive technical objectives, which, together with geographical and geological variation, has resulted in the map folios for each area being different.

In Scotland the relevance of EGMs has been tested at a green-field site near Glenrothes (Nickless, 1982), in an urban-fringe zone south-east of Edinburgh, and in an inner part of the City of Glasgow (Forsyth and others, 1983); additionally a geotechnical study has been undertaken along the Forth Estuary. All these studies have included consideration of solid and superficial geology, drift thickness, mining and hydrogeology, but each has had particular emphases which reflect the interaction of localized land-use planning problems and geology. The results for Glenrothes were presented, in the context of the possible expansion of this new town, as summary maps concerned with: development potential for building; priority areas for site investigation; and resource potential. South-east of Edinburgh the planning problems relate to the future land-use pattern of an area of agricultural land where there is still potential for the exploitation of sand and
Figure 1. Location map, Glasgow, Scotland.

Gravel, coal, and groundwater resources. In contrast, the planning problems of Glasgow are concerned primarily with urban renewal where there is a long history of surface and sub-surface mining which may result in the sporadic failure of existing buildings and make for relatively costly preventative measures to ensure adequate support for new structures.

HISTORICAL BACKGROUND

Glasgow grew in Roman times (ca 55 AD) around the most reliable ford to seaward over the River Clyde (Fig. 1). In the twelfth century the City and Burgh was established by Royal charter, with powers of local taxation and self government. In the succeeding four hundred years the population increased from 1,450 to 4,500 inhabitants and a university was founded in 1451. By the end of the sixteenth century, coal was being exported in flat-bottomed barges, but downstream development was necessary to allow safe passage for larger vessels. Subsequently a dredged channel was cut to allow ocean-going ships access to the city centre.

From 1732 onwards, the establishment of ironworks and forges increased the local demand for coal and ironstone at the expense of the export trade, and minerals were being won increasingly by sub-surface mining. Clay and sand from the Clyde's alluvial deposits were also being used for the manufacture of ceramics and glass at about this time.

By 1800 the population had increased to 70,000 reflecting the gathering momentum of the industrial revolution. The trend of increasing population and commercial success continued through the nineteenth century with the advent of steam trains and iron ships which made further demands on indigenous resources of coal and iron. As a result workings became deeper (greater than 90 m below ground), extractive techniques changed to longwall at the expense of pillar and room methods, and interleaved coal and ironstone once considered waste were also worked. The working of ironstone peaked around 1880, followed by a rapid decline as the ores proved unsuitable for steel production, and it finally ended after the Great War (1914-18). In contrast, the subsurface mining of coal peaked early in the twentieth century and came to an end as recently as 1983.

The growth of Glasgow also involved the exploitation of other local mineral resources, whose long abandoned, and often forgotten, workings now contribute to the problems of land-use planning. Historically, limestone and clay seatearths have been mined for use as a
flux and refractory bricks respectively. Simultaneously, the construction industries have worked sandstones, dolerites, clays, sand and gravel, and till for use as dimension stone, brick, aggregate and fill.

Historically it is possible to consider Glasgow as a nucleated early settlement surrounded by surface and sub-surface mineral workings. With time, however, Glasgow has grown out over these workings and absorbed the surrounding mining communities. Thus, some land-use planning and development problems of the present City, with its population of 900,000 stem from the underlying geology and from the cavities and infilled quarries left by many miners who operated between the sixteenth and twentieth centuries.

GEOLOGICAL BACKGROUND

Bedrock

The stratigraphy of the Mississippian and Pennsylvanian rocks is set out in Table 1, together with an indication of their contained resources; their sub-crop beneath superficial sediments is shown in Fig. 2.

The oldest rocks exposed are the basaltic lavas of the Clyde Plateau Volcanic Formation, its thickness being inferred from a seismic survey. The overlying upper Carboniferous Sandstone Measures are of fluviatile origin, with mainly sandy beds succeeded upwards by mudrocks; some coals, marine bands and limestones are also included. The Lower

Figure 2. Solid (bedrock) geology of Glasgow and vicinity.
Limestone Group consists of sedimentary cycles ('Yoredale') representing deltaic and marine shelf deposition, with mudstone lithologies dominant in the west and sandstones increasing eastwards. In contrast the sediments of the limestone coal Group suggest deposition in alluvial plain, lacustrine or paralic environments. Whereas the lower part is dominated by mudstone, with clayband and some backband ironstones but few coals, the upper portion contains more sandstone and many coals; limestones, despite the group name, are absent. The lower part of the Upper Limestone Group is characterized by thick, coarse-grained, channel sandstones, whilst the remainder consists mainly of fine-grained sandstones and marine mudstones; thin limestone occurs throughout the group. The Passage Group consists of pebbly sandstone and interbedded seatclays, with thin marine mudstones. The Mississippian-Pennsylvanian boundary is currently placed within this group.

The Coal Measures sediments are believed to represent deposition in alluvial and lacustrine environments. The basal beds of the Lower Coal Measures are lithologically similar to the Passage Group, being mainly arenaceous. However, the overlying strata, together with most of the Middle Coal Measures, consist of sandstones and mudstones in approximately equal proportions, with numerous coals and rare marine bands. The uppermost Middle Coal Measures, together with most of the Upper Coal Measures are characterized by the appearance of channel sandstones, but the youngest beds preserved are mainly mudrocks.

The tectonic setting of the Lower Carboniferous rock is dominated by major north-easterly trending faults which may owe their existence to deep-seated re-activated structures of Middle Devonian Age. The Upper Carboniferous rocks are cut by a younger suite of generally easterly trending faults of Hercynian origin. The associated fold structures are modest, the major structures being a northerly trending syncline with a number of subsidiarly anticlinal and synclinal folds. Such isopachyte data as are available for Carboniferous rocks suggest that the north-easterly trending faults exercised a degree of local control on the developing Dinantian and Namurian sedimentary basins, but by Westphalian times Glasgow was part of a much larger moderately subsiding "shelf" area which extended across most of Central Scotland. Growth faults and folds are likely to exist but are not clearly defined. Intrusive igneous rocks also occur. The dykes, which trend east-west, are quartz-dolerites of Stephanian Age. The sills consist of olivine-dolerite and are of late Westphalian Age.

Superficial Deposits

These deposits occur extensively throughout the area, with thicknesses exceptionally in excess of 90 m. The oldest Quaternary (=Drift) sediments are proglacial lacustrine muds of limited distribution. They are overlain by the Baillieston Till Formation which formed in early to middle Devensian times. In the north of the City, this is overlain by glaciofluvial-lacustrine sand and gravel (Cadder Formation). These deposits contain wooly rhinoceros remains, dated to 27,500 years BP, and frost wedge casts. In the south of the City, glaciotectonized, proglacial lacustrine muds (Broomhill Formation) occur discontinuously above the Baillieston Till Formation. The distribution of the mud suggests the existence of a lake in the Clyde valley with shorelines above 70 m Ordnance Datum (OD). The overlying Wilderness Till Formation was deposited during the Great Ice Age by a 1.5-km-thick ice sheet which covered most of Britain 27,000 to 14,000 years ago.

The pattern of deglaciation of the main late Devensian Ice Sheet is complex. Proglacial lake muds (Bellshill Formation) succeed the Wilderness Till Formation and occur extensively in the Clyde Valley east of Glasgow at levels from 60 m to 180 m OD. The variation in height is due to the north-westerly retreat of the wasting glacier, meltwaters escaping from the lake basin by way of lower outlets.

While the Clyde ice was retreating to the Highlands, the sea was also making inroads into the ice occupying the Firth of Clyde. Inevitably the ice dam between Glasgow and the sea failed and a marine embayment formed. Evidence of these complex events is given by eskerine sand and gravel (Broomhouse Formation) associated with a terminal moraine in the east of the City. Palaeocurrents indicate upstream transport. In
contrast, further deposits of sand and gravel (Bridgeton Formation), now buried by younger glaciomarine muds, were carried by down-stream currents; this formation is thought to be part of a submarine outwash fan.

Glaciomarine muds occur widely, draping the sides of drumlins. The oldest muds (Paisley Formation) are characteristically highly colored and laminated, with many silt layers (ice clearance facies). When the formation was deposited 13,700 to 13,000 years ago, relative sea-level was about 40 m OD. The muds of the Linwood Formation are mainly massive and the upper third is monosulphide rich. The unit contains a rich high-boreal fauna appropriate to the Windermere Interstadial. Slow sedimentation rates are indicated by the range in marine-shell radiocarbon dates from the base of the unit (12,600 to 11,200 years BP). During the period of deposition of the Paisley and Linwood formations, relative sea-level fell (isostatic deformation) and by 11,000 BP had returned to about present datum.

During the following mini Ice Age of the Loch Lomond Stade (11,000 to 10,300 years BP), valley glaciers formed in the Highlands and advanced to within 14 km of the City. The extent of the ice is marked by the distribution of the Gartocharn Till Formation and by terminal moraines. Periglacial conditions prevailed in the City (frost wedge casts) and proglacial muds were laid down in the western Clyde (Balloch Formation) with an arctic fauna. During this period, sea-level may have fallen below present (by at least 10 m), and in the City this event may be represented by a buried valley incised into pre-existing sediments. The narrow valley is floored by a basal gravel overlain by sand (with shell fragments) forming the Longhaugh Formation. This unit passes up into well-bedded muds (Erskine Formation). Both these formations are of Flandrian age and formed between 10,000 and 5,000 years ago. The relationship between these deposits and the formerly extensive coastal peat bogs of the area is unclear. At the acme of the Flandrian marine transgression about 6,000 years BP, local relative sea-level stood at 13 m OD. There may have been other smaller events about 8,000 and 4,000 years BP.

**ENVIRONMENTAL ISSUES**

The existence of mineral workings beneath a major city poses many environmental problems. In this context the decision to sterilize or allow the extraction of remaining mineral resources is a relatively low priority consideration. A more pressing issue is the possible effects of such workings on groundwater resources. The associated problems of waste disposal in old workings assume importance when the groundwater regime is at risk, especially where the subsurface movement of toxic elements is of concern. Important as these issues are, the one that concerns the general public most directly is that of ground stability and its possible effects on property.

In Glasgow there is visible evidence of damage to property which can be attributed to inadequate construction in relation to the prevailing ground conditions. This evidence could lead some financial institutions to map the city into areas where they would permit financial investment and others where they would not. Such action, perhaps formulated without reference to geological criteria, would be of concern to all, including developers, politicians and local authority officials. Land-use planners and those involved in building control, now recognize the need for appropriate geological studies to provide a framework for decision making. Particularly they are concerned to delineate areas with few problems as opposed to those with many. In practice, this means identifying areas requiring relatively low-cost site investigations and preventative works in contrast to those in which extensive, detailed and expensive site stabilization will be required prior to development. In summary, land-use planners require early warning of ground conditions to allow them to formulate a number of costed options for future development or re-development.
The geological input into such advice will take account of the existence and location of relevant records (mine plans, borehole logs, etc); the sites of open-pit operations and their backfill; the subsurface level, extent and methods of working of the various mined minerals; the nature, disposition and geotechnical properties of both superficial sediments and solid rocks; the groundwater regime. Most land-use planners practicing in the United Kingdom are not qualified geologists. Consequently, they have formulated a requirement to have the traditional maps of the Geological Survey broken down into simple cartographic presentations of elements (or themes) of interest to them, with subsequent combinations of elements leading to summary maps at appropriate scales and relevance to particular planning problems.

ENVIRONMENTAL GEOLOGY

The first phase of the Glasgow study was completed in March 1983, with funds provided by the Department of the Environment in association with the Scottish Development Department, and describes an area of 100 square kilometers in the east of the City (Forsyth and others, 1983). The subsequent phase in an adjacent area to the west is still on-going, with additional financial support from the Glasgow District Council, which is taking an active interest in steering the work.

Available Information

The primary geological survey of Glasgow was undertaken between 1850 and 1860 with revision surveys in 1900 and 1950. The standard of each varies according to the competence and objectives of the surveyors and the maps are drawn on differing topographical bases reflecting the dates of survey. About 15,000 borehole records have been collected over the years and this database grows daily. The information from the bores relates mainly to Quaternary sediments and some is not always reliable, often comprising only a driller’s log, rather than a geologist’s. However, a significant number of cores and samples have been subject to geotechnical tests and others have been examined by Survey geologists. In contrast, the 3,000 or more boreholes penetrating the Carboniferous rocks beneath the City have nearly all been examined by Survey geologists in collaboration with staff, as appropriate, from the National Coal Board (NCB) and engineering consultants. As a result, the litho-stratigraphy and inter-correlation of the rocks is considered to be secure.

The charting of old mine workings is another aspect of the work in which large quantities of data must be brought together from diverse sources. Too often, if plans ever existed for workings pre-dating the Mining Act of 1865, they are now lost. Mine Abandonment Plans are held by the NCB for coal and other minerals, if worked with coal, but this is not a complete collection. Some ancient working documents have been recovered from other NCB archives and also from the collections of individual collieries which pre-date nationalization. In Glasgow unique plans were also recovered from archivists of the University and City, libraries, mining engineering companies, Strathclyde Regional Council, Scottish Records Office, estates and individuals. Fortunately, non-coal mine plans for Scotland, formerly held by the Health and Safety Executive in London, are now maintained by BGS in Edinburgh. The mining records involved are numerous (greater than 600) but many commonly fail to provide data in the area of most concern where workings come within 30 m of rockhead.

Procedures

To assist in the manipulation of existing data a computerized borehole database was created and is operated under an appropriate database management system. For each borehole, reference information (including name, grid coordinates, surface level, etc) summary Carboniferous stratigraphy and details of Quaternary sediments are encoded. Using menu-driven programs, graphical output is obtained at appropriate scales for:

1. Borehole Sites, options: all sites; Quaternary; or Carboniferous sites.
2. Depth to rock (drift thickness).
3. Depth of borehole, rock not proved (minimum drift thickness).
4. Depth to top of Glacial Till.

5. Depth to rock, no Till present.

6. Thickness of man-made deposits.

7. Lithology of first natural soil, greater than set thickness.

8. Cumulative thickness of subsoil type in borehole (eg Till).

9. Numbers of each subsoil type in borehole, separated by more than one metre of a different type.

The information required from existing geological maps and mine plans was abstracted manually, although future production by more automated methods is the subject of experiment.

Output

From discussions with the customers, and other potential users, it was obvious from the outset that their requirements would be met best if the results of the study were presented in map form. Discussions then centred on the choice of scale for the final presentation, as opposed to the working scale, and the topic to be displayed. The results of the first phase were presented as a folio of up to seventeen manuscript maps for each 25 square kilometre sheet area, resulting in a total of 68 maps for the 100 square kilometre grid rectangle surveyed. The commissioning departments received a number of complete sets, but the masters of each map are held on open-file and sold separately to other customers on demand. The maps included in the folio are listed in Table 2, with explanatory notes in Appendix I.

All the maps are available at the 1:10560 scale, except for the maps of hydrogeology, bedrock lithology and undermining by non-coal workings, which are drawn at the 1:25000 scale and cover the whole 100-square kilometre rectangle. Other maps could be produced by combining two or more of the maps listed to address particular questions, like hazard or mineral resource potential. The selection of a depth of 30 m below rockhead to distinguish shallow from deep undermining, with its implications of potential hazard to existing and future development, is an empirical compromise following detailed discussions with NCB subsidence experts and private sector consulting engineers who specialize in similar problems. Nevertheless it is recognized that although such a depth is considered by some to be the conservative (=worst) case, others would adduce evidence for surface collapses which have been initiated by undermining at depths below 200 m.

CONCLUSIONS

The relevance of this type of study to the daily work of planners, architects, engineers and all concerned with the control of building in the employ of a local authority is demonstrated by Glasgow District's financial contribution to the second phase. However, their needs differ in degree from those of national authorities and this is reflected in the restricted number of maps being proposed as output from the current work, together with increased emphases on engineering aspects.

It has been concluded (Forsyth and others, 1983) that some of the maps (Table 2) are of more use to planners than others. These are: contoured drift thickness, drift lithology, solid geology, shallow versus deep mining, engineering properties. This thesis is supported by the take-up of map sales to engineering consultants in the private sector and by Glasgow District's current requirements. However, the present authors conclude that the facets of particular interest to land-use planners concerned with Glasgow may be summarized in one map which is subdivided areally into four categories concerned with the presence or absence of superficial deposits and their relationship to the occurrence or absence of mine workings within 30 m of rockhead. Such an analysis has implications for development within each area which will vary from the extremes of thin (less than 5 m) drift on unmined solid rock to thicker, soft drift sequences overlying shallow mining. In planning terms the use of such a map is about cost-effective options and not hazard assessment specifically; its use is, therefore, most appropriate at the strategic rather than local planning level.
For an engineering assessment of ground stability, however, such a summary is too generalized. An analysis of structural damage to property is currently being undertaken, but preliminary results suggest that, although the nature and thickness of superficial sediments, man-made deposits, and the presence of mining activity may contribute to failure, the main cause could be inadequate building and/or maintenance. However, this type of analysis does demonstrate the need for the site specific geological information which is available in the full EGM folio and for further investigation of this aspect.

It is recognized that further research could well re-define the categories proposed for use on the summary map and therefore lead to a more useful end product. It has been argued (Rankilir, 1984, p. 179) that where a site is undermined, the viability of any proposed development is likely to be determined most cost effectively by a relatively detailed preliminary study of the drift deposits beneath the site. This proposal accords with the authors' opinion that a study of the superficial sediments concerned to model the three-dimensional distribution of the various lithologies (and their associated geotechnical properties) within the sequence would have scientific and economic benefit. It would be appropriate to undertake such a study in the Glasgow area now that a unique computer database of appropriate parameters has been established. An additional conclusion, therefore, is that there must be a continuing commitment of staff time and resources to the maintenance and development of existing databases which will facilitate future work.

In respect of the mined solid rocks it is imperative to distinguish the as yet unknown areas and levels mined by pillar and room methods, as opposed to longwall workings, because the former are more likely to suffer collapse due to roof or pillar failure. Further research therefore would include: improvements to geophysical methods for cavity location, with the emphasis on resolution and speed of areal survey; geotechnical studies into the strength of the pillars; and the physical and chemical effects of groundwater movements on pillars of various lithology. An associated hydrogeological study would be concerned to determine the effects of ground stabilization on the groundwater regime and whether or not grout screens would cause sub-surface damming with resultant impounding in some workings and dewatering of others with possible surface effects.

The overall conclusion must be that, although the concept of environmental geology maps continue to be relevant to the solution of a wide range of current land-use problems, to undertake comprehensive surveys on every occasion is unlikely to be cost effective. It is inevitable, therefore, that such studies will differ from each other to the extent that they reflect differing geological settings and the varying requirements of the commissioning agencies. Thus the Glasgow study has been concerned exclusively with superficial sediments, man-made deposits and historical undermining because together they present today's planners and developers with real problems which require immediate attempts at solution.

ACKNOWLEDGEMENTS

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APPENDIX I: DESCRIPTIONS OF MAPS PRODUCED FOR PHASE I
OF THE GLASGOW STUDY
(modified after Forsyth and others, 1983)

Map No. 1: Boresites - Solid. This map shows the sites of all boreholes and
shafts, the records of which were used in the construction of the
solid geology maps. At each site at least one named lithostatigraphic bed in the succession has been recognized with reasonable
certainty. Most of the boreholes have been logged by B.G.S. staff.
Also shown are sites designated for possible opencast coal
extraction.

Map No. 2: Boresites - Drift. This map shows the sites of boreholes used in
the interpretation of the drift deposits. Information from a group
of boreholes has been used rather than relying on any individual
borehole record. Most of the records are boremasters' reports, a
few were logged by B.G.S. staff.

Map No. 3: Total drift thickness and minimum drift thickness. This map shows
posted values in metres for full thickness of drift (3a) in bores
which reached rockhead, and minimum thickness of drift (3b) in
bores which did not reach rockhead. Any disturbance of the ground
subsequent to the drilling of a borehole may have rendered the
recorded thickness invalid.

Map No. 4: Drift thickness - contours. Contours of drift thickness which have
been constructed from the evidence presented on Map 3 and on
Map 9 are shown on this map. These contours are drawn at inter­
vals of 5 m up to 20 m thickness, and at 10 m intervals
thereafter. Control for the drawing of contours is adequate except
for the northern halves of the NW and NE quadrants where the
contours are highly conjectural. In places the contours may not re­
flect thicknesses shown on Map 3 as individual borehole records
may have been accorded different reliability. Locally, extra con­
tours have been added to highlight the sites of former quarries
which are now infilled. Map No. 4a is a presentation of the four
quadrant maps reduced to the 1:25000 scale.

Map No. 5: Rockhead level, posted values. Presented here are boresites where
rockhead was proved and at which a reliable surface level is avail­
able. The posted values give the level of rockhead in whole
metres above or below Ordnance Datum (OD).

Map No. 6: Rockhead contours. Contours of rockhead are depicted at 5 m in­
tervals up to 20 m above O.D. and down to 20 m below O.D.
Out with these limits intervals of 10 m were chosen. The contours
were constructed from the posted values on Map No. 5 and from
the intersection of the drift-thickness contours on Map No. 4 with
the Ordnance Survey topographic contours. The accuracy is vari­
able and is dependent on the amount of information available. Map
6a is a reduction of the four quadrant maps to 1:25000 scale.

Map No. 7: Depth to till and rock. On this map, plots of boresites showing
thicknesses of "soft", cohesive and non-cohesive materials overlying
either till (7a) or rock (7b) are presented. These materials are
broadly interpreted to include man-made deposits, peat, clay, silt,
sand, and gravel. The resulting data are used to assist in the prepa-
ration of Map No. 16 which shows simplified drift foundation conditions.

Map No. 8: Drift lithology. This map is constructed from evidence obtained from field surveys and from borehole records held in the computerized database. Most lithologies are mapped if there is evidence that they exceed 1 m in thickness. However, man-made deposits have been mapped from borehole records only where they exceed 3 m in thickness over a significant area. Unlike standard drift maps, the age and origin of the drift deposits is not featured. To illustrate the subsurface relations of the drift deposits, cross-sections of these deposits are shown.

Map No. 9: Geomorphology. This map is designed mainly to show areas of higher ground formed by drumlins, which are usually associated with thicker than normal drift deposits. A knowledge of their distribution aids in the construction of drift-thickness contours where borehole information is lacking. The back features of former beach and river terraces are also presented as these landforms can mark changes in the surface lithology and drift-thickness. This map is a simplified statement on the geomorphology of the area.

Map No. 10: Solid geology. This is a simplified geological map of the Carboniferous rocks which shows distribution of the various groups of rocks (Table 1) into which the succession is divided. All known major faults are depicted, together with an indication of the general dip of the strata. As the presence of old coal workings, which may be at shallow depths, is one of the major considerations in the project, outcrops of the worked coal seams are shown. The various types of intrusive igneous rocks have been grouped together; except for one dyke, all are sills. Mine working can occur below them. The extensive thick cover of drift means that only a few outcrops have been verified from surface observation. Therefore, the mapping is based largely on information from boreholes and mine plans.

Map No. 11: Bedrock lithology. This map, on the 1:25000 scale, is derived from Map No. 10 and shows generalized lithologies of the Carboniferous rocks over the whole area.

Map No. 12: Mining information. Shown on this map are areas under which mining is known to have taken place based on mine plans. The map has been subdivided into areas where only one seam is known to have been extracted and into areas where more than one seam was worked. It is obvious from other evidence (e.g. boreholes proving wastes) that mining occurred in areas for which there are no extant mine abandonment plans.

Map No. 13: Present day mining. This map shows where mining activity was taking place at the time of survey. Cardowan Colliery was the only working pit in the area but it is now closed. The final operations in the Limestone Coal Group were at depths in excess of 400 m.

Map No. 14: Mining excluding coal. This map shows those areas where ironstone, fireclay, limestone, sandstone and brick clay have been mined. All of the ironstone workings are deep but the other minerals were mined within 30 m of rockhead in places. Scale is 1:25000.
Map No. 15: Mining within 30 m of rockhead. This map highlights known workings within 30 m below rockhead in one or more seams. Also portrayed are the sites of all known old mine shafts and of boreholes where coal wastes were observed within 30 m of rockhead, many of these being outwith the limits shown on mine plans.

Map No. 16: Drift lithology - Engineering properties (generalized). This map presents three categories of surface materials likely to be encountered in foundation work: rock at surface, till at surface and "soft" materials at surface. These categories are related to Groups and Classes of materials referred to in British Code of Practice for Foundations CP 2004 (1972) H.M.S.O. The thickness of "soft" materials is indicated by contours at 5 m intervals.

Map No. 17: Hydrogeology. The hydrogeology of the areas shown on this map is extremely complex due to the:

a) multi-aquifer sequence within the Carboniferous bedrock;
b) perched aquifers in unconsolidated drift deposits of the Clyde valley;
c) extensive network of old mine workings, the majority of which are flooded.

A large amount of the water is contained within the old workings and is of low quality, with a high iron content and a low pH. The map displays a shaded area where rest-water levels within the superficial deposits are thought to be within 5 m of the surface. Infilled quarries are often saturated with water and may present a problem from the standpoints of stability and water quality; the latter especially so if the quarry has been infilled with domestic refuse. Greenoakhill landfill site is Scotland's largest recipient of liquid waste. A pollution plume within underlying groundwater has developed from this and nearby landfill sites and is moving in a westerly direction. It will eventually discharge into the River Clyde where dilution will render the pollutants harmless. It is important to note, therefore, that groundwater quality to the west of the area, within the superficial deposits, is likely to be extremely low.

REFERENCES


