

INDUSTRIAL ROCKS AND MINERALS OF THE PACIFIC NORTHWEST

Proceedings
of the 25th Forum
on the Geology of Industrial Minerals
April 30 to May 2, 1989, Portland, Oregon

1990



STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
DONALD A. HULL, STATE GEOLOGIST

STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
910 State Office Building, 1400 SW Fifth Avenue
Portland, Oregon 97201

SPECIAL PAPER 23

**INDUSTRIAL ROCKS AND MINERALS
OF THE PACIFIC NORTHWEST**

**Proceedings of the 25th Forum on the Geology of Industrial Minerals
April 30 to May 2, 1989, Portland, Oregon**

Compiled and edited
by
Ronald P. Geitgey and Beverly F. Vogt

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1990



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**CHRONOLOGY OF THE FORUMS
ON THE GEOLOGY OF INDUSTRIAL MINERALS**

1st	1965	Columbus, Ohio
2nd	1966	Bloomington, Indiana
3rd	1967	Lawrence, Kansas
4th	1968	Austin, Texas
5th	1969	Harrisburg, Pennsylvania
6th	1970	Ann Arbor, Michigan
7th	1971	Tampa, Florida
8th	1972	Iowa City, Iowa
9th	1973	Paducah, Kentucky
10th	1974	Columbus, Ohio
11th	1975	Kalispell, Montana
12th	1976	Atlanta, Georgia
13th	1977	Norman, Oklahoma
14th	1978	Albany, New York
15th	1979	Golden, Colorado
16th	1980	St. Louis, Missouri
17th	1981	Albuquerque, New Mexico
18th	1982	Bloomington, Indiana
19th	1983	Toronto, Ontario
20th	1984	Baltimore, Maryland
21st	1985	Tucson, Arizona
22nd	1986	Little Rock, Arkansas
23rd	1987	North Aurora, Illinois
24th	1988	Greenville, South Carolina
25th	1989	Portland, Oregon

NOTICE

The Oregon Department of Geology and Mineral Industries is publishing this paper because the subject matter is consistent with the mission of the Department. To facilitate timely distribution of information, authors' manuscripts were not edited to our usual standards. Readers who have difficulty finding references cited in various papers should contact the appropriate authors directly.

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PREFACE

The 25th Forum on the Geology of Industrial Minerals was held in Portland, Oregon, from April 30 through May 2, 1989. The meeting, entitled "Industrial Minerals of the Pacific Northwest," was attended by 120 industrial minerals specialists from the United States, Canada, and Great Britain. About a third of the attendees were employees of various government agencies, and the rest were employed in private industry.

The Forum consisted of technical sessions, a local field trip, and an optional three-day trip. All of the papers presented at the technical sessions are contained in this volume. The Portland portion of the Forum concluded with a field trip to local industrial mineral producers, shippers, and users. Ross Island Sand and Gravel provided a tour by barge of its Willamette River dredging operation, which supplies aggregate for the Portland metropolitan area. The Port of Portland hosted a tour of the Hall-Buck Marine, Inc., bulk mineral loading facility through which talc, bentonite, and soda ash are transferred from unit trains to ocean freighters for export. A tour of the Blitz Weinhard Brewery included discussion of the brewery's diatomaceous earth-filtration system and a stop in the hospitality room to test the efficacy of that system.

An optional field trip took 45 participants to industrial mineral operations in eastern and central Oregon. Stops included Ash Grove Cement West in Durkee, producing cement and limestone for sugar beet refining; Teague Mineral Products in Adrian, producing bentonite and the zeolite clinoptilolite; Eagle-Picher Minerals in Vale and Juntura, producing filter-grade diatomite; the Cascade Pumice Company in Bend, producing lightweight aggregate; and stops and discussions at various points of historical and geologic interest.

The gracious hospitality of the companies visited on both field trips is gratefully acknowledged. The willingness of their employees to discuss details of their respective operations made the field trips particularly instructive and enjoyable. Several organizations also made financial contributions that helped considerably to underwrite the costs of social events and publications. These or-

ganizations included Ash Grove Cement West, Inc.; the Oregon Concrete and Aggregate Producers Association; Eagle-Picher Minerals, Inc.; the Northwest Mining Association; and the Society of Economic Geologists Foundation, Inc.

The support of the Washington Division of Geology and Earth Resources during the meeting was greatly appreciated. Particular acknowledgment must be made to Donald A. Hull, State Geologist, and the entire staff of the Oregon Department of Geology and Mineral Industries, who were involved as either active participants or indulgent victims through nearly two years of planning, execution, and the aftermath of the Forum. I must express special appreciation to Beverly F. Vogt, Proceedings Editor, who unlike most of us at the completion of the Forum, had to face the fact that her work had just begun, and Klaus K. Neuendorf, who produced the document on the Department's desktop publishing system. Finally, my deep appreciation to all Forum speakers and authors, who had to find the time and resources to produce abstracts and manuscripts on a schedule to permit timely publication of the proceedings. The dubious distinction of submitting the latest manuscript went to the Forum Chairman.

The Forum's 25th Anniversary was appropriately marked by meeting in a location far removed from its beginnings in Columbus, Ohio. It is a tribute to the vitality of the field and to the organizational skills of Robert L. Bates (or more accurately, his choice to apply those skills only lightly) that this loosely knit nonorganization now migrates annually back and forth across the United States and Canada, propelled by the interest and enthusiasm of specialists in industrial mineral exploration, analysis, marketing, and production.

—Ronald P. Geitgey, *Industrial Minerals Geologist*
Oregon Department of Geology and Mineral Industries
Chairman, 25th Forum on the Geology of Industrial Minerals
Portland, Oregon

Industrial minerals in Oregon

by Ronald P. Geitgey, Oregon Department of Geology and Mineral Industries, 910 State Office Building, Portland, Oregon 97201

ABSTRACT

A wide variety of industrial minerals is produced in Oregon for regional, national, and international markets. The estimated total value of nonfuel mineral production in Oregon in 1988 was \$169 million, virtually all of which was from industrial minerals. Sand, gravel, and crushed rock accounted for approximately \$115 million.

Limestone is quarried from one location for cement production and sugar-beet processing and from two other locations for agricultural uses. Diatomite is produced by two companies, one for filter aids and the other for pet litter and oil absorbents. Bentonite clay from two operations is used primarily for civil-engineering applications, and structural clays are used by two brick manufacturers. Pumice from two areas is sold to concrete-block producers, and lesser amounts are used for landscaping and for stone-washing certain garments. The zeolite mineral clinoptilolite is processed for absorbents and odor-control products. Exploration and limited production of perlite continues, and emery is produced for nonskid surface coatings. Quartzofeldspathic beach dunes supply material for container glass production, and quartz is quarried for nickel smelting, filter beds, poultry grit, and decorative uses. Talc, in

the form of soapstone, has an international market as fine-quality art-carving material, and gemstone production includes agates, opal, obsidian, and sunstone, a calcic plagioclase feldspar.

Many commodities produced in the past in Oregon merit re-evaluation. Some of these are brick clays, chromite, expandable shales, foundry sands, gypsum, iron-oxide pigments, peat, and building stone, including gray granites, white marble, black marble, sandstones, and volcanic tuffs. Production ceased for most of these because of market conditions and increased costs rather than product quality or deposit reserves.

Several other commodities have the potential for new or increased production. Some have been evaluated; others are known occurrences that have geologic potential for commercial development. They include bentonite clay, borates, feldspar, ferruginous bauxite, fuller's earth, kaolin clay, nepheline syenite, perlite, and talc.

INTRODUCTION

In Oregon, a wide variety of industrial minerals is produced for regional, national, and international markets. The state's estimated total value of non-fuel mineral production in 1988 was

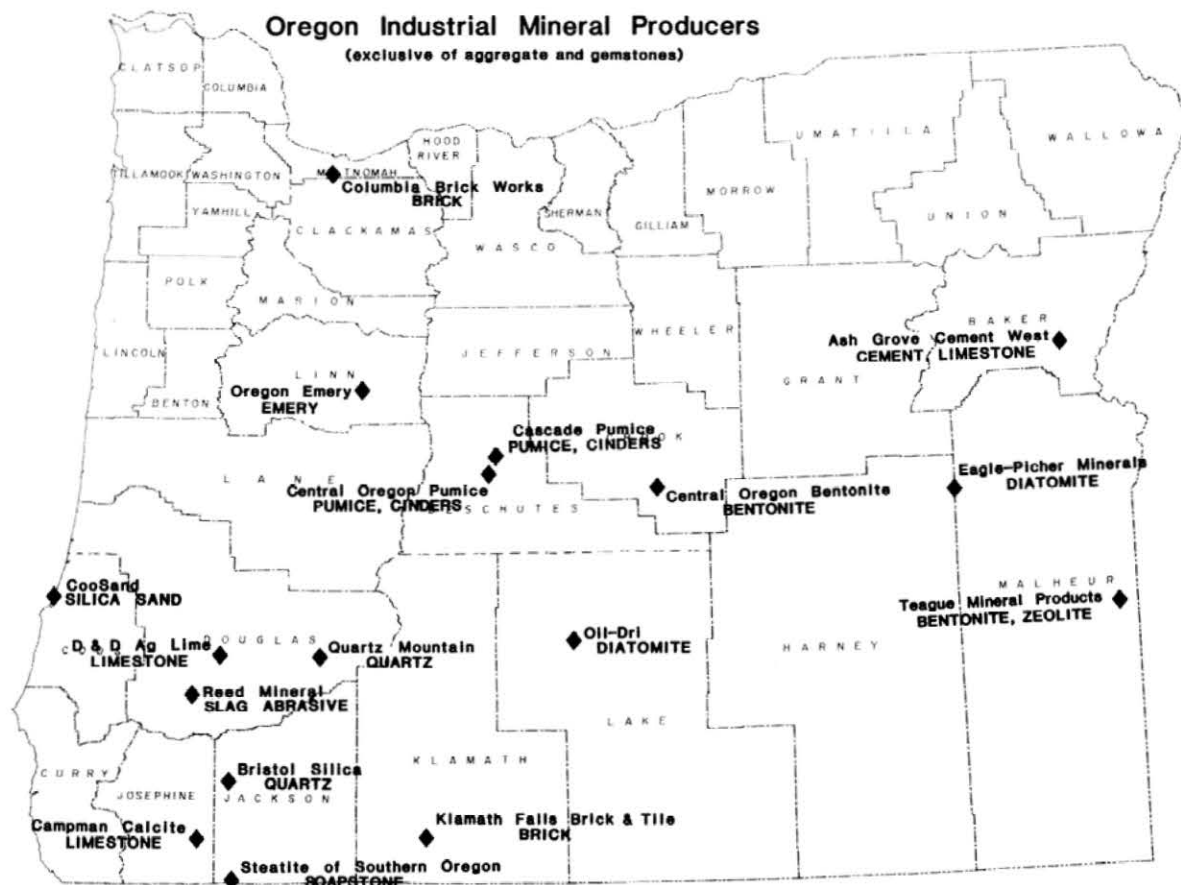


Figure 1. Current producers of industrial minerals in Oregon.

Table 1. *Production and occurrence of industrial minerals in Oregon. A=Documented occurrence. B=Past production. C=Present production*

Mineral	A	B	C
Abrasives			
Alumina	X		
Emery	X		X
Garnet	X		
Silica	X	X	X
Slag	X		X
Aggregates			
Crushed stone	X	X	X
Sand and gravel	X	X	X
Alumite	X		
Asbestos, chrysotile	X	X	
Barite	X		
Bauxite, ferruginous	X		
Borates	X	X	
Building stone			
Basalt	X	X	
Granite	X	X	
Limestone	X	X	
Marble	X	X	
Sandstone	X	X	
Tuff	X	X	
Chlorite	X		X
Chromite	X	X	
Cinders	X	X	X
Clays			
Bentonite	X		X
Fuller's earth	X		
Kaolin	X		
Refractory	X	X	
Structural	X	X	X
Diatomite	X	X	X
Expandable shale	X	X	
Feldspar	X		
Fluorspar	X		
Foundry sand	X	X	
Gemstones			
Agate, jasper	X	X	X
Garnet	X	X	
Jade, nephrite	X	X	
Obsidian	X	X	X
Opal	X	X	X
Rhodonite	X	X	
Sunstone, feldspar	X	X	X
Graphite	X		
Gypsum/anhydrite	X	X	
Iron oxides	X	X	
Lithium minerals	X		
Limestone			
Agricultural	X	X	X
Cement	X	X	X
Sugar refining	X		X
Mica	X		
Nepheline syenite	X		
Olivine	X		
Optical calcite	X		
Peat		X	X
Perlite	X	X	X
Pumice	X	X	X
Silica			
Cristobalite	X		
Quartzite	X	X	X
Sand	X	X	X
Sulfur	X		
Talc, soapstone	X	X	X
Vermiculite	X		
Wollastonite	X		
Zeolites			
Chabazite	X		
Clinoptilolite	X		X
Erionite	X		
Mordenite	X		
Phillipsite	X		

\$169 million, of which virtually all was from industrial minerals. Sand, gravel, and crushed rock accounted for approximately \$115 million. Current producers are shown in Figure 1, and documented occurrences, past production, and present production of various industrial minerals are summarized in Table 1.

AGGREGATES

Aggregate materials are produced by private companies and various federal, state, and county agencies. Crushed stone, almost exclusively basalt, is produced in all 36 counties (Figure 2); sand and gravel is produced in all but five counties; and volcanic cinders are produced in eight counties for construction uses and for ice control on highways. Production methods include open pits, quarries, and floating dredges. Areas of high demand and production are areas of high population, and urbanization continues to encroach on aggregate sources. Some areas do not have adequate known reserves, particularly for concrete aggregate where critical specifications must be met. In the past, small amounts of material have been imported for concrete aggregate when transportation costs were favorable. Offshore sand and gravel resources have been identified, but as yet they have not been fully evaluated.



Figure 2. Hard-rock quarry operation of Bayview Transit Mix, Inc., near Seaside in Clatsop County, producing crushed rock for road construction. The newly developed operation was honored with the 1988 Outstanding Operator Award of the Oregon Department of Geology and Mineral Industries, Mined Land Reclamation Program.

COMMON CLAY

Common clay is produced in 11 counties for engineering applications, for cement manufacture, and for brick production. Columbia Brick Works, Inc., at Gresham near Portland in Multnomah County, operates a high-volume facing brick plant utilizing clay mined on its property. Klamath Falls Brick and Tile Company in Klamath Falls (Figure 3) is a smaller, specialty-brick company producing a wide variety of colors of facing and paving bricks from clays mined in Klamath County and several other western counties.

LIMESTONE

Limestone crops out in the northeastern counties, the southwestern counties, and, to a lesser extent, in some northwestern counties of the state. Historically, these deposits have been utilized for agricultural lime, dimension stone, cement production, and the production of calcium carbide.

Limestone and shale are quarried near Durkee in Baker County by Ash Grove Cement West. The shale and some of the limestone is used to manufacture portland cement which is marketed in Idaho, Oregon, and Washington.

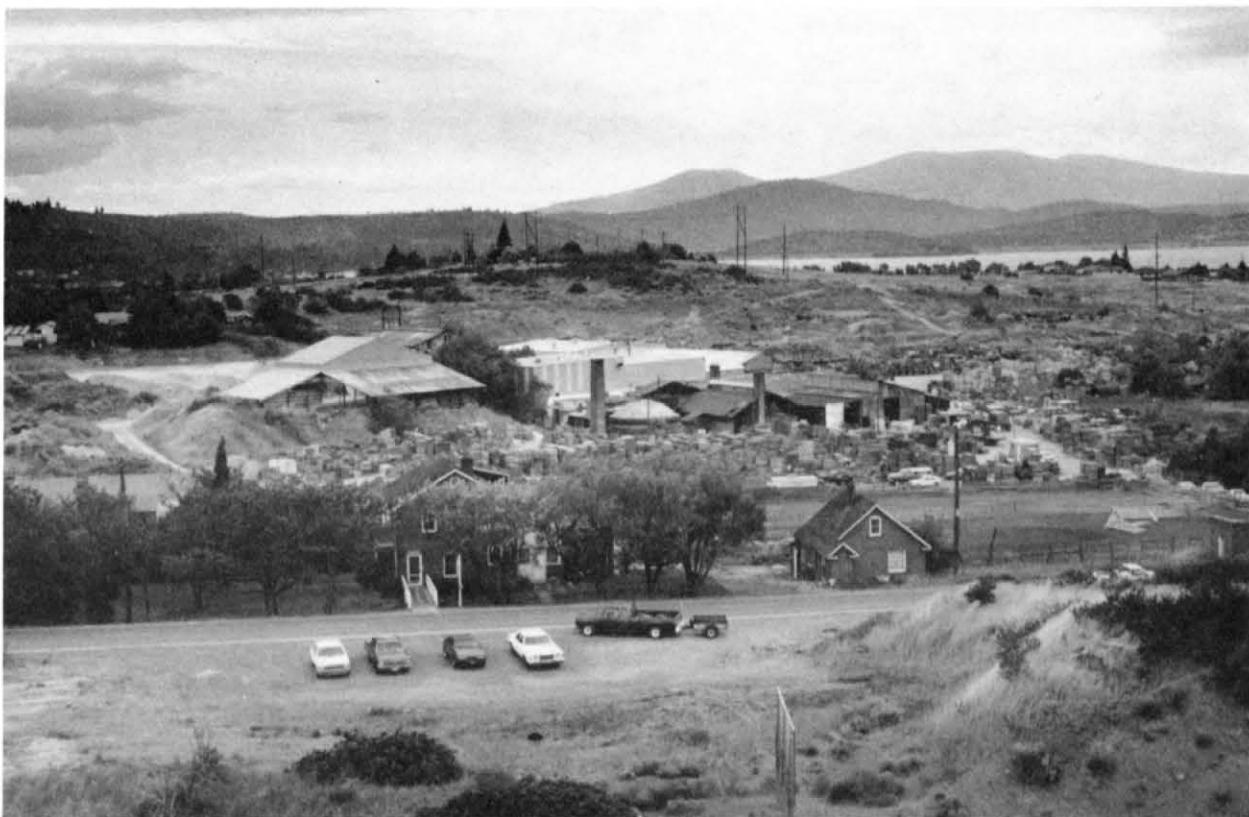


Figure 3. Klamath Falls Brick and Tile Company in Klamath Falls, Klamath County.

Higher purity limestone from the same quarry is crushed and screened to various sizes and sold as sugar rock, that is, rock used in sugar-beet refining. Sugar-beet refiners calcine (fire) the limestone to quicklime which is then added to the sugar solution during processing to precipitate phosphatic and organic impurities. The lime is then precipitated by bubbling carbon dioxide (recovered from the calcining operation) through the sugar solution to form calcium carbonate, and the sugar solution is clarified by filtration. Sugar rock is sold to refiners in Idaho and eastern Oregon.

The combined value of portland cement and sugar rock from the Durkee operation has been about \$25 million each year for the last five years. Ash Grove also operates a lime kiln in the Portland area, but its feed stock is high-calcium limestone barged in from the company's quarry on Texada Island near Vancouver, British Columbia.

Limestone is also produced from two quarries in southwestern Oregon. D and D Ag Lime and Rock Company produces a small amount of agricultural limestone southeast of Roseburg in Douglas County. Campman Calcite Company has acquired the Jones marble deposit near Williams in Josephine County and is producing calcium carbonate products for agricultural and paper pulp uses.

A comprehensive study of limestone occurrences in the state prepared by Howard Brooks of the Oregon Department of Geology and Mineral Industries is currently in press (Brooks, 1989).

PUMICE

Oregon has ranked first in pumice production in the U.S. for seven of the last eight years. According to U.S. Bureau of Mines statistics, Oregon pumice production during that period has remained at about 200,000 short tons per year, valued at about \$1.5 million per year. Pumice occurs in many counties, particularly in those east of the Cascade Range, but it is mined on a large scale only near the city of Bend in Deschutes County. Cascade Pumice and Central Oregon Pumice mine 15- to 40-ft-thick air-

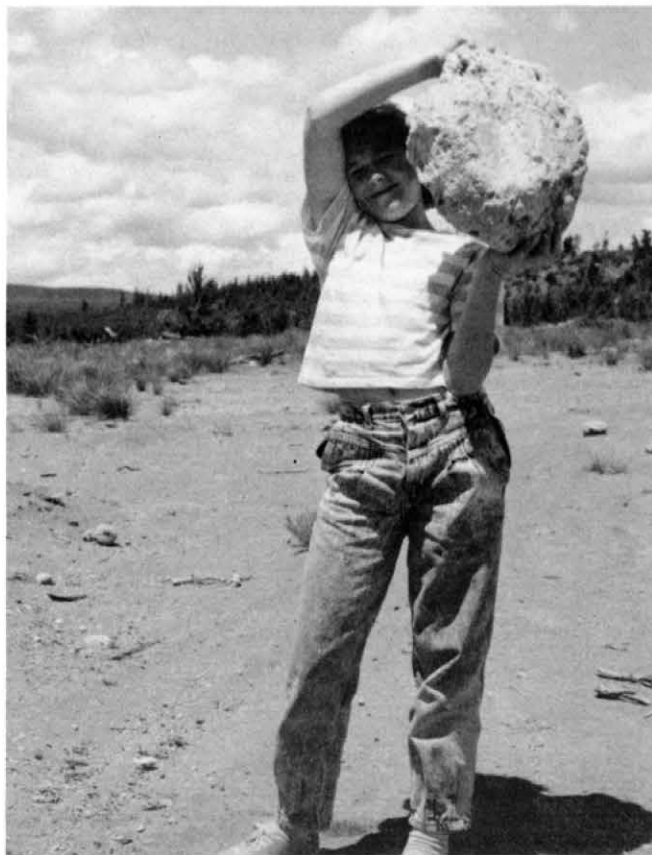


Figure 4. Pumice blocks such as the one easily held here by a child are used for landscaping purposes.

fall-pumice beds with overburden ratios up to 1:1. Overburden is removed, stockpiled, and finally backfilled by pan scrapers, and the pumice is mined by front-end loaders. Pit-run pumice is stockpiled and air dried, then crushed and screened to various size ranges. The major end use for products from both companies is lightweight aggregate in poured concrete and in structural and decorative concrete blocks. Both companies serve, by truck and by rail, markets in northern California, Oregon, Washington, and British Columbia. The market area for pumice as lightweight concrete aggregate will probably remain regional, limited by transportation costs and competing sources in Idaho and California.

Lesser amounts of pumice are sold for landscaping (Figure 4), roofing, floor sweep, pet litter, and horticultural soil mixes. Cascade Pumice is also marketing a small tonnage of 2- to 4-in. lump pumice mined in Klamath County for stone-washing jeans and other denim garments. This small segment of the pumice market is of high enough value to bear shipping costs to the midwestern and eastern parts of the country.

CINDERS

Most volcanic cinder production in the state is used for road surfacing and for ice control, and most is produced by various government agencies. Neither Central Oregon Pumice nor Cascade Pumice sell to this particular market, but both mine red and black cinders for concrete-block aggregate, landscaping, and other uses. Cinder aggregate produces a heavier but higher strength block than pumice aggregate alone, and both may be blended for various strength and color characteristics. Landscaping products range from pea-sized grains up to boulders several feet in diameter.

SILICA

Silica resources in Oregon include quartzofeldspathic sands and quartz replacement bodies. The sands include coastal dune sands, interior dune sands, onshore marine sands, and fluvial and lacustrine sands. The high-purity quartz bodies are the result of silicification of carbonate units and of rhyolitic volcanics. A reconnaissance survey of silica sources in the state is currently being conducted by the author.

Silica is produced by three companies, in one case from dune sands and in two from quartz bodies. CooSand Corporation mines quartzofeldspathic dune sands on the north shore of Coos Bay in Coos County. The deposit has a particle-size distribution ideal for glass manufacture and is located on a rail line. The sand is shipped to a plant near Portland where magnetic separation is used to lower the iron content sufficiently to meet specifications for container glass manufactured by Owens-Illinois in Portland. CooSand also sells some material for construction sand and for engine traction sand. Beneficiation testing, which includes scrubbing, froth flotation, and magnetic separation, has shown that some of the coastal dune deposits could be upgraded to meet flat-glass standards. The deposits are also well situated for rail or barge transportation to domestic or offshore markets.

Bristol Silica and Limestone Company, near Gold Hill in Jackson County (Figure 5), produces crushed and screened quartz in various size ranges for filter beds, poultry grit, landscaping, and exposed-aggregate concrete panels. The quartz body was formed by replacement of a carbonate lens, and in the past the company has also produced limestone and dolomite products from unaltered portions of the deposit. Bristol has been in production at this location for over 50 years.

Crushed quartz is also produced from Quartz Mountain, a silicified rhyolite in eastern Douglas County. Formerly, all production went to Hanna Nickel Company at Riddle, Oregon, for use in nickel smelting. Glenbrook Nickel, the new operator of the Nickel Mountain property, also uses this same source for silica. The owners of Quartz Mountain are seeking additional markets for their high-purity quartz.



Figure 5. Part of Bristol Silica and Limestone Company operation in Jackson County.

SLAG

During its smelting of nickel at the Nickel Mountain property in Douglas County, Hanna Nickel produced several million tons of granulated slag. Part of the slag was purchased by Reed Minerals and stockpiled in Riddle. Reed crushes and sizes the slag into several grades of air-blast abrasives, which are marketed under the Green Diamond brand name. The abrasive products have the advantage of high durability and absence of free silica, and they are marketed primarily to West Coast shipyards and steel-tank manufacturing and maintenance companies.

EMERY

Oregon Emery Company in Halsey, Linn County, produces abrasive and wear-resistant products from an emery deposit in eastern Linn County (Figure 6). The corundum-spinel-mullite-magnetite emery is apparently the result of contact metamorphism of ferruginous bauxites and is one of several such deposits owned by the company in the Cascade Range. Processing includes crushing and screening to produce specific particle shapes and size ranges. Oregon emery is used primarily in skid-resistant and hardened surfaces with concrete or epoxy systems in such areas as industrial floors, ramps, and traffic ways and on steel-bridge decking.



Figure 6. Emery outcrop in Douglas County deposit currently held under claim by Oregon Emery Company.

DIATOMITE

Central and eastern Oregon have had a long history of lacustrine environments and silicic volcanism, which resulted in numerous occurrences of fresh-water diatomite beds. Two companies currently are mining and processing diatomite in Oregon: Oil-Dri Corporation of America, at Christmas Valley in Lake County, and Eagle-Picher



Figure 7. View of Eagle-Picher diatomite mine (center of photo) in northeastern Harney County.

Minerals, in northern Harney and Malheur Counties.

Oil-Dri produces crushed and screened granules for floor absorbents and cat litter for several distributors as well as for the company's own brand name products. Eagle-Picher trucks diatomite ore from mines near Juntura (Figure 7) to its plant near Vale where the diatomite is crushed, dried, flux-calcined, and sized for filter-aid products. The robust skeleton of the dominant diatom species in this deposit is particularly well suited to high-pressure and high-volume filtration of a wide range of mineral oils, edible oils, juices, beverages, and food products (Figure 8).

PERLITE

Miocene silicic volcanism also formed perlite deposits in eastern Oregon. Some have been mined in the past, others have been drilled, and one, on Dooley Mountain in Baker County, is currently being mined by Supreme Perlite Company. Supreme Perlite has an expansion facility in Portland that processes raw perlite from Oregon and New Mexico to produce cryogenic, horticultural, masonry, and construction products.

A perlite deposit on Tucker Hill in southern Lake County has been drilled and evaluated by several companies. Although reportedly of commercial quality and quantity, the deposit is not well located with respect to market areas, and no development has yet been started.

BENTONITE CLAYS

Sodium and calcium montmorillonite clays, generally known as swelling and nonswelling bentonites, respectively, occur throughout the volcaniclastic sediments in eastern Oregon. A reconnaissance survey of occurrences was recently completed by Gray, Geitgey, and Baxter (1988) of the Oregon Department of Geology and Mineral Industries. Preliminary testing suggests that these clays have potential for civil engineering, foundry, drilling, filler, binding, and absorbent applications.

Two companies are currently producing bentonite: Central Oregon Bentonite, 40 mi southeast of Prineville in Crook County, and Teague Mineral Products in Adrian in Malheur County. The principal market for swelling bentonite from both operations has been in engineering uses, including sealants for ponds, ditches, building foundations, and waste disposal sites.

ZEOLITE

Bedded deposits of several zeolite minerals including clinoptilolite, chabazite, mordenite, erionite, and phillipsite have been documented in eastern Oregon. Several deposits are held by various companies, and many have been drilled and evaluated, including

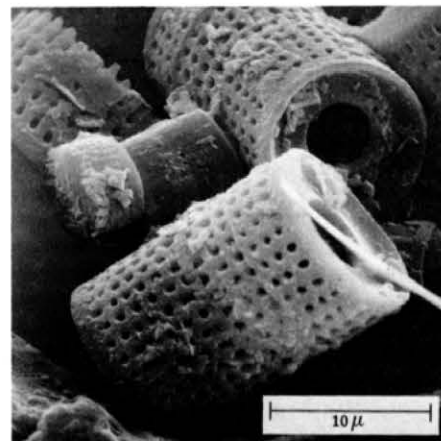


Figure 8. Scanning electron photomicrograph of diatoms (μ = micron = one-millionth meter. One inch has 25,400 microns).

occurrences in the Harney Basin in Harney County; the Durkee Basin in Baker County; and the "Rome Beds," the Sucker Creek Formation, and the Sheaville area in Malheur County. These localities all have zeolites of sufficient accessibility, thickness, areal extent, cation-exchange capacity, and absorption characteristics to be of economic interest, but, as with natural zeolites in general, large-volume markets remain elusive. Only Teague Mineral Products is currently producing zeolite in Oregon. Teague mines clinoptilolite from the Sucker Creek Formation in Malheur County and processes it at a mill in Adrian for absorbent and odor-control products. The mineral has also produced favorable test results in preventing uptake of radioactive cesium by plants in contaminated soils on Bikini Atoll and in removing heavy metals from mine drainage waters (Leppert, 1988).

TALC

Ultramafic rocks crop out in northeastern and southwestern Oregon. Alteration of serpentinite bodies in these areas has produced talc and talc carbonate (dolomite or magnesite) deposits that may be of commercial importance. Amphiboles are present in some occurrences, but others are free of both amphiboles and chrysotile. Ferns and Ramp of the Oregon Department of Geology and Mineral Industries have recently reported on talc occurrences in the state (Ferns and Ramp, 1988).

Talc, or soapstone, is being produced by Steatite of Southern Oregon from deposits on Elliott Creek Ridge at the southern edge of Jackson County (Figure 9). The company's principal product is asbestos-free art sculpture stone in a variety of colors for domestic and international markets. Recently, the company has also begun to supply dimensional blocks and crushed material for heat-storage liners in ovens and fireplaces.

GEMSTONES

Gem and lapidary material has been produced from Oregon for many decades, but, as is typical in most areas, it is very difficult to estimate accurately an annual value of production. Material is mined from lode claims, placer claims, private land, and free sites on federal land. Agates are often associated with areas of recent volcanism and silicification, and several varieties are valued for their colors, banding, inclusions, and graphic patterns. Specimens of petrified wood often show unusually well-preserved cell structure. One of the most highly prized materials is the thunder egg, a type of nodule or geode formed in silicic volcanics, particularly ash-flow tuffs. Thunder eggs may be filled with quartz crystals or with banded or patterned opal or chalcedony. Several varieties of opal, including a small amount of very high quality precious



Figure 9. Talc outcrop in Jackson County deposit mined by Steatite of Southern Oregon.

opal, are mined at Opal Butte in Morrow County.

Oregon sunstone, a faceting-grade, gemmy, calcic plagioclase feldspar, is mined near the Rabbit Hills in Lake County and in southeastern and northwestern Harney County (Figures 12 and 13). The sunstones occur in basalt flows as transparent megacrysts up to 3 in. long with compositions ranging from about $Ab_{40}An_{60}$ to $Ab_{25}An_{75}$. Colors range from clear to pale yellow, pink, red, green, and blue, with increasing copper content. Some specimens exhibit aventurescence or schiller due to exsolved platelets of metallic copper. Current retail prices range from about \$20 to \$150 per carat, with the higher prices commanded by deeper colors, larger stones, or more elaborate cuts.

PAST PRODUCTION

Many industrial minerals produced in Oregon in the past are no longer mined. Some, such as chromite, were mined in small tonnages and only as a result of wartime shortages. Others, including building stone and brick clays, were victims of shifts in architectural tastes and changes in construction techniques with the increased availability of portland cement. Production ceased for most in response to changing market conditions and increases in mining costs rather than because of noncompetitive product quality or the lack of reserves. Many of the industrial minerals listed in Table 1 as having had past production merit reevaluation with respect to new mining, beneficiation, and transportation methods and with respect to changes in demographics and in domestic and offshore markets. Three examples are given below.

(1) Historically, over 60 brick and tile plants have existed in

Oregon, as shown in Figure 10. Many were small, local operations meeting immediate needs for construction materials and field tile. The number of active operations has dwindled to only two, but now there appears to be an increasing market for bricks in the Northwest. The larger volume producers were located in the far western quarter of the state, and this area still is highest in concentration of population and fuel, electric power, and transportation facilities. Most of the clays were simply dug as needed, and few deposits were drilled and evaluated ahead of production. The light firing clays in the area around McMinnville, Grand Ronde, and Willamina in Yamhill County are of particular interest, since yellow, buff, and white bricks were produced from those deposits.

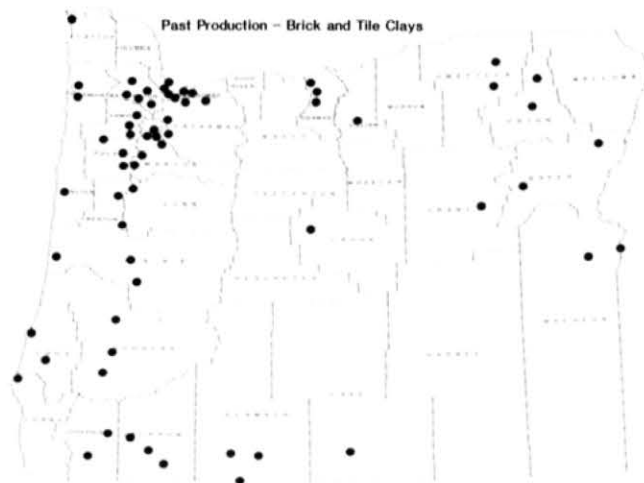


Figure 10. Location map of past production of brick and tile clays in Oregon.

(2) Currently, no building stone quarries in Oregon are continuously active, although there have been numerous operations in the past as shown in Figure 11. At the turn of the century, many dimension-stone quarries provided structural, decorative, and monumental stone for local and regional markets, including Portland and San Francisco. Rock types included buff to yellow sandstone, gray granites, white and black marbles, and variegated volcanic tuffs. Many quarries closed due to changes in architectural style, changes in construction techniques, and high costs of transportation from what were at that time remote locations. By mid-century, only highly colored and figured volcanic tuffs were being produced for decorative facing stone. The quality of many of the marbles,

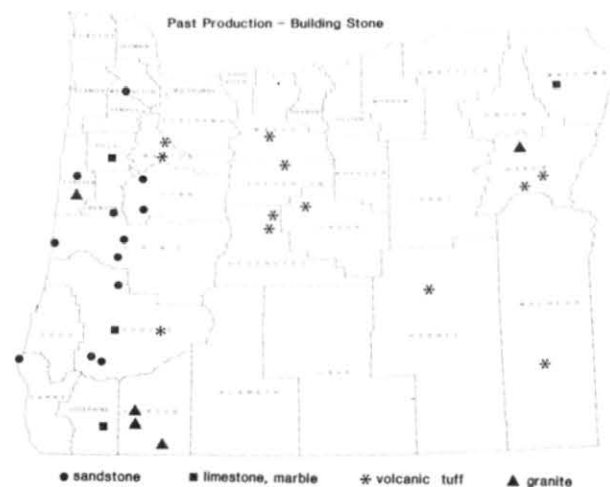


Figure 11. Location map of past production of building stone in Oregon.

granites and tuffs is high, and with modern quarry methods and transportation they could again be marketable.

(3) Borates were mined from two locations at the turn of the century. Small pods of priceite in ultramafic rocks were mined in Curry County north of Brookings, and surface efflorescences were processed at Borax Lake in the Alvord Valley of southern Harney County—until more accessible deposits were discovered in California. It is unlikely that the Curry County occurrence could ever be economic, and shallow drilling has been unproductive in Harney County. However, the possibility of borates in the Alvord Valley at depths exploitable by solution mining remains untested.

DOCUMENTED OCCURRENCES

Table 1 also lists documented occurrences of industrial minerals that have not been produced in the state. Many have been documented only by brief, unpublished reports, and their potential is difficult to assess. For example, little information is available about an occurrence of massive garnet on Antelope Peak in Baker County, a wollastonite occurrence on Foster Creek in Douglas County, or nepheline syenite on Table Mountain and other peaks in Lincoln County. Others, such as the ferruginous bauxites in northwestern Oregon and kaolin on Hobart Butte in Lane County, have been studied in detail but are not amenable to processing approaches currently used in the United States.

SOURCES OF INFORMATION

The Oregon Department of Geology and Mineral Industries has published a total of nine bibliographies of the geology and mineral resources of the state, the latest supplement extending through 1984 (Neuendorf and Yost, 1987). A mineral resources map (Ferns and Huber, 1984) showing the location of various metallic and nonmetallic mineral occurrences is available, and a

computer data base of mines, prospects, and occurrences is in preparation. The Department has a noncirculating library of current and out-of-print periodicals, theses and dissertations, and published and unpublished reports, including reports written for the War Office during World War II. The Department also maintains files of unpublished information on most of the commodities listed in Table 1. Summaries of these commodities were published in the Department's Bulletin 64, *Mineral and Water Resources of Oregon* (Weissenborn, 1969). Comprehensive Department studies on talc and bentonite have been published recently; a limestone survey is in press; a silica summary is in progress; and similar studies of other commodities are planned for future work.

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Limestone deposits in Oregon

by Howard C. Brooks, Oregon Department of Geology and Mineral Industries, Baker City Field Office, 1831 First Street, Baker City, Oregon 97814

OREGON DEPOSITS

Oregon's production of crushed and ground limestone is estimated at about 40 million tons. Most of it was used in the production of about 19 million tons of cement. About 5 million tons were consumed in lime, sugar, and paper manufacture, agriculture, and miscellaneous uses.

The distribution of the limestone-bearing areas in Oregon is shown in Figure 1. More than 80 percent of past production is from deposits in the outlined area including Baker in the northeastern part of the state. The remaining 20 percent is from deposits in the outlined areas near Grants Pass, Roseburg, and Dallas in western Oregon.

The productive deposits in northeastern and southwestern Oregon are limestones averaging in excess of 95 percent calcium carbonate. They are of marine origin and of late Paleozoic and Mesozoic age. The deposits near Dallas in northwestern Oregon are sandy limestones, which average between 50 and 60 percent calcium carbonate. They are of Tertiary marine origin.

Most of the pre-Tertiary deposits are structurally deformed and largely recrystallized. Dolomite deposits are rare. Small portions of some limestone deposits in northeast Oregon are dolomitic to the extent of being unusable for cement.

Most Oregon limestones are some shade of gray. Rock from the Black Marble deposit near Enterprise is black. Part of the Jones Marble deposit near Grants Pass contains a limited tonnage of White limestone. White limestone is common in the Eagle Cap Wilderness Area, which is closed to mineral development.

Commercial cement production began in 1916. Four cement plants have been built and operated, three by Oregon Portland Cement Company, which is now Ash Grove Cement West, Inc., and one by Ideal Cement Company. OPC Company operated plants at Lake Oswego near Portland (1916-1982) and at Lime (1923-1980) and Durkee (1979-present) in northeast Oregon. Ideal's plant (1917-1967) was at Gold Hill in southwest Oregon. The Lake Oswego and Gold Hill plants have been dismantled. Output of the Durkee operation has averaged 439,000 tons of cement and 228,000 tons of "sugar rock" annually since 1985.

Limestone feed for the plant at Lake Oswego came from quarries near Roseburg in Douglas County (1916-1935), Dallas in Polk County (1916-1967), Lime and Durkee in Baker County, and Texada Island, British Columbia (1963-1982). The plant at Lime utilized limestone from quarries near the plant (1923-1968) and the Durkee quarry (1959-1980). Limestone for the Gold Hill plant came from small quarries near Gold Hill in the early years of its operation and later (1923-1967) from the Marble Mountain quarry.

Deposits whose products have been used mainly to make chemical-grade lime include the Black Marble quarry near Enterprise in the Wallowa Mountains and the Marble Creek and Baboon Creek Quarries in the Elkhorn Ridge area near Baker, all in northeastern Oregon. The Horsehead lime deposit and the Muck quarry in the Williams Creek area in southwest Oregon were small producers of lime rock. Agricultural limestone has been produced from a number of sources, including small quarries in low-grade limestone in the Dallas and Marquam areas in northwestern Oregon. However, while Oregon Department of Agriculture statistics indicate that annual agricultural consumption of ground limestone and dolomite during the 10 years 1979-1988 averaged 105,000 tons and 16,000 tons, respectively, about 99 percent of the limestone and all of the dolomite were from out-of-state sources.

The main limestone units in northeastern Oregon are the Martin Bridge Limestone and the Nelson Marble. Both are composed mainly of recrystallized limestone. The Jett Creek Member of the Weatherby Formation and the Elkhorn Ridge Argillite contain lenses and blocks of limestone as minor but locally important constituents. The Robertson Formation contains large areas of low-grade limestone.

The Martin Bridge Limestone is exposed mostly in wilderness areas in Wallowa County. Exposures cover at least 50 mi². Some of the largest exposures are in the Hurricane Creek (locality 1, Figure 1), Lostine River (2), and Eagle Creek (3) areas in the Wallowa Mountains and the Big Bar area (4) of the Snake River. Exposures along the lower parts of Hurricane Creek and the Lostine River are outside Wilderness boundaries but still in steep terrane.

Locality 5 represents the Black Marble quarry, which is about

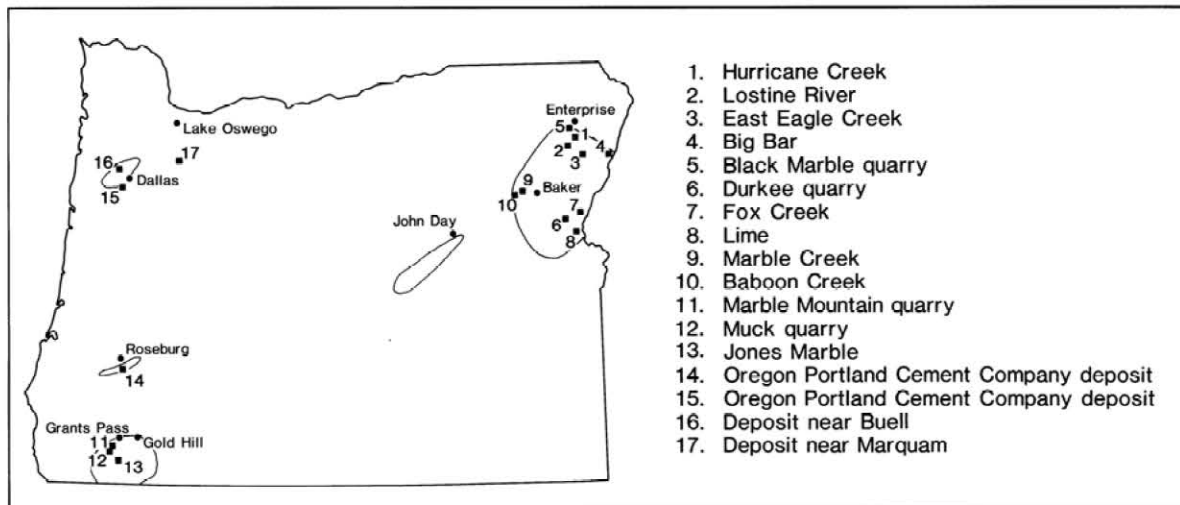


Figure 1. Map of Oregon showing locations of marble mines and deposits. Areas of high concentration of limestone have been outlined.

5 mi southwest of Enterprise on the north slope of the Wallowa Mountains. The quarry is in an isolated block of Upper Triassic limestone that probably is not part of the Martin Bridge Limestone. This quarry was operated intermittently from 1925 to 1961. Total production has been about 300,000 tons, most of which was produced after 1950 by Pacific Carbide and Alloys Company, who hauled the stone to its plant in Portland for use in making calcium carbide. Fine sizes were marketed as agriculture stone to farmers in the Willamette Valley and southwest Washington.

The rock is sooty black, due to carbonaceous material that is eliminated by calcining. Assays average around 99 percent calcium carbonate. Reserves are estimated at about 3 million tons.

The Durkee quarry (6) and the Fox Creek (7) localities shown on the map are in the Nelson Marble. Exposures of the Nelson Marble form a belt about 20 mi long and up to a mile wide. The largest exposures are in the Fox Creek area. The only development is the Durkee quarry. Several areas have been extensively sampled and appear to constitute enormous reserves of high-quality limestone. Some areas are dolomitic. The Nelson Marble has been and likely will continue to be Oregon's chief source of high-calcium limestone.

Development of the Durkee quarry was started in 1953 by Morrison Knudsen Company. Initially most of the product was used by sugar refineries in Idaho and Oregon. Because the sugar refineries require screened high-quality limestone of certain size range, large amounts of undersize and sub-grade stone accumulated in stockpiles. In 1959, Oregon Portland Cement Company bought Morrison Knudsen's share of the property and began utilizing the latter material to make cement. The sugar rock markets have been maintained and in recent years have expanded. During 1984-1988, sugar rock sales averaged close to 228,000 tons per year.

The cement plant at Durkee began operating in late 1979. Total construction cost was about \$47,000,000. The quarry has produced 15,613,842 tons of limestone through the year 1988. About 65 percent (10,376,219 tons) of this production was used in cement, and 35 percent (5,237,624 tons) was sold to others. Most of the latter was sold to sugar refineries operated by Amalgamated Sugar Company in Oregon and Idaho. Some has been used for agricultural purposes and glass manufacture. During its nine years of operation (1980-1988), the Durkee plant has produced 3,215,124 tons of cement.

The limestone is uniformly bluish gray and crystalline and averages over 98 percent CaCO_3 . Shale and clay for use in manufacturing cement are mined from a pit on company property less than half a mile east of the limestone quarry.

Company reports indicate that limestone reserves in and adjacent to the quarry are sufficient for about 50 years of operation at the present rate of production.

The quarry face is 600 ft high. It is developed by thirteen working benches. Bench faces are maintained as close to vertical as practical, forming a 75° angle from the horizontal plane. Bench widths are maintained at 35 ft, with vertical intervals at 45 ft. This bench pattern is designed to give an overall backslope of 4° . In less than two years, the benches will be to the quarry floor, and the quarry method must be changed.

An air-circulated rotary drill is used to drill $7\frac{1}{4}$ -in. by 48-ft blast holes. Ammonium nitrate and oil are used for blasting. The quarry is shot at two-week intervals, providing about 60,000 tons per blast. Rock from the quarry is sized by screening and crushing. The minus 2.5-in. rock is used to make cement and, from the plus 2.5-in. rock, three different sizes of sugar rock ranging from 1.5 to 4.5 in. are produced.

When constructed, the Durkee plant was the first dry-process cement plant equipped with a preheater rotary kiln in the Pacific Northwest. Process equipment and operating conditions are monitored electronically in a central control room. The inside of the kiln and the raw mill and finish mill are monitored with color

television cameras. The kiln has a length of 216 ft 6 in. and a diameter of 14 ft $3\frac{1}{4}$ in. and has a rated capacity of 1,500 tons of clinker per day. During 1983-1986, the Durkee plant utilized an average of 544,500 tons of limestone and about 136,000 tons of shale and clay.

The cement plant and quarries at Lime (8) are adjacent to U.S. Interstate 84 and the Union Pacific Railroad, 40 mi southeast of Baker. Initial capacity of the plant was 94,000 tons of cement per year. This was increased to 225,000 tons per year in 1956 by adding a second kiln. Cement output of the plant during 58 years of operation (1923-1980) totals about 6.5 million tons. The quarries produced more than 9,024,591 tons of limestone. Of this amount, approximately 4,442,342 tons was used in cement manufacture at Lime, 4,033,741 tons was shipped to the Company's cement plant in Lake Oswego, and 264,871 tons was shipped for use in sugar factories.

By 1963, the quarries had become expensive to operate, and from then on, the bulk of the limestone used in producing cement at Lime was trucked from the Durkee quarry. Since mining ceased, the walls of the larger quarries in Marble Creek canyon have collapsed, and the working floors are covered by landslides.

The limestone is part of the Jett Creek Member of the Weatherby Formation of Early and Middle Jurassic age. The limestone unit at Lime is irregular in shape, about 3 mi long, and up to a mile wide. It consists of interbedded calcareous siltstone, siltstone, limestone, and dolomitic limestone. Only small, scattered deposits were found to be large enough and pure enough for use in making cement.

Brooks (1989) reports that five samples from several different places in and near the walls of the upper quarries in Marble Creek Canyon averaged 94 percent CaCO_3 and 3.3 percent MgCO_3 . A significant amount of cement-grade limestone remains on the property, but it is scattered, and selective mining would be required.

Localities 9 and 10 on the map (Marble Creek and Baboon Creek) represent quarries in two separate limestone bodies about 3 mi apart in the Elkhorn Ridge area west of Baker. The deposits are in the Elkhorn Ridge Argillite. The quarries were operated by chemical Lime Company during 1957-1971. Chemical-grade lime was made from the stone at a plant about 5 mi north of Baker. About 350,000 tons of lime were sold during the operation.

SOUTHWESTERN OREGON

Most of the limestone occurrences in southwestern Oregon are in Josephine and Jackson Counties in the Applegate Formation and in Douglas County in the Otter Point Formation. The important limestone deposits are lenses and blocks a few hundred to a few thousand feet in longest dimension.

The larger limestone operations have been the Marble Mountain quarry in the lower Applegate area of Josephine County, which was last operated by Ideal Cement Company in 1967, and a quarry operated by Oregon Portland Cement Company during 1916-1935 in the Roseburg area of Douglas County. Most of the production from these quarries was used for making cement. Some was used for agricultural purposes, paper manufacture, and other uses.

There has been small production from a number of other deposits including the Muck, Jones, and Horsehead deposits in the Lower Applegate area, and the Colvig Gulch, Lyons Gulch, Bristol Dolomite, Lively, and Baxter deposits in the Gold Hill area. The cement plant formerly located at the west edge of Gold Hill was operated by Beaver Portland Cement Company (1917-1940) and later by Pacific Portland Cement Company (1940-1952) and Ideal Cement Company (1952-1967). Initially, the plant used limestone from small deposits near the plant site. After 1923, most of the limestone came from the Marble Mountain quarry (11) 28 mi to the southwest. Originally the plant had a rated capacity of 900 barrels of cement per day. This was increased to 2,000 barrels in the early 1940's.

The Marble Mountain quarry located near the top of the north slope of Marble Mountain about 16 mi southwest of Grants Pass was operated during 1923-1967. Between 4 and 5 million tons of limestone have been removed from the quarry. Most of it was used in cement manufacture. Some of the highest quality stone was used in making paper.

Libbey (1957) reported that the quarry stone averages about 95 percent CaCO_3 , but some bands that run approximately 99 percent CaCO_3 can be quarried when desired. Diamond drill results and surface sampling indicate reserves of between 10 and 12 million tons of high-calcium stone.

The Muck quarry (12) is about 16 mi southwest of Grants Pass via Cheney Creek and half a mile south of the Marble Mountain quarry. The history of the property is poorly known. Ten rail carloads of the limestone were shipped to Pacific Carbide and Alloys Company in Portland in 1948-1949. The quarry face is about 300 ft long and up to 80 ft high. The limestone exposure is 150 to 250 ft wide, trends N. 30° E., and is traceable upslope for a horizontal distance of about 900 ft. The limestone is gray, crystalline, and massive. Four chip samples across the foot of the quarry face averaged 99 percent CaCO_3 and 1 percent MgCO_3 (Brooks, 1989).

The Jones marble deposit (13) is 23 mi by road south of Grants Pass and 4 mi west of Williams. The deposit is well exposed along the crest of a north-trending ridge. The main development is a shallow open cut about 200 ft long, 80 ft wide, and 30 ft deep. The deposit was worked periodically in early days as a source of monument stone. About 5,000 tons of agricultural limestone was produced in 1939-1940. Brice Campman purchased the property in 1988 for the purpose of producing agricultural limestone.

The exposure is about 1,700 ft long and 300 ft wide. The rock is thoroughly recrystallized. Crystal lengths range from 0.3 to 5 mm and average about 1 mm. The rock in the central part of the deposit is white. Some is variegated or banded white and gray. Most of it is high quality. Analyses of samples from several different parts of the deposit indicate that much of the limestone runs in excess of 99 percent CaCO_3 . Impurities include a few small lenses, streaks, and knots of chert and argillite, a diorite dike about 6 ft wide, and a little pyrite locally.

The purity and strength of the marble make it acceptable for most uses including carbide and other chemicals, paint and paper filler, and architectural stone. Reserve estimates made by different individuals range between 2 and 5 million tons.

The Roseburg area includes several small widely spaced limestone deposits in a northeast-trending belt about 8 mi south and east of Roseburg. The deposit (14) operated by Oregon Portland Cement Company in 1916-1935 is the only one having significant past production. Small production of limestone, mainly for agricultural purposes, has come from the Dodson deposits and from the edges of the Oregon Portland Cement Company quarries.

NORTHWESTERN OREGON

The large, low-grade limestone resource area in northwestern Oregon is in the eastern foothills of the Oregon Coast Range near Dallas in Polk County. Small deposits of similar character occur near Buell (16) and near Marquam (17) in Clackamas County. Local relief is about 300 ft, and slopes are gentle.

The deposits in Polk County are part of the Rickreall Limestone Member of the Yamhill Formation. The Marquam deposits are in the Marquam Member of the Scotts Mills Formation. Both units are of Tertiary age and of marine origin.

The limestone consists largely of abraded shell fragments in a sandy matrix of basaltic rock fragments, feldspar, a few quartz grains, and clay. The cement is precipitated calcite. The limestone typically varies from less than 50 percent to as much as 80 percent CaCO_3 .

The fresh rock varies from light gray to dark greenish-gray.

Bedding is flat to gently dipping. Individual beds range from several inches to several feet thick. Beds 3 to 5 ft thick are most common. Total thicknesses of 50 ft are common in the larger exposure areas. The largest exposures of the Rickreall Member are a few miles southwest of Dallas, where they underlie an area about 4 mi long and one-half to 1 mi wide (Baldwin, 1964).

The Oregon Portland Cement Company quarry (15) 4 mi southwest of Dallas was operated from 1916 until 1967. About 50 acres was quarried to depths averaging 40 to 50 ft. Total limestone removed probably exceeds 5,000,000 tons. The limestone was shipped to the cement plant in Lake Oswego. The product averaged 55 percent CaCO_3 . Because the CaCO_3 content was below minimum requirements for portland cement, the limestone was blended with higher quality limestone obtained initially from company-operated quarries near Roseburg (1916-1935) and Lime (1935-1963). Production records are scarce for years prior to 1954. The 1954-1967 production totals 1,538,719 tons, and all but 3,068 tons were used in cement. Production decreased sharply after 1963, when the Lake Oswego plant began utilizing limestone from Texada Island, British Columbia.

At least four small quarries in the Dallas-Buell-Marquam area have produced low-grade limestone for agricultural use. The largest output was from the Lime Products Company quarry located about half a mile south of the Oregon Portland Cement Company quarry. Polk County production of ag-lime between 1929 and 1959 was over 100,000 tons. There has been small periodic production since that time, but no records are available.

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Talc and soapstone in Oregon

by M.L. Ferns, Oregon Department of Geology and Mineral Industries, Baker City Field Office, 1831 First Street, Baker, Oregon 97814

More than 100 separate Oregon talc occurrences (Figure 1) in 18 talc areas are described in a paper by Ferns and Ramp (1988). The talcs, in the form of talc, talc-amphibolite, talc-chlorite, and talc-carbonate schists, are hosted in serpentinites in the older pre-Tertiary terranes of northeast and southwest Oregon. Some of the deposits are apparently hydrothermal in origin and are spatially associated with lode and/or placer gold deposits. Others are metamorphic in origin.

Oregon talcs are generally characterized by high abundances of iron and the presence of accessory amphibole minerals. Analyzed Oregon talcs contain from between 3.5 and 8.9 weight percent Fe_2O_3 and 0.01 to 0.42 weight percent CaO (Table 1). Associated minerals often include one or more of the amphibole minerals tremolite, anthophyllite, or cummingtonite. The amphibole minerals often occur in asbestiform habits and are considered as unacceptable contaminants in industrial talcs.

There are, however, two areas that appear to host appreciable amounts of amphibole-free talcs. One of these is the Elliott Creek Ridge area in the Klamath Mountains of southwestern Oregon. Here talc occurs as rinds on and completely replacing small antigorite serpentinite slices in the top of the highly contorted schists of Condrey Mountain. The deposits occur as lenticular lenses as much as 30 ft wide and more than 100 ft long. The deposits are being mined by Steatite of Southern Oregon for carving-grade soapstone. As of the end of 1986, more than 900 tons of high-grade soapstone had been mined from the deposits. The massive soapstone appears to be free of amphibole minerals. Unlike most of the other southern Oregon talc occurrences, the Elliott Creek Ridge deposits formed in a thrust-fault metamorphic environment under elevated pressure conditions. The schists of Condrey Mountain locally contain high-pressure metamorphic minerals such as glaucophane. The schists are structurally overlain by a higher tem-

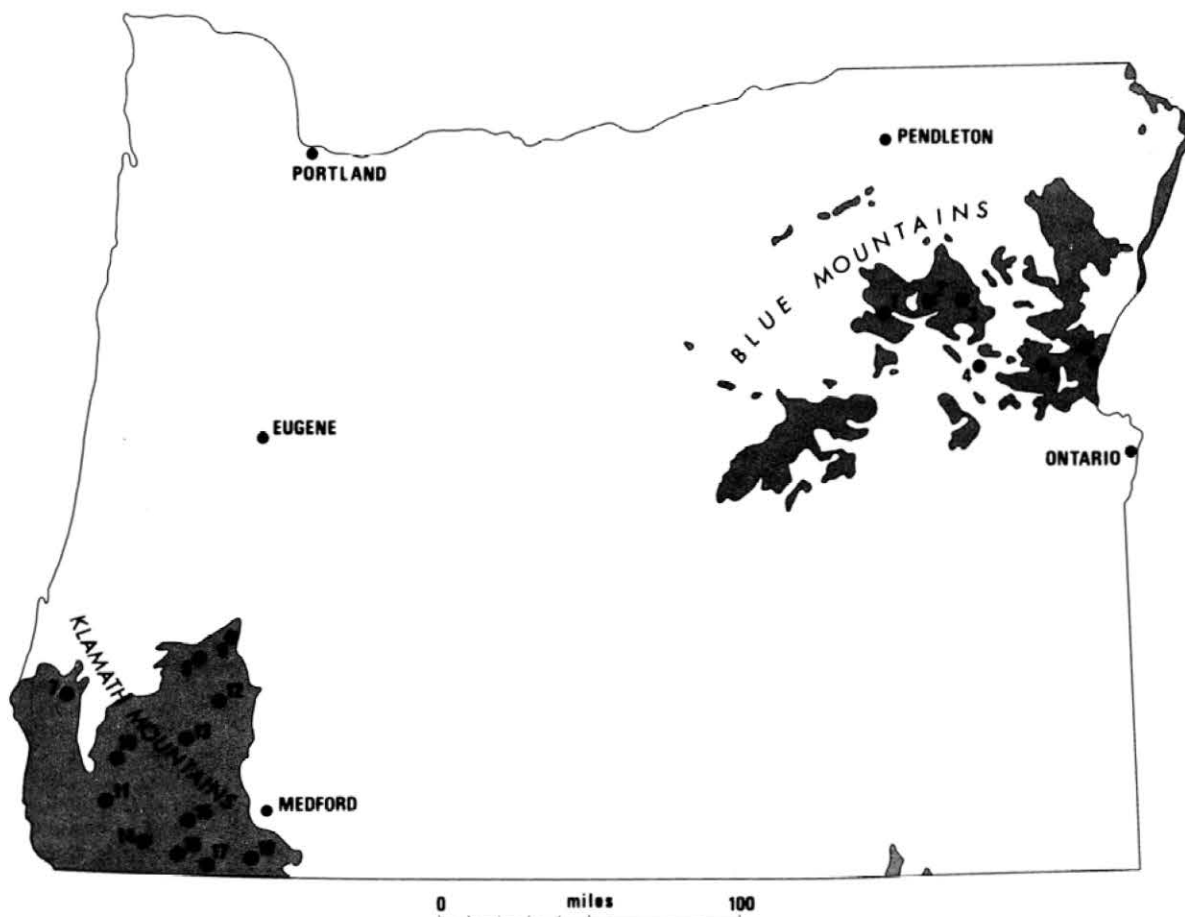


Figure 1. Oregon talc areas. Shaded areas indicate rocks of Late Jurassic and greater age. Numbered areas are as follows: 1 = Greenhorn, 2 = Sumpter, 3 = Elkhorn, 4 = Dooley Mountain, 5 = Basin Creek, 6 = Connor Creek, 7 = Powers-Agness fault zone, 8 = Coast Range thrust, 9 = Myrtle Creek, 10 = Galice, 11 = Pearsoll Peak, 12 = Red Mountain-Upper Pleasant Creek, 13 = Greenback, 14 = Sucker Creek, 15 = Williams, 16 = Carberry Creek, 17 = Elliott Creek Ridge, 18 = Siskiyou Peak. These areas and the talc potential for Oregon are discussed in detail in Ferns and Ramp (1988).

Table 1. Major-element abundances in various commercial and Oregon talcs (all values are in weight percent)

Oxide	Pure talc theoretical	Carbonate Vermont	Flotation talc Vermont Johnson Mine	Roofing granules Georgia Southern Talc Co. Yellowston Mine	Stearite Montana Yellowstone Mine	Talc ore New York Talcville	Talc Texas	Talc-carbonate Oregon Sumpter area (Average of 5)	Talc amphibole Oregon Sumpter (Average of 3)	Talc Elliott Creek	Talc-tremolite Oregon Elliott Creek	Talc Oregon Cow Creek	Talc-carbonate Oregon Little Applegate
SiO ₂	63.36	35.98	59.15	47.92	62.65	59.8	54.92	49.76	56.2	58.5	50.9	59.1	31.2
HgO	31.98	32.95	31.34	26	30.23	27.45	27.2	29.6	22.9	29.9	28.4	31.2	36.0
Fe ₂ O ₃	---	0.65	3.36	6.82	1.51	0.05	0.46	7.96	4.03	5.08	7.55	3.82	7.24
TiO ₂	---	0.02	---	0.15	---	---	---	0.12	0.08	0.04	0.05	0.04	0.03
Al ₂ O ₃	---	0.43	0.26	7.35	0.31	0.57	5.76	2.21	1.38	0.89	5.15	0.18	0.14
CaO	---	---	0.15	4.14	tr	6.8	---	0.29	0.21	0.01	0.25	0.27	0.19
K ₂ O	---	---	---	---	0.05	---	---	0.01	0.02	0.01	0.01	0.01	0.01
Na ₂ O	---	---	---	---	0.15	---	---	<.01	<.01	<.01	<.01	<.01	0.03
CO ₂	---	20.45	1.76	---	0.27	1.18	---	---	---	---	---	---	---
H ₂ O	4.75	2.73	4.3	0.05	4.87	---	---	---	---	---	---	---	---
MnO	---	0.41	---	---	---	0.39	---	---	---	---	---	---	---
S	---	0.06	---	0.09	---	0.03	---	---	---	---	---	---	---
NiO	---	0.21	---	---	---	---	---	---	---	---	---	---	---
Cr ₂ O ₃	---	0.18	---	---	---	---	---	0.3	0.71	0.25	0.25	0.12	0.53
P ₂ O ₅	---	0.01	---	---	---	---	---	0.02	0.03	0.01	0.01	0.01	0.01
LOI	---	---	---	7.51	---	4.75	10.76	9.41	4.9	5.31	7.08	5.62	24.3

tr = Trace

perature, lower pressure, regionally metamorphic terrane containing sillimanite. We believe that this is an example of an interrupted geothermal gradient, in which a high-temperature slab was thrust

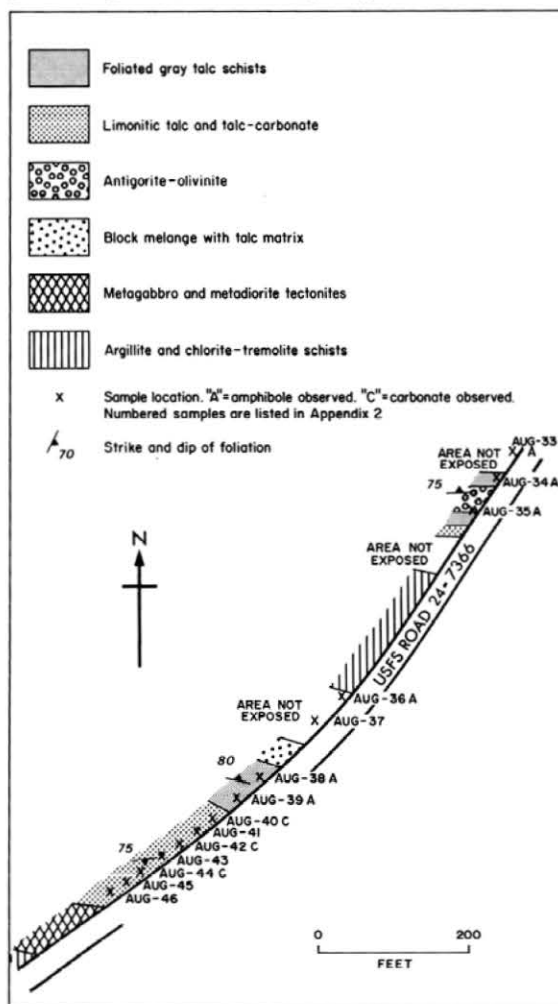


Figure 2. Sketch map of the Upper Corral Creek talc zone, Sumpter, Baker County, northeastern Oregon.

out over a cooler mass. Talc formed from antigorite serpentinite slices in the top of the lower plate during thermal readjustment under elevated pressures.

The Sumpter area (Figure 2) in northeastern Oregon contains the largest volume of amphibole-free talcs in Oregon. The amphibole-free talc occurs as talc-carbonate masses in a structurally disrupted belt of Paleozoic and Mesozoic rocks that is intruded by the Late Jurassic Bald Mountain Batholith. This 2-mi-wide belt, known as the McCully Fork mixed-rock zone, includes (1) an outer zone of slab melange that is made up of discreet lensoid slices and elongate slabs of argillite, serpentinite, pyroxenite, gabbro, diorite, quartz diorite, basalt, volcanoclastic breccias and conglomerates, chert, and limestone, with little or no recognizable intervening matrix, and (2) an inner zone of block melange with abundant metaserpentinite matrix.

The talc occurrences lie within the contact metamorphic aureoles of the Bald Mountain Batholith. The talc occurs within a talc-carbonate envelope at distances from 3,000 to 9,250 ft from the batholith. Metaserpentinites closer to the batholith include

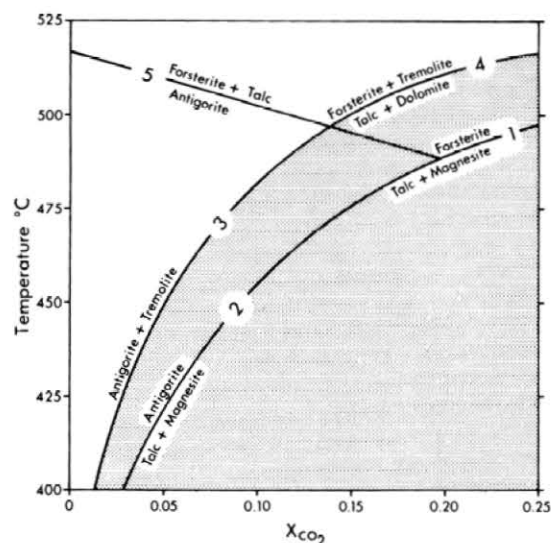


Figure 3. T-XCO₂ diagram at 2,000 bars total pressure (from Trommsdorff and Evans, 1977). Shaded area shows the temperature and fluid composition conditions under which tremolite would be an unstable mineral phase that would not be expected to coexist with talc and carbonate minerals.

talc-olivinites and enstatite-olivinites. The metaserpentinities beyond 9,250 ft from the batholith are antigorite schists. Serpentinities within the talc-carbonate envelope are totally converted to either talc-carbonate rock or talc-amphibole schists. Our petrographic and X-ray diffraction studies indicate that the amphibole minerals are confined to carbonate-free rocks. Talc-carbonate rock is limonitic and massive as compared to the greenish foliated talc amphibolites. Apparently amphibole-free talc-carbonate masses occur in zones over 200 ft wide that can be traced along strike for 1,000 ft and over vertical distances of over 500 ft. More than 20 separate talc-carbonate zones have been identified within the talc-carbonate envelope.

One of the larger talc-carbonate masses is exposed along road cuts on upper Corral Creek near the innermost limit of the talc-carbonate envelope. Talc-amphibolites north of the talc-carbonate mass are strongly foliated and contain abundant anthophyllite. Seven samples, taken at 25-ft intervals across the talc-carbonate zone, were analyzed petrographically and by X-ray diffraction and found to be free of amphibole.

Amphiboles in carbonate-free talcs include tremolite, cummingtonite, and anthophyllite. Carbonate minerals include both magnesite and dolomite. Other accessory minerals include magnetite, chlorite, and chromite.

Amphibole minerals were not recognized in the Sumpter area talc-carbonates. The CO₂-rich fluids associated with formation of the talc-carbonates apparently prevented the formation of amphibole

in these rocks. Experimental work by Trommsdorff and Evans (1977) shows that calcium necessary for the formation of tremolite is used in forming carbonate minerals (Figure 3). The reason for the absence of the magnesium-iron amphiboles cummingtonite and anthophyllite in the talc-carbonates is not clearly understood. The talc-carbonates weather to a pronounced rusty red, suggesting that the carbonate minerals contain an appreciable amount of iron. The difference in weathering color between the greenish-weathering talc-amphibolites and red-weathering talc-carbonates suggests that Fe⁺² is preferentially taken up by carbonate minerals and is not available for forming cummingtonite or anthophyllite.

There is a large volume of talc-carbonate rock in the Sumpter area. Further work is necessary before it can be determined if substantial amounts of amphibole-free talc can be recovered from these deposits. Any such work should focus on producing by-products such as magnesite, chromite, and/or nickel during talc beneficiation. The high iron content of the raw talc-carbonates severely restricts their suitability for direct industrial usages.

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Oregon bentonite

by Jerry J. Gray, Oregon Department of Geology and Mineral Industries, 910 State Office Building, Portland, Oregon 97201

INTRODUCTION

This paper is based on the Department's recently published Special Paper 20, *Bentonite in Oregon: Occurrences, Analyses, and Economic Potential*, by Jerry J. Gray, Ronald P. Geitgey, and Gary L. Baxter.

BENTONITE DEFINED

Bentonite is a rock name for a claystone that consists mainly of the mineral species montmorillonite, with varying ratios of sodium (Na) to calcium (Ca) to other exchangeable ions of the mineral group smectite. Bentonites are divided into two general classes: (1) those that swell extensively and form a gel (Na-montmorillonite) when mixed with water, and (2) those that do not swell appreciably (Ca-montmorillonite) or form a gel when wetted. For some segments of the clay industry, the term "fuller's earth" is used interchangeably with the term "Ca-bentonite."

NATIONAL INDUSTRY STRUCTURE

Figure 1 presents U.S. Bureau of Mines statistics showing end usage tonnage (1975 to 1986) for combined bentonite and the montmorillonite portion of fuller's earth output. The output grew from 3.7 million short tons in 1975 to 5.7 million in 1981 and decreased to 3.8 million in 1986. Two trends have combined to lower the demand for bentonite: (1) the decrease in production of iron pellets in Michigan and Minnesota, and (2) a precipitous decline in oil and gas drilling. Bentonite, however, is used in increasing amounts in civil engineering applications, including sealing sanitary landfills, sewage lagoons, and cyanide leach pads for heap leaching of gold ore and for "slurry trench" well construction.

The foundry industry seems to exhibit a more steady demand than the oil and gas industry. Specifications are high for this industry, but different users have slightly different specifications, and a pro-

ducer must be able to meet those individual specifications to be successful in the marketplace.

The market for absorbents is growing. Major reasons may be the continuing urbanization of the nation and direct advertising to the nation's auto garages and pet owners. There are no formal specifications for this use; however, general characteristics must include high liquid and odor absorbency, no-dust quality, uniform granule size, and wet strength. The market is concentrated in population centers, and the product is often sold in 10-lb sacks. Lower grade bentonite can be used for this market, but by the time transportation and bagging are added, the product commands a high per-ton value.

A good overview of the national and international bentonite industry appears in *Industrial Minerals* (O'Driscoll, 1988).

In addition to being produced in Oregon, bentonite/fuller's earth was produced in several other states, such as Montana and Wyoming, which are the sources of the 150,000 to 212,000 short tons of bentonite that are exported from Portland or Seattle annually. As Figure 2 shows, over the last few years, annual exports of bentonite (fuller's earth not included) have ranged from \$42 to \$55 million. The figure also shows that exports from the two Northwest ports have been a steady percentage of the nation's total export value. The two ports shipped to 24 of the 92 countries that received U.S. bentonite. Oregon shipped three to eight times the tonnage that Seattle shipped.

BENTONITE EXPORTS, U.S. vs PACIFIC NORTHWEST

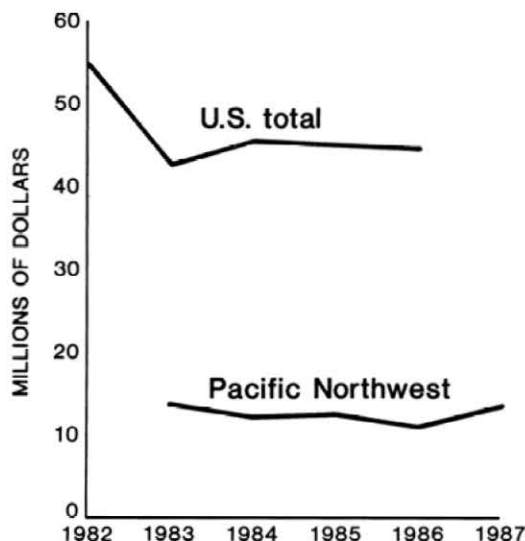


Figure 2. Bentonite export dollars, showing both the U.S. total and the Pacific Northwest portion.

OREGON PRODUCERS

Figure 3 shows the location of Oregon's two producers, Central Oregon Bentonite Company, Roberts Route, Box 500, Prineville, Oregon 97754, and Teague Mineral Products, Route 2, Box 35C, Adrian, Oregon 97901.

Central Oregon Bentonite started producing bentonite in 1958 and in 1959 built an eight- to ten-ton-per-hour mill and bagging plant near the mine. The output was marketed for cat litter, binder

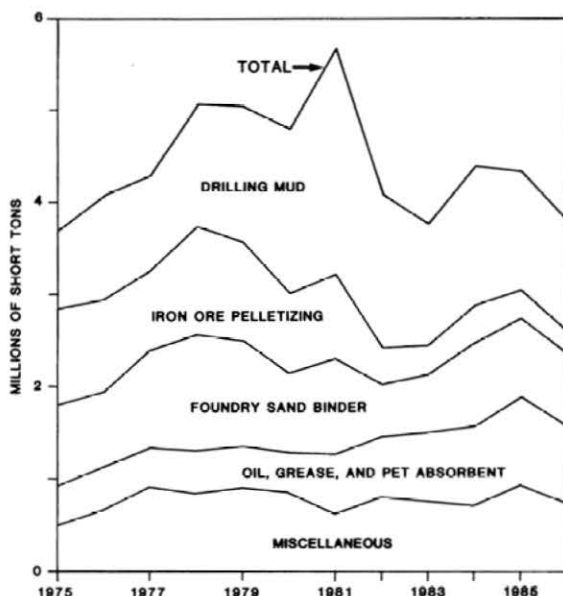


Figure 1. Bentonite, including Ca-bentonite/fuller's earth, sold or used by domestic producers for specified uses. Data from U.S. Bureau of Mines Minerals Yearbooks, v. 1, 1963 to 1986.

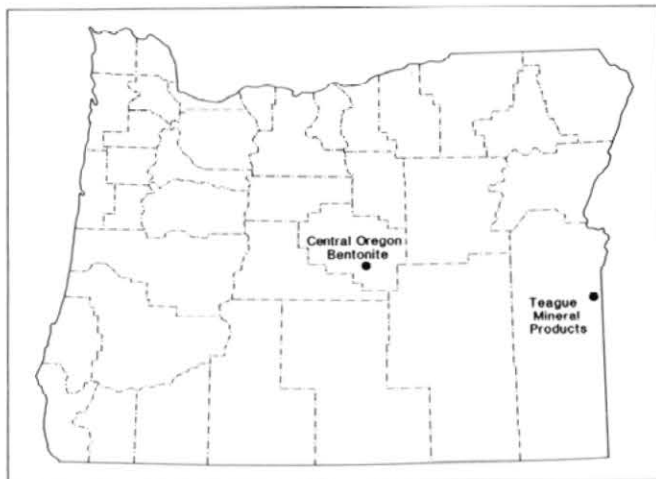


Figure 3. Oregon bentonite producers.

in making stock-feed pellets, ditch and pond sealant, pitch control in paper mills, fire retardant, oil-well drilling mud, and filler in insecticides and fungicides. The bentonite bed is mined from a 3- to 4-ft thick bed in the John Day Formation with a stripping ratio of less than 1:1.

Teague Mineral Products started producing bentonite in 1974. Figure 4 shows the office, milling-bagging (three to seven tons per hour) plant located 1 mi south of Adrian. The bentonite mines are located 20 mi south and east on Succor Creek. Figure 5 shows the tilted older bentonite beds, and Figure 6 shows the flat-lying younger beds. According to the firm's unpublished data, the two beds being mined are from 20 to 30 ft thick and have drilled reserves of 2.5 million tons at a stripping ratio of 1:1. Bentonite from this operation has been marketed mainly for use as sealants for sewage lagoons, hazardous-waste sites, gold-ore cyanide leach pads, and drill holes. Other uses are cattle food supplement, water-well drilling mud, and slurry type of trench excavation.

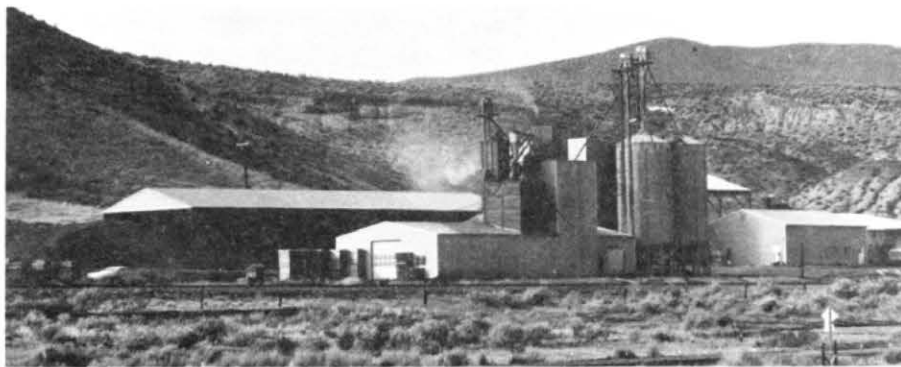


Figure 4. Teague Mineral Products office, mill, and bagging plant.



Figure 6. Mining of the younger, flat-lying bentonite bed on Succor Creek by Teague Mineral Products.



Figure 7. Material from the flat-lying bed being loosened and windrowed by a disk and scraper.

MINING AND MILLING OF BENTONITE

Oregon bentonite is produced by open-pit methods. Overburden is removed and stockpiled for later use in reclamation. A bentonite bed is mined in 3- to 4-in. lifts. A disk and scraper (Figure 7) is used to loosen and to shave and windrow the top few inches off the bentonite bed. The loosened bentonite is air dried for a day or two and may be windrowed again to allow more air drying.

After air drying, the bentonite is removed and loaded into trucks with a front-end loader or with a wheeled elevator (Figure 8) and taken to the mill, where it is stored under cover. At the mill, it is fed into a primary crusher, slicer, or breaker unit. At this stage, it may be further dried in a rotary kiln and sent over a screen to produce granules for cat litter. The material may go from the dryer to a pulverizer (Raymond roller mill), where cyclone dust collectors extract the minus-200-mesh pulverized product.

From the screens and/or cyclone, the material is moved to storage silos. Small amounts of soda ash are added to the bentonite at the mine or at the mill to improve the swelling property of the bentonite. The product is marketed either in bulk form or in bags of various sizes ranging from 2,000-lb supersacks to 10-lb cat-litter bags.

FIELD SURVEYING

The reconnaissance-level field surveying started with the bentonite deposit model of bentonite forming from bedded air-fall volcanic ash or tuff that was deposited into a marine or alkaline-lake environment and subsequently altered to bentonite. Such lakes may or may not have been heated by hot springs.

Figure 9 shows the locations of several large, eastern Oregon basins ranging in age from 4 to 40 million years. During the time each of these basins was receiving sediments, major volcanic activity was occurring, giving rise to air-fall tuffs whose deposition, in turn, disrupted drainages and produced alkaline lakes. The basins trapped transported bentonite, and the volcanic centers produced heat and hydrothermal fluids that caused hydrothermal alteration.

The reconnaissance-level field survey included sampling of bentonite beds, mine stockpiles, and finished products of bentonite producers. In addition, roads crossing the identified sedimentary



Figure 5. Older bentonite bed mined by Teague Mineral Products on Succor Creek in southeastern Oregon.



Figure 8. Three- or 4-in. lifts of air-dried bentonite being removed and loaded into trucks with a wheeled elevator and moved to stockpiles.

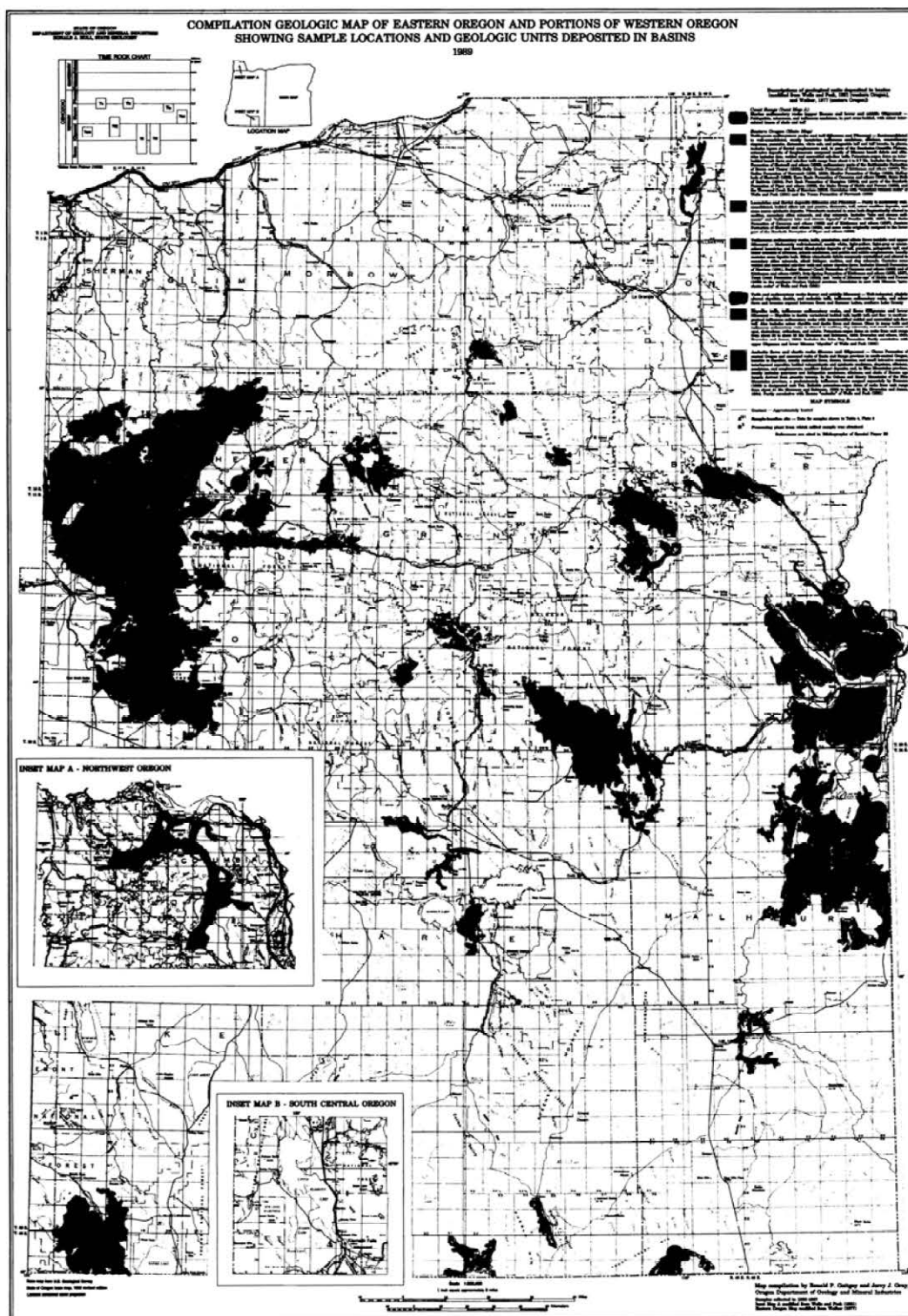


Figure 9. Map of eastern Oregon showing generalized locations of several large basins ranging in age from 4 to 10 million years.



Figure 10. Typical roadcuts sampled for bentonite.

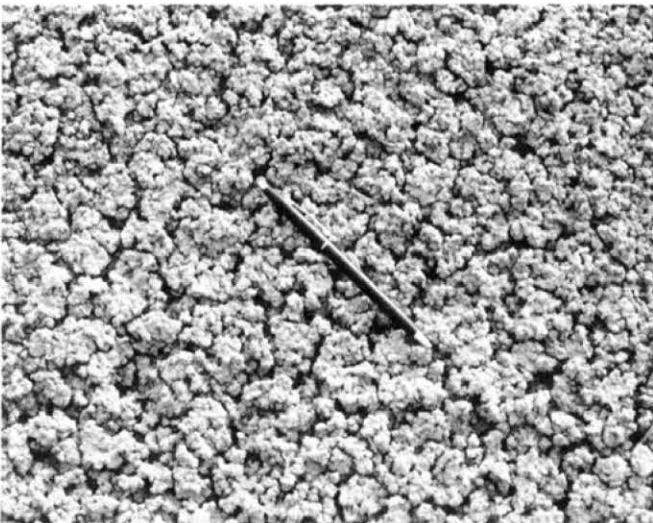


Figure 11. Popcorn weathering of bentonite.



Figure 12. Alligator-hide weathering of bentonite.

basins were driven for an estimated total of 25,000 mi. Roadcuts (Figure 10), excavations, and outcrops visible from the roads were examined for signs of swelling bentonite such as popcorn weathering (Figure 11), alligator-hide weathering (Figure 12), and unvegetated hillsides, such as those shown in the next few photographs. When a likely outcrop was found, a shallow trench or a series of small pits were dug to below the popcorn or alligator hide, and a sample was taken. Figure 13 shows several bentonite beds of the Mascall Formation. Figure 14 shows some hand augering on an outcrop of the Mascall Formation.

The next two photos are of the Deer Butte Formation in Malheur County. Figure 15 shows bentonitic and siltstone beds in one outcrop. Figure 16 shows the series of small pits dug for samples across another outcrop. Most of the pits showed a siltstone and were not sampled.

STUDY RESULTS

During field surveying, 152 samples were taken and tested for swell, grit, and water loss. The samples were tested two years after they had been originally collected because the Department laboratory was being remodeled. During the original field season, black-and-white pictures and slides were taken, and a small amount

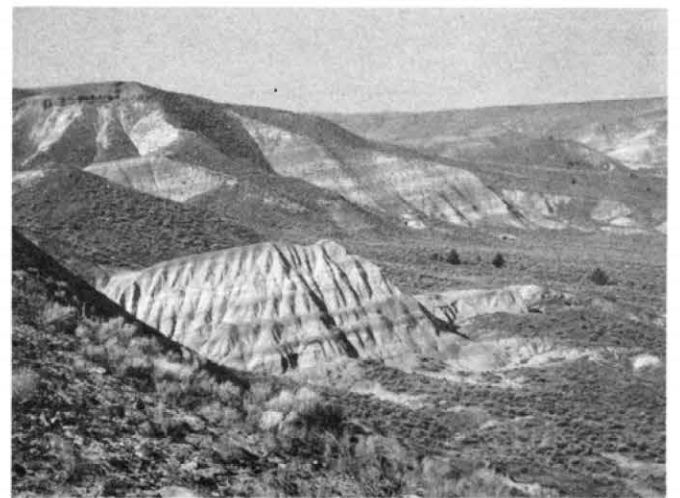


Figure 13. Several bentonite beds of the Miocene-age Mascall Formation are shown as the darker bands.



Figure 14. Hand augering of the Mascall Formation bentonite beds.



Figure 15. Bentonitic and siltstone beds of the Deer Butte Formation.

of hand augering was done in what appeared to be promising areas, based on field evidence. Of course after the laboratory results came back, we realized that we had drilled in the wrong place and had photographed the wrong outcrops.

SUMMARY

In summary, Oregon produces commercial grades of bentonite. A sampling program with 152 samples is a very small survey



Figure 16. The Deer Butte Formation was sampled by digging a series of small pits down across this outcrop. Most pits contained siltstone and were not sampled.

for a state the size of Oregon. Test results of samples collected from Oregon bentonite occurrences show that Oregon bentonite has physical properties similar to those of samples obtained from commercial producers.

The three physical tests (swell, grit, and water loss) show that many of the deposits that were sampled warrant resampling, detailed mapping, and detailed testing for specific markets. The study results indicate that Oregon has bentonite resources that could meet a variety of end-use markets. Furthermore, Oregon's bentonite would have lower transportation cost to the Port of Portland than material from Montana or Wyoming.

A 150,000- to 200,000-ton(?) annual export market would seem to be ample incentive for private enterprise to take a close look at Oregon's bentonites.

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Developments in applications for southeast Oregon bentonites and natural zeolites

by Dave Leppert, Teague Mineral Products, Adrian, Oregon 97901

INTRODUCTION

Teague Mineral Products (TMP) produces high-purity, high-swelling bentonites from two geologically distinct deposits in southeast Oregon (Figure 1). These deposits, both of Miocene age, contain very large reserves of high-quality clay. Current production primarily goes to sanitary landfills, hazardous waste sites, and other facilities that require impermeable barriers. Lesser markets include use as a dairy-feed additive, water-well drill mud, granules for monitor wells, and other miscellaneous applications. Potential markets TMP hopes to penetrate include foundry applications and eventually oil-well drill mud. Though the sodium bentonites produced are of exceptional purity, the fact that they differ somewhat from Wyoming bentonites has slowed market penetration. Also, as a small company, TMP can supply only limited technical assistance to help market development.

TMP produces clinoptilolite zeolite, "clino," from three distinct deposits in southeast Oregon and southwest Idaho. Current production primarily sells for use as a fungicide carrier, animal feed supplements, and odor control applications, with small amounts for miscellaneous applications including radioactive waste treatment and hazardous waste solidification. In addition to increasing current markets, environmental and agricultural applications offer potential for large tonnage applications. Higher value specialty applications are also under development.

BENTONITE

Geology

Sodium bentonites are mined from two beds within the Miocene Sucker Creek Formation, which has been informally divided into an upper and lower unit. An angular unconformity separates these units, and they have distinctly different lithologies. Recent mapping divided the Sucker Creek into two distinct units (Ferns, 1989), and it may be appropriate to formally designate these as members within the Sucker Creek or split the lower unit out as a distinct formation.

The "Main Bed," an informal designation for one of the bentonite beds mined by TMP, is in the lower unit of the Sucker Creek Formation. It consists of a series of brown, green, and yellow-green bentonite beds with a cumulative thickness ranging from about 14 ft to over 20 ft in the pit area. Individual ash fall units have a relatively coarse textured basal unit that fines upward.

Mapped outcrop of the Main Bed totals at least 5 mi. Multiple faults subparallel to the strike greatly increase the outcrop of minable bentonite without excessive overburden. Core drilling, mostly in or adjacent to operating pits with scattered holes elsewhere in the region, defines reserves. Reserves in the immediate area of B-Pit, the site of current mining operations on the Main Bed, exceed 1 million tons at a strip ratio of 1:1. Probable reserves elsewhere within the Main Bed have not been calculated in detail but are obviously very large.

The "GB bentonite," an informal designation for another bentonite bed mined by TMP, occurs in the upper unit of the Sucker Creek Formation. Though eroded over much of the area, faulting preserved the GB bentonite in downdropped blocks. The GB bentonite received its name from this structure, a graben block.

Where currently mined, the GB bentonite ranges in thickness from over 20 ft up to 32 ft. Closely spaced core drilling in and adjacent to the GB-17-1 pit with widely spaced drill holes farther

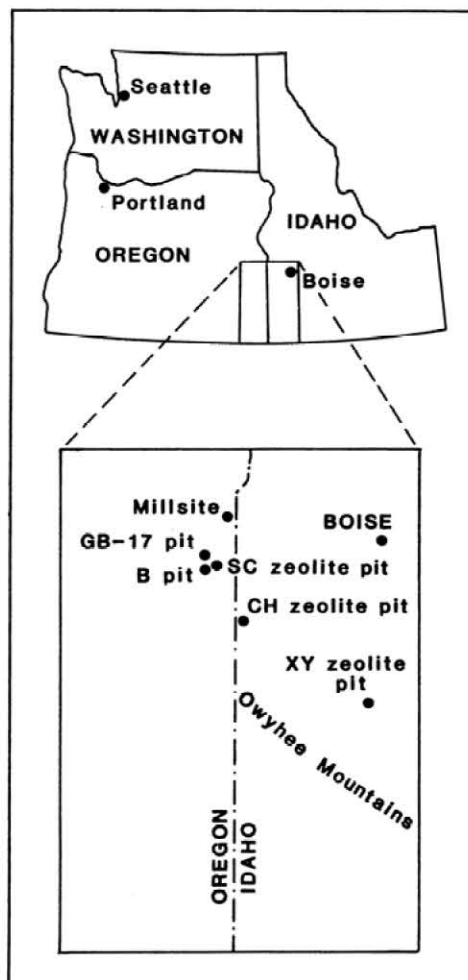


Figure 1. Map showing locations of TMP operations.

out indicates reserves of approximately 4 million tons in the block currently mined. Scattered holes reveal the presence of the GB bentonite elsewhere in the basin and indicate the potential for reserves at least an order of magnitude greater than those currently defined by drilling.

Physical and chemical properties

Both the GB bentonite and B-Pit bentonite exhibit surprisingly similar physical and chemical characteristics, despite the fact they occur in different units of the Sucker Creek Formation. Whole-rock analyses (Table 1) show a similar composition with an unusually high iron content. Technically, these bentonites are classified as iron-rich montmorillonites (Altaner and Grim, 1989). Semiquantitative X-ray diffraction and tests for colloid content show that the

Table 1. Whole-rock analyses of TMP bentonites and zeolites (Percent oxides recalculated to 100% dry weight basis)

	B-Pit bentonite	GB-Pit bentonite	SC zeolite	CH zeolite	XY zeolite
SiO ₂	63.00	65.43	74.6	75.0	73.8
Al ₂ O ₃	19.49	18.32	14.25	13.27	15.0
TiO ₂	1.80	1.60	0.54	0.50	0.29
Fe ₂ O ₃	9.35	8.79	4.42	3.59	2.58
CaO	2.41	2.28	2.66	0.93	3.23
MgO	1.27	1.48	0.50	0.86	1.27
Na ₂ O	1.47	1.42	0.44	1.05	1.60
K ₂ O	0.84	0.67	2.61	4.78	1.91

XRF analyses on mill samples

smectite (montmorillonite) content exceeds 90 percent for both deposits. Minor impurities primarily consist of a trace of gypsum with lesser amounts of quartz and feldspar. The grit content is extremely low, especially in the GB bentonite. A 200-mesh (75-micron) wet-screen analysis typically runs less than 0.1 percent retained in the plus 200-mesh fraction. Tests on samples submitted for foundry testing show 1.5 percent and 0.8 percent retained on a 500-mesh screen (25-micron) for B-Pit bentonite and GB bentonite, respectively. In contrast, Wyoming bentonites typically contain several percent plus 200-mesh grit.

The rheological properties, high yield, and low water loss make these bentonites excellent for most applications (Table 2). When first mined in 1985, TMP selectively mined the GB-17 pit on the basis of the rheological properties of core samples taken on 25-ft centers and analyzed in 6-in. increments. Mining split the bentonite into two stockpiles, and a small amount went to a waste pile. The primary goal was to produce a natural bentonite drill mud meeting American Petroleum Institute (API) 13A specifications with no chemical treatments. Oil-well drill mud is the largest market area requiring specific rheological properties. Industry sources indicate that virtually all Wyoming bentonites sold for drill mud use are chemically treated with organic polymers, primarily to increase the barrel yield. Apparently, the quality of bentonite available from Wyoming producers has steadily declined for the past 20 years (Estes, 1986).

Table 2. Typical analyses for rheology of TMP bentonites

Sample	600	300	PV	YP	H ₂ O	FIL
B-Pit	18	13	5	8	13	13.2
GB-17, #1 stockpile	41	34	7	27	13	13.1
GB-17, #2 stockpile	54	48	6	42	14	13.2
API Spec. 13A	30 Min	—	3XPV Max	10Max	15.0 Max	—
"European" Spec.	30 Min	—	6XPV Max	13Max	16.0 Max	—

Notes: Test results are based on standard API procedures (RP 13B) using a Fann 35A viscometer. Analyses are based on "typical" stockpile samples. 200 mesh wet sieve "grit" specifications for 13A and the proposed European specifications are 4.0 percent maximum and 2.5 percent maximum, respectively. Typical grit analyses for B-Pit bentonite is less than 0.5 percent and for GB-bentonite is less than 0.1 percent.

The GB bentonite exhibits excellent rheological properties for oil-well drill-mud applications. The barrel yield, water loss, and grit content easily meet API specification 13A with no chemical treatment. However, the API specification has a provision that the yield point:plastic viscosity (YP:PV) ratio should not exceed

3. This was reputedly included as part of the specification to prevent bentonite producers from adding excessive amounts of polymers or other chemicals to inferior clay. Overall, the GB bentonite has a naturally high YP:PV ratio. Therefore, the YP:PV ratio provided the main control for selective mining. Sampling of the GB bentonite, #1 stockpile, indicated an average PV:YP ratio between 4 and 6, slightly greater than the maximum allowed by 13A (Table 2).

The standard drill-mud test specifies the use of 22.5 g of bentonite in 350 ml of water. Although GB-17 #1 stockpile does not meet the 13A specification, it is interesting to note that if a sample is mixed using only 20.0 g of bentonite in 350 ml of water, it exceeds the specification in all respects. It easily surpasses the proposed International/European Grade bentonite specification.

Soil sealants

Use as a soil sealant to make impermeable barriers for waste sites, ponds, and other facilities provides the largest market for TMP bentonites. Permeameter testing demonstrates the excellent performance of both B-Pit and GB-17 bentonite for these applications, with the GB bentonite offering the best performance.

Several permeameter tests were run to directly compare the performance of the GB bentonite with commercially available products from Wyoming producers. Some of these products contain chemicals to improve performance in the presence of ionic solutions and/or organic compounds. In limited testing, the GB bentonite, without any chemical treatment, performed as well or better than the specialty products from Wyoming producers (Alther, written communication, 1986) with water and various ionic solutions used as the permeant fluid.

Foundry testing

Though not currently selling bentonite for foundry usage, test results, including one full-scale test, indicate TMP bentonites perform well for most foundry applications. Data show that the B-Pit and GB bentonites exhibit similar characteristics. The high green compression strength particularly interests many potential customers, but the relatively low hot strength inhibits use for some applications. Table 3 shows selected data comparing TMP bentonites with "typical" Wyoming bentonite meeting the "13T" specification for foundry use.

Table 3. Foundry test data on TMP bentonites

	GB17#1	B-Pit	"13T" (WY)
Green compression str. (psi)	23.6	24.0	15.4
Cone jolt toughness	20	18	10
Wet tensile strength (g/cm ²)	39.2	32.1	23.6
Hot strength, 1,800 F (psi)	258	225	485

All tests performed by George Fischer Foundry Systems, Inc., with a 6-percent mix and 40-percent target compactibility. Data compiled from test reports T-6585, T-6641, and T-6661.

Economic factors

The location of TMP's bentonite deposits in southeastern Oregon offers advantages in several market areas compared to Wyoming bentonites, the major source for sodium bentonite in the world. Freight generally makes up a major portion of the delivered cost of the bentonite, frequently costing more than the bentonite itself. As a relatively small producer, the per-ton production costs for TMP bentonites are somewhat higher than the major producers in Wyoming. Also, the high green compression and wet tensile strengths mean that it takes significantly more horsepower to grind a ton of bentonite to a given product size. However, a significant freight advantage combined with superior performance for soil-

sealant applications allowed TMP to establish a market in the Pacific Northwest, despite higher production costs.

Overseas markets offer the greatest potential for increase of sales. Large quantities of Wyoming bentonite are shipped overseas through Portland and Seattle every year, primarily to Japan, Korea, and elsewhere in southeast Asia for foundry use. Though significantly depressed in comparison to the late 1970's and early 1980's, a significant portion still goes for oil-well drill mud.

ZEOLITES

Markets

Zeolites offer excellent potential for many uses. Despite expectations, sometimes unrealistic, from industry observers over the last 20 years, markets continue to develop slower than expected. Reasons for this vary, but primarily relate to insufficient marketing efforts and/or expertise by companies involved with them. Also, it takes numerous years to establish markets for industrial minerals, especially for new applications, and many companies gave up without allowing sufficient time for market development.

TMP produces clinoptilolite zeolite ("clino") from three different deposits in southeastern Oregon and southwestern Idaho. These deposits, designated as SC, CH, and XY zeolite, each have unique physical and chemical characteristics that make them uniquely suitable for different applications. Other deposits in the region are under study for possible use.

Testing/characterization

Testing and characterization of zeolite deposits presents many problems. Since the desirable properties vary with the intended end use, no single parameter can be used to quantify how "good" a zeolite deposit is. Simple as it may seem, determination of a single property may be difficult.

For example, prospective customers frequently ask about the purity of a zeolite that interests them. Like clays, no single analytical technique can adequately quantify the purity. The most common technique, X-ray diffraction (XRD), can be considered only semi-quantitative under the best circumstances. In select instances, it does not work well at all. Union Carbide's exploration program in the late 1950's and early 1960's used XRD for routine screening of tuffaceous samples sent in by its field geologists to determine the zeolite content. Based on initial XRD runs, the chabazite bed Union Carbide tested at Bowie, Arizona, had a relatively low zeolite content. Gas absorption data and more detailed XRD work revealed that this bed contained a high percentage of chabazite, and it ultimately went into production.

Determination of the cation-exchange capacity (CEC) can also contribute to determination of the purity of a deposit. Like XRD, it can be used only as a guideline. Several different test methods for CEC all give different results, and it is virtually impossible to obtain total exchange, as demonstrated by Loizidou and Townsend (1987). Cations such as potassium in the structure that are difficult to remove will also reduce the apparent CEC. Impurities may block exchange sites to decrease the effective CEC.

Scanning electron microscopy, petrographic examination of thin sections, and other techniques can also contribute to estimating the "purity" of a zeolite sample, primarily by identifying and quantifying the impurities present.

The American Society of Testing Materials (ASTM) recently established a committee to develop standardized test procedures for natural and synthetic zeolites. It will look at a wide variety of physical and chemical properties and hopefully establish test procedures that are relatively simple and with good repeatability. Ultimately, however, as with all industrial minerals, it is up to the customers to determine the specifications of materials to meet their needs. Some properties such as odor absorption will remain very difficult to quantify. Other properties such as color are totally

irrelevant to ion-exchange applications but of utmost importance to customers interested in fillers or similar applications.

Zeolite geology and production

TMP zeolite production began in 1975 with a small pit on the CH zeolite deposit. This very large deposit contains minable reserves of at least 20 million tons, with probably several times this amount actually present (Teague, unpublished data, 1989). Drilling has concentrated on the area of the current pit, with scattered holes elsewhere on the deposit. Thickness of the zeolite bed ranges from 80 to 100 ft, with approximately 6,000 ft of outcrop subparallel to the strike. This potassium-rich clino has high purity, probably averaging about 80 to 85 percent clinoptilolite, possibly better. Good attrition resistance makes it suitable for many ion-exchange applications in addition to many agricultural uses.

Production of SC zeolite began in 1983 with enlargement of a small quarry that had originally produced "picture rock," a semi-precious ornamental jasper used for jewelry. The zeolite bed is approximately 30 ft thick with 1½ mi of outcrop subparallel to the strike. Recent laboratory work confirms previous suspicions that the primary zeolite mineral is heulandite, not clinoptilolite (Altaner and Grim, 1989). Heulandite has characteristics very similar to clinoptilolite and cannot be distinguished from it by XRD alone. SC zeolite performs well for general odor-control uses and has also been used to a minor extent for hazardous-waste solidification/stabilization.

Production of the XY zeolite was started in 1987 with a small pit adjacent to previous drill cores and test trenches. Where currently mined, the purity is exceptional, roughly estimated at 95+ percent on the basis of (1) XRD analyses on numerous samples, (2) the high CEC, and (3) general lack of impurities. The primary impurity is a very minor amount of black scale precipitated along joints in the rock. An interesting aspect of this zeolite is the unusually low bulk density, which gives it excellent absorption characteristics. XY zeolite should prove suitable for many of the higher value applications.

Applications

Although there are a wide variety of potential applications for natural zeolites, very few have been commercially developed to any extent. Compared to the rest of the world, markets for natural zeolites in the U.S. remain minuscule. Though numerous factors help explain this, it seems primarily due to the fact that the large companies that attempted to get into the natural zeolite business did not aggressively pursue marketing opportunities. The primary exception to this has been production of chabazite from the Bowie deposit in Arizona. Although it is expensive to mine the 6-in.-thick chabazite bed, Union Carbide markets it with its line of synthetic zeolites at prices of several dollars per pound and up. In contrast, most natural zeolites sell for prices ranging from \$50 up to \$500 per ton (\$0.025 to \$0.25 per pound).

Small but steadily growing applications of natural zeolites include such uses as odor control, a carrier for agricultural chemicals, and feed supplements for chickens and other animals. Primary market areas under development by TMP include environmental and agricultural applications. Environmental applications fit well with established markets for TMP bentonites, since some customers may have uses for both. A location adjacent to a highly productive farming area offers opportunities for development of agricultural applications.

Environmental applications

Though zeolites offer potential for use in a wide variety of environmental applications, TMP's efforts are primarily restricted to development of uses relying on the ability of clino to selectively absorb heavy metals, radionuclides, and other cations. Due to limited in-house research capabilities, TMP primarily offers suggestions

to interested parties and supplies samples and background data. Another aspect of TMP research is cooperation with Nyssa High School, which has one of the top secondary school science programs in the state of Oregon.

Several nuclear projects have used clinoptilolite supplied by TMP. It is already used to remove radionuclides from contaminated water, and work on the use of zeolites in sorbent barriers for low-level radioactive waste disposal sites provides much interesting information. Researchers at Hanford (Freeman and others, 1986) and West Valley have been the most active in this area. Researchers at Los Alamos are also intensively investigating the sorption characteristics of natural zeolites, since the tuffs at Yucca Mountain, the proposed site for a high-level nuclear waste repository, contain zeolites that should inhibit the migration of radionuclides.

TMP's suggestion of the possible use of clinoptilolite as a soil amendment to reduce cesium uptake by food crops on Bikini Atoll led to field trials that started in 1986. The initial results from these trials looked excellent, with reduction of cesium to well below target levels (Leppert, 1988). It remains unknown whether the final solution to the problems there will include this approach, but zeolites were used as feed additives for livestock to inhibit uptake of radionuclides in some areas downwind from Chernobyl (Forberg and others, 1989).

Development of applications for clinoptilolite utilizing its ability to selectively absorb many heavy metals remains elusive, but steady progress indicates they may ultimately provide a cost-effective approach for many sites with heavy-metal contamination. Since clinoptilolite selectively absorbs lead better than most other metals and since lead poses the greatest health threat at numerous Superfund sites, efforts have been concentrated in this direction.

EPA Region X recently completed a research project (Hoye and Davis, 1988; Krawczyk and others, 1989) on the possible use of clinoptilolite as a soil amendment at Bunker Hill, Idaho. Unfortunately, experimental difficulties made much of the data they generated unreliable and nearly worthless (Leppert, 1989). In spite of the experimental difficulties with the first portion of their project, it was hoped that the second portion of the study would give better results. The second portion of the study consisted primarily of amending contaminated soils with zeolites and growing beans, dandelions, and fescue in the soil. Despite discussions between TMP and the EPA prior to collecting soil samples at Bunker Hill with target levels of about 2,000 or 5,000 ppm lead for use in these experiments, the sample obtained contained 22,000 ppm lead and 10,000 ppm zinc. It seems reasonable to assume that any contaminated soil with this extreme contamination would need to be disposed of in a secure landfill or possibly even reprocessed for recovery of the metals. Due to the excessively high metal levels in the soil sample used, it is not surprising that the plants either failed to germinate or grew only a short time before dying.

Other research on the use of zeolites for metal sorption includes a project at the U.S. Bureau of Mines in Reno. This project primarily involves the use of ionexchange columns filled with zeolite from a variety of sources to test the ability of zeolites to remove metals from contaminated water, focusing on water from active and abandoned mine sites. The primary difficulty the Bureau has encountered is competing cations in solution that inhibit uptake of metals by the zeolite. Excessive calcium and iron particularly cause problems. Details remain unpublished but may be available sometime in 1989.

The sorbent barrier concept, which was largely developed for use at radioactive waste disposal sites as briefly described above, should be applicable to sites with heavy-metal contamination. Basically, instead of attempting to contain metal-contaminated leachates with impermeable barriers, sorbent barriers would allow the migration of contaminated water but remove metals from it. In addition to use in new disposal sites, sorbent barriers could be built around existing contaminated sites with slurry trench methods, replacing the impermeable clay with zeolite. Figure 2 illustrates

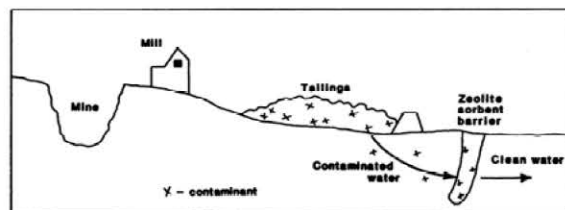


Figure 2. Vertical sorbent barrier using natural zeolites for heavy-metal sorption.

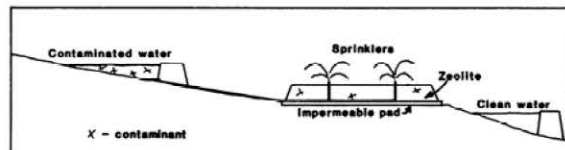


Figure 3. Heap absorption with natural zeolites.

the use of a sorbent barrier to trap metals leaching out of a tailings pond at a mine site.

"Heap absorption" (Figure 3) may provide a cost-effective approach for treating large volumes of contaminated water. The concept is simple. Make a large pile of crushed zeolite and sprinkle the contaminated water over it, similar to the way many gold mines leach piles of ore to extract the gold. Several heap-absorption units run in series would provide maximum efficiency, similar to the way ion-exchange columns are typically run in series. Once loaded to capacity, it may be feasible to regenerate the zeolite with a brine solution or ship it to a smelter for metal recovery.

Agricultural applications

Agricultural applications currently provide one of the larger markets for TMP zeolites, primarily for use as a fungicide carrier and feed additive. Though these markets continue to grow steadily, they do not offer the potential for very large tonnages. Soil-amendment applications may eventually develop into a very large tonnage market. Although farmers in other countries recognize the benefits of adding zeolites to the soil, most U.S. farmers simply rely on chemical fertilizers to provide nutrients. In addition to the high cost of chemical fertilizers, contamination of surface and ground water from agricultural chemicals poses a public health threat. Increasing awareness of the hazards of excessive chemical use should contribute to the growth of this market.

Primary benefits from use of zeolites as a soil amendment include improved retention/utilization of nutrients and water. Therefore, sandy soils benefit most from zeolite additions. With some soils, particularly those with a high clay content, increased water retention may cause problems if zeolite with a large percentage of fine particles is added.

Since effectiveness varies from one area to another with differences in soils, crops, and the specific zeolite used, published data provide only general guidelines for the use of zeolites. Therefore, TMP efforts in this area concentrate on developing data applicable to local conditions. Locally, zeolites could prove to be very effective and cost-effective for use by farmers. In addition to the advantage of low freight costs, the predominance of high-value crops and sandy soils throughout the area make it attractive.

Since researchers at local agencies designed to help farmers either have shown minimal interest in the possibilities for use of zeolites as soil amendments or require relatively large amounts of funding, TMP takes an alternative approach to developing information in this area. Research by local high school students

provides a primary source of information for the use of zeolites as a soil amendment.

Fortunately, Nyssa High School has one of the best secondary school science programs in Oregon. Every year, TMP provides suggestions for science projects utilizing bentonites or zeolites, provides samples with which to work, and offers advice throughout the project. With a little guidance, the students perform excellent work, better in some cases than research on zeolites we have seen from "reputable" laboratories. In fact, Nyssa High School regularly wins many of the top awards at the Northwest Science Exposition in Portland, with several bentonite or zeolite projects taking first or second in their category. Though research by large companies may generate more detailed data, findings generally remain proprietary.

Three Nyssa High School students, Tiffany Olsen (1987), Christine Howell (1988), and Jason Berrett (1989) researched the use of zeolites as a soil amendment. All won first place in their category at the Northwest Science Exposition. Olsen was selected to attend national science events at West Point and in Puerto Rico. Howell received three awards at the International Science and Engineering Fair in Knoxville, Tennessee.

Olsen's project, "Influence of Zeolite as a Soil Additive on Plant Phosphorus Uptake," extended the work of Eberl and Lai (1986) on the use of zeolites with phosphate rock. Eberl and Lai showed that mixing zeolite with phosphate rock increases the effective solubility of the "insoluble" calcium phosphate (apatite), presumably by acting as a sink for calcium. Many western soils contain abundant phosphate from the use of phosphatic fertilizers, but the presence of calcium in the soil puts it into a relatively insoluble form. Therefore, use of zeolite as a soil amendment should help make some of the "insoluble" phosphate available to plants. Olsen's experiments, which consisted of growing plants in control and zeolite-amended soils, demonstrated this nicely.

Howell's project, "Influence of Zeolite as a Soil Additive for Fertilizer Retention," extended the work of several researchers in this area, with greater focus on the environmental aspects of the problem. Her primary experiments consisted of filling five-gallon buckets with control and zeolite-amended soils, adding water, and collecting the "runoff" from the surface and leachates at depth. Howell also measured germination rates and sampled local rivers to determine their nitrogen and phosphorus content.

Berrett's project, "Influence of Zeolite Soil Amendments on Root Crop Production," primarily looked at the yield and sugar content of radishes and carrots in control and zeolite-amended soils. As expected, both the yield and sugar content increased significantly (Table 4). Sugar content means not only a higher quality product but also more money to farmers for crops such as sugar beets, where price is on the basis of sugar content.

Table 4. Radishes and carrots grown in zeolite-amended soils

	Control	6 T/acre	12 T/acre
Radishes:			
Mean weight (500) (g)	10.63	11.71	12.18
Invert sugars (g/100 RDS)	39.69	46.82	41.70
Carrots:			
Mean weight (200) (g)	22.07	22.94	28.08
Invert sugar (g/100 RDS)	52.74	54.65	59.72

These and other projects TMP assists with demonstrate that students can perform excellent research. They provide a way for a small company with limited in-house research capabilities and funding to obtain meaningful data. Other companies developing new applications for their products may find a similar approach beneficial, not only to themselves but also to the community.

SUMMARY

TMP controls excellent reserves of sodium bentonites and natural zeolites, but production remains limited due to insufficient market development. Overseas markets offer the greatest potential for expansion of bentonite markets, especially for foundry applications, in southeast Asia. These prospective customers already use bentonite, primarily from Wyoming/South Dakota. In addition to a significant freight advantage, TMP bentonites offer characteristics desired by foundries such as a higher green compression strength. Though market penetration remains hindered by a lack of technical expertise specific to the foundry industry, penetration seems inevitable. Demand for soil sealants continues to grow as new regulations for landfills and other facilities come into effect.

Development of zeolite markets requires a continued commitment and research and development program. In a few instances, zeolites may replace other materials, but most markets are new uses, and creating the demand for them poses a substantial challenge. With limited resources, TMP concentrates on development of agricultural and environmental applications, two areas with potential for large tonnage markets. To some extent, these areas overlap, since agricultural use should help mitigate the environmental consequences of using chemical fertilizers.

ACKNOWLEDGMENTS

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Industrial minerals in Washington—1988: Production and potential

by Nancy L. Joseph, Washington Department of Natural Resources, Division of Geology and Earth Resources, Spokane County Agricultural Center, N. 222 Havana, Spokane, Washington 99202

ABSTRACT

In 1988, more than 18 companies mined and produced industrial minerals, including limestone, dolomite, silica, olivine, clay, and diatomite (Figure 1, Table 1). Two companies produced portland cement, and nine plants produced lime, calcium chloride, precipitated calcium carbonate, ground limestone, or silicon (Figure 2, Table 2). In addition, more than 900 pits and quarries were permitted to mine sand and gravel and crushed stone.

The value of nonfuel mineral production in the state of Washington was more than \$400 million in 1988, according to figures compiled by the U.S. Bureau of Mines and the Washington Division of Geology and Earth Resources. Industrial mineral production accounted for nearly three-fourths of this total (Figure 3). Northwest Alloys, Inc., was highest value mineral operation in the state because of its large production volume and the value added to the dolomite mined from the quarry through the production of magnesium metal at the plant. Other high-volume minerals and industrial mineral products are sand and gravel, crushed rock (which includes limestone and dolomite), and cement.

DOLOMITE

Introduction

More than 800,000 tons of dolomite were extracted in Washington in 1988. Most of the rock was quarried in Stevens County,

in the northeastern part of the state. The dolomite is used primarily in the production of magnesium metal, with the remainder utilized as decorative rock and in agriculture.

Dolomite for magnesium metal

Dolomite is used in the production of magnesium by Northwest Alloys, Inc., a wholly owned subsidiary of Aluminum Company of America (Alcoa). The company is the largest producer of dolomite in the state, extracting approximately 790,000 tons of Cambrian-Ordovician Metakine Formation from the Addy Dolomite quarry. Chemical analyses of the stone mined at the quarry have indicated that the rock averages 30.3 percent CaO, 21.3 percent MgO, and less than 1 percent insolubles (Bennett, 1944).

The magnetherm process is used to produce magnesium metal from dolomite. In this process, pelletized dolomite, alumina flux, and ferrosilicon are mixed and heated to 1,600 °C. Nine resistive electrical furnaces are presently in use at the Stevens County plant. Magnesia in the calcined dolomite is reduced by the silicon; the magnesium vapor condenses externally and is remelted under flux. Ten tons of dolomite are needed to produce one ton of magnesium metal by this method (O'Driscoll, 1989).

The 13-year-old plant produces more than 80 million pounds of magnesium per year, which accounted for 16 percent of the world's production of the metal in 1988. Northwest Alloys is one

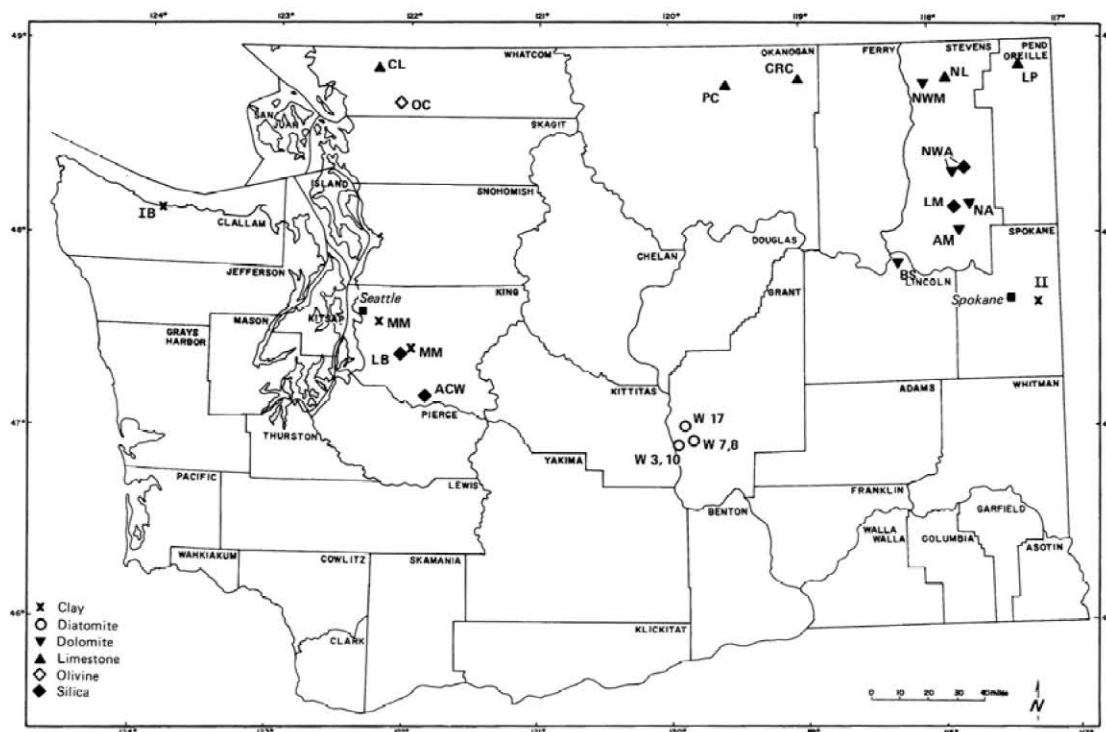


Figure 1. Map showing locations of companies mining industrial minerals in Washington in 1988. See Table 1 for company names represented by initials on this map.

Table 1. Companies mining industrial minerals in Washington in 1988 (exclusive of sand and gravel).
Figure 1 shows locations of companies

Commodity	Map symbol	Property	Owner and/or operator	County	1988 production and development
Clay	IB	Twin River quarry	Ideal Basic Industries, Inc.	Clallam	Mined 100,000 tons
Clay	II	Mica mine, plant and Pottratz pit	Interpace Industries Inc.	Spokane	Mining
Clay	MM	Elk pit	Mutual Materials Co.	King	Mined 28,500 tons
Clay	MM	Sec. 31 pit	Mutual Materials Co.	King	Mined 85,000 tons
Diatomite	W 7, 8	Sec. 7 and 8 pits	Witco Corp.	Grant	Mined 90,000 tons
Diatomite	W 17	Sec. 17 pit	Witco Corp.	Grant	Hauled 10,000 tons
Diatomite	W 3, 10	Sec. 3 and 10 pit	Witco Corp.	Grant	Newly permitted
Dolomite	AM	Gehrke quarry	Allied Minerals Inc.	Stevens	Mining and milling
Dolomite	BS	Crystal City mine	Blue Silver Mining	Lincoln	Mined 30,000 tons
Dolomite	NA	Several quarries	Nanome Aggregates, Inc.	Stevens	Mining from several pits
Dolomite	NWA	Addy Dolomite quarry	Northwest Alloys, Inc.	Stevens	Mined 760,000 tons
Dolomite	NWM	White quarry	Northwest Marble Products	Stevens	Mining
Limestone	CL	Bear Mountain pit	Clauson Lime Company	Whatcom	Mining
Limestone	CRC	Wauconda quarry	Columbia River Carbonates	Okanogan	Mined 35,000 tons
Limestone	LP	Champagne Placer	Lehigh Portland Cement Co.	Pend Oreille	Mined 241,860 tons
Limestone	NL	Northport Limestone (Hemphill Brothers, Inc.)	Northport Limestone Co.	Stevens	Mined 45,000 tons
Limestone	PC	Tonasket Limestone quarry	Pacific Calcium, Inc.	Okanogan	Mining and milling
Olivine	OC	Swen Larsen quarry	Olivine Corp.	Whatcom	Mining
Silica	ACW	Superior quarry	Ash Grove Cement West, Inc.	King	Mined 45,000 tons
Silica	LB	Ravensdale pit	L-Bar Products, Inc.	King	Mining
Silica	LM	Lanc Mountain Silica (Hemphill Brothers, Inc.)	Lanc Mountain Silica Co.	Stevens	Mined 300,000 tons
Silica	NWA	Blue Creek mine	Northwest Alloys, Inc.	Stevens	Mined 20,000 tons

of three producers of magnesium metal in the U.S. and the only company at present using the magnetherm process. Northwest Alloys is presently enjoying a strong market for the metal, which in January 1989 was selling for approximately \$1.60 per pound (99.8 percent pure ingots; American Metal Market), resulting in annual sales of more than \$100 million (Spokane Journal of Business, March 30, 1989). The market for the metal is cyclic and is presently buoyed by the capacity production of the majority of the aluminum smelters in the region. Two-thirds of the production from the Stevens County plant is used by the parent company as an alloy of aluminum in the manufacture of aluminum cans and aircraft-grade aluminum. The remainder is sold on long-term contract for uses that include desulfurizing steel (Spokane Journal of Business, March 30, 1989). A 69,000-metric-ton capacity plant being built in southern Alberta, Canada, by a joint venture that includes Alberta Natural Gas Company will begin limited initial production by the end of 1989, thereby increasing competition for noncaptive sales of the metal.

Northwest Alloys reports a 15- to 20-year supply of dolomite at its present quarry and nearly a 100-year supply at a nearby site. The plant operates 24 hours a day, seven days a week. The company has a payroll of more than \$18 million and, with nearly 500 workers, is the largest employer in the county (Spokane Journal of Business, March 30, 1989).

L-Bar Products, Inc., produces fertilizer marketed as Ag-Mag-K and deicer utilizing the dross from the Northwest Alloys plant. The firm is reported to generate 15,000 tons of product from the recycled material annually (Spokesman Review, May 22, 1988).

Crushed and ground dolomite

Dolomite quarried by the other producers in the state is used as agricultural additive, architectural aggregate, and mineral filler.

Allied Minerals, Inc., extracts dolomite from the late Proterozoic Stensgar Dolomite at the Gehrke quarry in Stevens County. The rock is crushed, ground, dried, and bagged at the plant near Springdale. The dolomite is used as a filler in fertilizer and as decorative

garden rock. The company was purchased in 1988 by a employee-owner group.

Nanome Aggregates, Inc., selectively mines dolomite from more than 14 quarries in Stevens County to produce white and various colors of architectural aggregate. White fine-ground dolomite is ground in the Raymond mill at the plant and is used in highway paint and in agricultural products.

Northwest Marble Products produces white dolomite from the White quarry for use in the ceramic industry. Primary crushing is done at the quarry, and further processing is completed at its plant at the railhead near Chewelah.

Blue Silver Mining produced small quantities of dolomite in 1988 from its quarry near Miles on the south side of the Spokane River in Spokane County. The stone is reported to contain as much as 31.5 percent CaO and 21 percent MgO (Bennett, 1944). The Crystal City quarry is in white marble formed by contact metasomatism of the Cambrian-Ordovician Metaline Formation.

Pacific Calcium, Inc., produces crushed limestone and dolomite for agricultural uses from two quarries in Okanogan County. The rock is crushed at its plant near Tonasket.

LIMESTONE

Introduction

More than 325,000 tons of limestone were mined in Washington in 1988. Producers of carbonate products on the east side of the state generally use limestone extracted near the site of beneficiation. Most of the limestone used in the Puget Sound area is imported from Texada Island in British Columbia, which is less than 200 mi by barge from Seattle.

Crushed and ground limestone

Columbia River Carbonates, a joint venture between Bleck Management, Inc., and Genstar Carbonates, Inc., mines white marble in Okanogan County and produces fine- and ultrafine-ground calcium carbonate at its plant near Vancouver (Figure 4). More

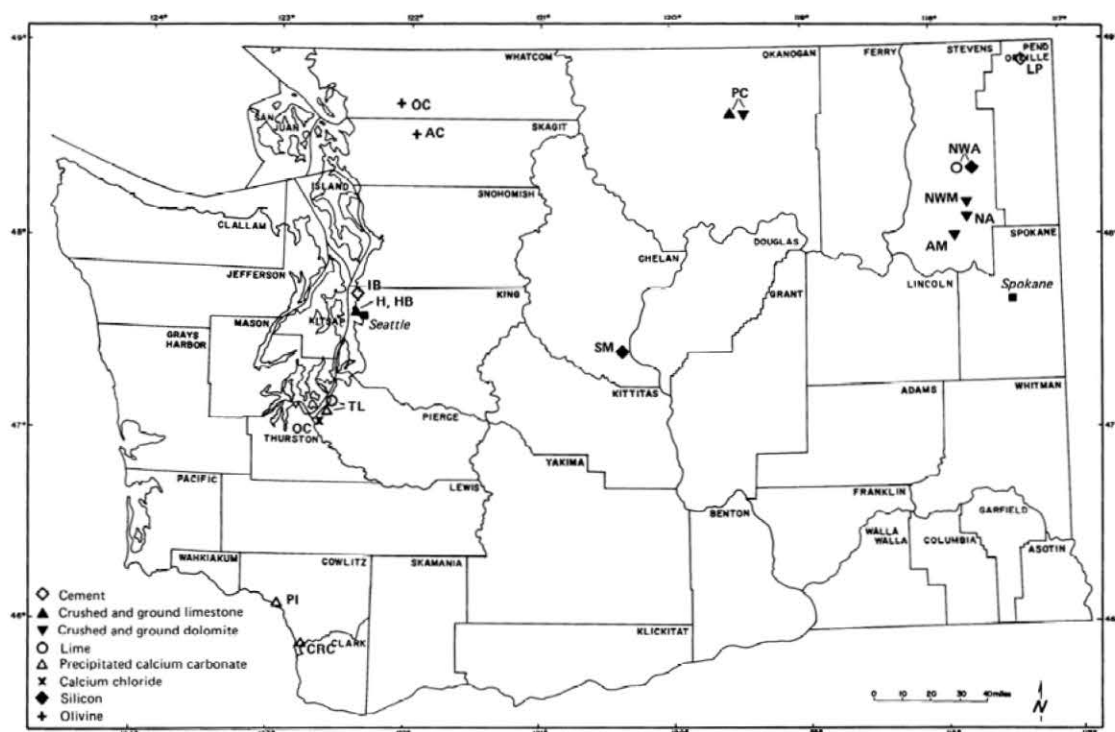


Figure 2. Map showing locations of producers of selected industrial mineral products in Washington in 1988. See Table 2 for company names represented by initials on this map.

than 35,000 tons of the Permian Spectacle Formation was extracted from the Wauconda Whitestone quarry in 1988. Reserves at the site are reported to be in excess of 10 million tons averaging 98 percent CaCO_3 , 1 percent MgO , and 1 percent acid insolubles (O'Driscoll, 1989). The rock is crushed to approximately 6 in. and then screened, eliminating the fraction (0.5-0.75 in.) that carries clay and therefore is waste.

The limestone is trucked 64 mi to near Tonasket and then shipped by rail to the plant near Woodland in Cowlitz County. To reduce any contamination that may affect the quality of the ground product, the company has constructed a covered area in which to transfer the stone from the hopper cars to the plant. The rock is fed into vibratory pan feeders, then transferred by enclosed conveyors to the mill. The ore is gravity fed to a hammer mill, screened, transferred to a fine-grinding tube mill, and then air-classified, creating one group averaging 7 microns and one group averaging 3 microns. The finer material can be ground finer by the company's proprietary wet grinding system to produce to three grades of calcium carbonate that include two filler grades averaging 1.8 microns and a coating grade for paper. The coating grade, which is the finest of the slurry products, contains 99 percent of the particles less than 5 microns, 90 percent less than 2 microns, and 65 percent less than 1 micron, with a calcium carbonate content of 98.9 percent and a brightness of 96 ± 1 (Elrepho). The three grades produced by the dry grinding are characterized by mean particle sizes from 3 to 10 microns, an average brightness of 93 ± 1 (Elrepho), and a purity of 98 percent calcium carbonate. The dry ground material is mainly used in paints and plastics.

The company is in competition with Tacoma Lime, Inc., and Pfizer, Inc., producers of precipitated calcium carbonate, to provide coating and filler-grade white calcium carbonate to the paper industry in the Pacific Northwest. Markets will increase if more manufacturers of white paper switch from the acid papermaking

process to alkaline sizing, which is popular in Europe and which produces longer lasting paper.

Northport Limestone Division of Hemphill Brothers, Inc., extracts limestone from the Cambrian-Ordovician Metaline Formation near Northport in Stevens County. The stone is used as a flux at the Cominco, Ltd., smelter at Trail, British Columbia, 15 mi due north of the quarry.

Producers of calcium carbonate products in the Puget Sound area import limestone from British Columbia, most of which comes from Texada Island. Hemphill Brothers, Inc., barges limestone from the island to its Seattle plant, where the stone is crushed and ground to produce various grades of calcium carbonate; agricultural applications are among the major uses of the rock. The finer white fraction of the crushed rock is sent through a Raymond mill owned by Hueber Corporation and run by Hemphill Brothers to produce several grades of fine-ground calcium carbonate.

Lime

Quicklime and hydrated lime are produced in Tacoma by Tacoma Lime, Inc., a division of Continental Lime, Inc. The company purchases crushed limestone from the Ash Grove Cement West, Inc., quarry on Texada Island, and the stone is barged to the plant on tidewater in Tacoma. The lime is produced for use in the steel and the pulp and paper industries in the Pacific Northwest. Twenty-five percent of the company's quicklime production is used to produce precipitated calcium carbonate. Quicklime is also produced by Northwest Alloys at its plant in Addy.

Precipitated calcium carbonate

Tacoma Lime, Inc., a division of Continental Lime, Inc., operates one of the few free-standing precipitated calcium carbonate (PCC) plants in the country. The plant, which was brought on line in 1987, is designed to produce 125 tons per day of PCC. Approx-

Table 2. Producers of selected industrial mineral products in Washington in 1989. Figure 2 shows locations of producers

Commodity	Map symbol	Owner and/or operator	County
Portland cement	IB	Ideal Basic Industries, Inc.	King
Portland cement	LP	Lehigh Portland Cement Co.	Pend Oreille
Lime	TL	Tacoma Lime, a division of Continental Lime, Inc.	Pierce
Lime	NWA	Northwest Alloys, Inc.	Stevens
Precipitated calcium carbonate	PI	Pfizer Inc. (under construction)	Cowlitz
Precipitated calcium carbonate	TL	Tacoma Lime, a division of Continental Lime, Inc.	Pierce
Calcium chloride	OC	Occidental Chemical Corp.	Pierce
Ground limestone	H	Hueber Corp.	King
Ground limestone	CRC	Columbia River Carbonates	Cowlitz
Crushed limestone	HB	J.A. Jack and Sons, Inc. (Hemphill Brothers, Inc.)	King
Ground, crushed dolomite	NA	Nanome Aggregates, Inc.	Stevens
Ground dolomite and limestone	PC	Pacific Calcium, Inc.	Okanogan
Ground dolomite	AM	Allied Minerals Inc.	Stevens
Crushed dolomite	NWM	Northwest Marble Products Co.	Stevens
Ground olivine	AC	ATMCOR	Skagit
Refractory olivine	OC	Olivine Corp.	Whatcom
Silicon	SM	Silicon Metaltech, Inc.	Chelan
Silicon	NWA	Northwest Alloys, Inc.	Stevens

imately 25 percent of the company's quicklime production is combined with recycled waste carbon dioxide from the lime plant to manufacture the high-grade calcium carbonate product. The plant is designed to produce 1- to 2-micron particles for use by the local paper industry.

Pfizer, Inc., announced plans in late 1988 to construct a PCC plant at the Weyerhaeuser Paper Company paper plant in Longview. This is the first satellite PCC plant to be built in Washington. The new plant follows a growing national trend toward building satellite PCC plants at or near pulp mills. The trend has been spurred by the increase and demand for alkaline sizing for high-quality white paper. The purpose of the plant is to convert recovered carbon dioxide, lime, and water from the lime kilns at the paper plant to form Pfizer's specialty pigment, Albacar HO, used in premium-quality white coated and uncoated paper. The PCC pigment will be pumped in slurry form directly to the adjacent paper plant to insure the availability of the carbonate product while reducing costs. Pfizer has provided a mobile plant for use at the site while the PCC plant is under construction (O'Driscoll, 1989).

Cement

More than 660,000 tons of portland cement were produced in Washington in 1988. The two plants currently producing portland cement in the state face continuing competition from imports. However, demand for portland cement in the state presently exceeds internal production. An estimated 0.8 million tons of cement and clinker were imported into Seattle in 1988, ranking the port seventh in the U.S. to receive these products. Eighteen percent of the cement imported to the U.S. from Canada and 12 percent of that imported from Japan is brought through the Port of Seattle (Ullman, 1989). Lafarge Corporation, CBR Cement, Holderbank, Lone Star Industries, and Onoda Cement Company are among the foreign importers of portland cement and clinker that have ownership of terminals in the state (Ullman, 1989). Lafarge plans to open a new 6,000-ton terminal in Seattle to be supplied from its Richmond, British Columbia, cement plant (Grancher, 1989).

Lehigh Portland Cement Company in Metaline Falls is presently the sole manufacturer of cement to mine limestone in the state. More than 240,000 tons of limestone were mined from the Champagne Placer (quarry) in 1988, resulting in the production of 171,820 tons of portland cement at the 40-year old plant. The rock is mined from the limestone unit of the Cambrian-Ordovician Metaline Formation and transported by an aerial tram to the 185,000-ton-per-year, dry-process facility. Crushed quartzite, alumina-rich material, slag,

and gypsum are added to the limestone to produce type 1-2 and type 3 portland cement; a minor amount of mortar is produced. The operation employs 59 workers. Lafarge Corporation, a large French company and one of the largest foreign exporters of cement and clinker to the U.S. (Ullman, 1989), has recently purchased the cement plant and the company's terminals in Spokane and Pasco (Grancher, 1989; Huhta, 1989).

Ideal Basic Industries, Inc., produces 490,000 tons of portland cement annually at the wet-process facility in Seattle. Limestone from Texada Island and clay from its Twin River quarry are barged to the plant site. Although it is unusual for a cement plant to be offsite from the limestone quarry, the proximity of the plant to tidewater, rail, and the market in Seattle helps the operation stay competitive. The electric rotary kiln used at the plant is reported to be one of the largest in the world. Ideal Basic is one of the top 10 cement manufacturers in the U.S.; a 67-percent interest in the company was acquired in late 1986 by the giant cement producer, Holderbank (O'Driscoll, 1989).

Ash Grove Cement West, Inc., is currently an importer of cement. The company is planning a new state-of-the-art portland cement plant on tidewater in Seattle that is scheduled to go on line in 1991. The company formerly operated a cement plant at the site. Limestone mined by the company on Texada Island will be used at the new plant; limestone is also sold to outside producers for the production of cement, lime, and calcium chloride.

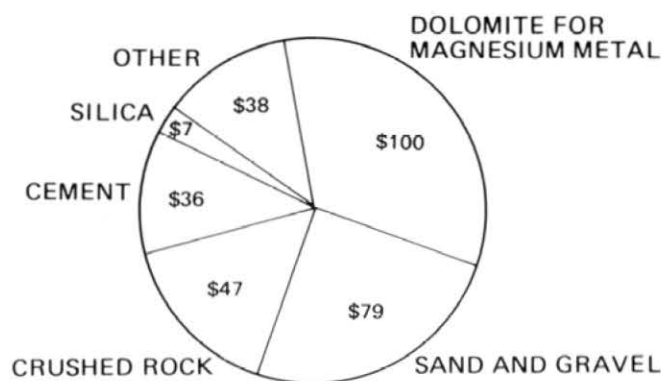
Columbia Northwest Cement Corporation, formerly the largest producer of portland cement to mine limestone in the state, was purchased by Tilbury Cement (CBR Cement) in mid-1987. The Bellingham plant is now used to grind clinker imported from CBR's plant near Vancouver, British Columbia, and the Kendall quarry located 20 mi east of Bellingham is now idle.

Ciment Quebec, Inc., announced in 1988 that it is planning to build a \$80-million, state-of-the-art, coal-fired, dry-process portland cement plant in Okanogan County near Ellisforde. If the project goes ahead, the company doing business as Interstate Portland Cement, Inc., would mine Permian limestone (98 percent CaCO_3) on the Reed Limestone property, which is currently leased by Lucky Three Mining Company.

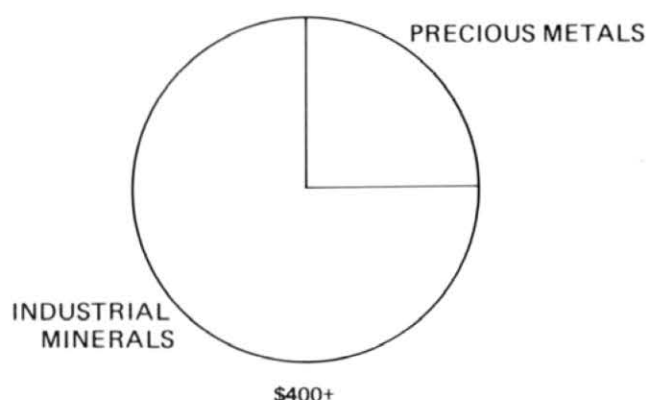
SILICA AND SILICON

Nearly 500,000 tons of silica were produced at four quarries in 1988. Lane Mountain Silica Company, which is owned by Hemphill Brothers, Inc., is the largest producer of silica in Washington and produces some of the highest quality silica products in the

INDUSTRIAL MINERALS - 1988



MINERAL PRODUCTION - 1988



FIGURES APPROXIMATED IN MILLIONS OF DOLLARS

Figure 3. Value of nonfuel minerals and industrial minerals (includes value-added processing for some minerals) in Washington in 1988. Prepared from data compiled by the U.S. Bureau of Mines and the Washington Division of Geology and Earth Resources.

Northwest. The company mined 300,000 tons of quartzite in 1988 from the Lane Mountain quarry. The quarry is in a friable area of thick-bedded, white quartzite in the lower part of the upper Proterozoic-Cambrian Addy Quartzite. The rock is crushed, ground, floated, dried, and screened at the plant in Valley (Figure 5). A new dryer and magnetic separators were installed in 1986 to produce a silica flour that is 99+ percent SiO_2 . Uses for the silica include plate glass, glass bottles, foundry sand, blasting sand, and roofing granules.

In western Washington, L-Bar Products, Inc., continues to mine silica sand from the Eocene Puget Group. The rock is reported to average between 60 and 70 percent quartz, between 15 and 20 percent feldspar, and between 10 and 20 percent kaolinite (McLucas, 1982). Sandstone from the company's Ravensdale pit is mined, washed, screened, and dried to produce silica for colored glass bottles, fiberglass, and cement. In competition with L-Bar for cement-grade silica on the west side of the state is Ash Grove Cement West, Inc., which has been mining quartzite from the Superior quarry in southern King County since 1987. The deposit is unique in that it is part of a silica cap resulting from hydrothermal alteration associated with Miocene volcanic rocks at the margin



Figure 4. Columbia River Carbonates produces fine- and ultra-fine-ground calcium carbonate at this plant in Cowlitz County. The enclosed conveyor system at the plant reduces contamination of the white rock. Photo courtesy of Columbia River Carbonates.

of a caldera (McCulla, 1986). The silica cap, which is 3.5 mi long and as much as 1 mi wide, is also being explored by others for gold. The rock is composed of 94 percent silica and less than 0.1 percent alkalis. The material is generally crushed to 1 in., and most is sold for cement, but it is suitable for other uses. Ash Grove originally explored and developed the site as a silica source for its new cement plant in Seattle, which will come on line in 1991.

Northwest Alloys, Inc., resumed quarrying silica from the Addy Quartzite at its Blue Creek quarry, where 20,000 tons of rock were mined. Renewed mining coincided with resumed production of 75 percent ferrosilicon at the Addy plant. The furnaces were shut down in 1986, when prices were lower. In 1988, when the price of ferrosilicon increased, production was restarted at the plant, which is capable of producing 50,000 tons per year. Ferrosilicon is used in the production of magnesium metal from dolomite.

Approximately 17,000 tons of silicon and ferrosilicon are produced annually at the Rock Island plant near Wenatchee. The plant, previously owned by M.A. Hanna Company, was purchased by a newly formed Seattle-based partnership, Silicon Metaltech, Inc., in 1988.

OLIVINE

Washington is one of two states to produce olivine. Olivine Corporation mines approximately 85,000 tons of olivine from the Swen Larsen quarry in Whatcom County. Here, the company obtains the fresh, unaltered olivine from the Jurassic Twin Sisters dunite, which is reported to be the largest body of olivine in the U.S. (Teague, 1983). Olivine Corporation has concentrated on the development of modular olivine slabs for both wood and municipal waste incinerators (Figure 6). These units, which use from 20 to 100 tons of olivine each, account for 95 percent of the company's revenues. These waste incinerators are marketed throughout the country and to Pacific Rim countries.

Applied Industrial Materials Corporation (AIMCOR) formerly mined an olivine-bearing till from the depleted Twin Sisters quarry. It now purchases olivine from Olivine Corporation. AIMCOR produces 10 grades of olivine for blast furnaces, refractory uses, foundry sands, blasting sands, and other applications at its plant near Hamilton. Because of the superior quality of the olivine, only dry crushing and processing are required. The product is sold domestically as well as to South America and the Pacific Rim countries. Exported products are mostly foundry sands. The olivine flour is used for sand blasting, because using olivine instead of silica sands eliminates the hazard of silicosis (Teague, 1983).



Figure 5. Mill and plant at Lane Mountain Silica quarry in Valley.

DIATOMITE

Witco Corporation is the sole producer of diatomite in the state. In 1988, the company mined 100,000 tons of diatomaceous material from three pits in Grant County. Of these, the Section 7 pit was most active. The Section 3 and 10 pit was permitted in early 1989. Although mining from that site will likely begin late 1989, the new pit will not increase total production.

The Miocene deposits consist of freshwater diatom tests deposited in lakes that formed on flows of the Columbia River Basalt Group. Ore contains almost 100 percent diatoms and has only minor amounts of clay. The average thickness of the diatom-bearing unit is 25 ft; the deposits pinch and swell and taper at the edges. Two grades, based on size of the diatoms, are recognized in mining. In several pits, the upper part of the deposit contains smaller tests than the lower part; in places, the two units are separated by a thin, green sand-bearing bed.

Diatoms are processed and calcined in Quincy. The company has two plants at the site; one is presently on standby. The combined production capacity is 90,000 tons per year (O'Driscoll, 1989). Only minor additional crushing is necessary, because the sediments are poorly consolidated. Diatoms are air separated from waste material in a tower recently built at the plant site. Then the diatoms are fired and fluxed in a kiln and air classified. The diatoms are used for filters, including filters for high-fructose sugars and juices. Smaller particles are used as filler in paint, such as highway paint.

CLAY

More than 250,000 tons of clay were mined in 1988. Major uses of the material were structural brick and cement. Most of the state's clay comes from King and Clallam Counties, with lesser amounts mined in Spokane County.

Mutual Materials Company mined more than 100,000 tons of clay and shale from two pits in King County. The clay is used for red-fired structural bricks. The company also has clay pits in Pierce, Thurston, Cowlitz, and Chelan Counties.

Ideal Basic Industries, Inc., quarries approximately 100,000 tons of clay annually from its Twin River quarry west of Port Angeles. The Oligocene mudstone is barged to the Ideal cement plant in Seattle, where it is used to make portland cement.

Structural bricks have been produced near Mica in Spokane County since 1893. The Mica plant is now a wholly-owned subsidiary of Interpace Industries, Inc., of Kirkland, Washington. The company employs 80 people and processes 15 to 20 tons of clay per day, resulting in the production of nearly 50 million off-white and colored structural and decorative bricks a year. The gas-fired, computer-controlled kiln and the plant were updated in 1987, after

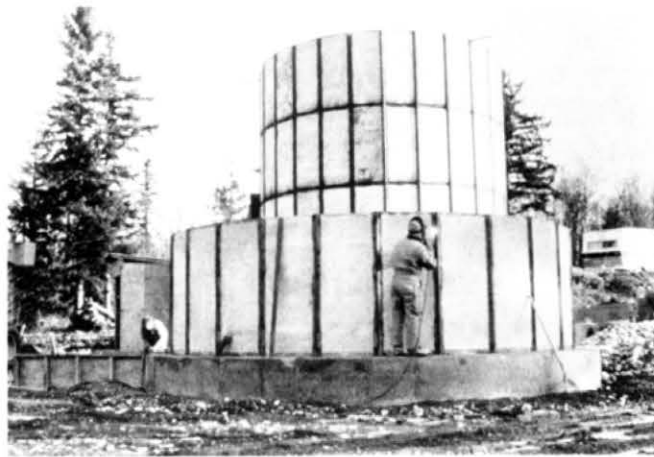


Figure 6. A wood incinerator made by Olivine Corporation using modular olivine slabs. Photo courtesy of Olivine Corporation.

the company was accepted for participation in bonds that were issued by the Washington State Community Economic Revitalization Board (*Journal of Business*, November 25, 1987).

The clay at Mica is mined from laterized lake-bed sediments of the Miocene Latah Formation. The 20-ft-thick sediments conformably overlie basalt saprolite of the Columbia River Basalt Group and unconformably overlie saprolitic Precambrian gneiss. The deposit consists of yellowish-orange to white clay and sand and is silty in places. Clay makes up 30 percent of the deposit, which contains kaolinite (as the major clay mineral) and illite (Hosterman, 1960). Al_2O_3 content of the clay is in the range of 25 to 32 percent; alkalis generally constitute less than half a percent. Saprolitic Precambrian gneiss and pre-Tertiary intrusive rocks in the area also contain residual clay reserves.

SAND AND GRAVEL

Approximately 900 pits and quarries are permitted by the state. Sand, gravel, asphalt aggregate, and other rock products produced more than \$79 million in sales revenues during 1988, according to the U.S. Bureau of Mines. A majority of the production comes from aggregate-rich, ice-margin deposits in the Puget Sound region and from late Wisconsin Lake Missoula flood deposits near Spokane.

Lone Star Northwest's facility in Steilacoom is the eighth largest sand and gravel operation in the U.S. and the only plant on the list of the top 10 producers in 1988 not located in California. Approximately 2.98 million tons of sand and gravel were produced in 1988 from the operation in Pierce County, down from 3.51 million tons produced in 1987 (Michard, 1989). While older mines in the Puget Sound area are being depleted, only one large new deposit, which is located near Shelton in the southern Puget Sound, is being permitted. The lack of new permits is the result of zoning pressures resulting from urban sprawl. Some large operators are acquiring previously permitted sites in order to circumvent the zoning process.

PRESENT EXPLORATION

Exploration for high-brightness, high-purity calcium carbonates, which was very active from 1984 to 1986, has tapered off. This boom in exploration, however, resulted in the discovery of the Wauconda Whitestone deposit, now mined by Columbia River Carbonates. Exploration is presently concentrated on the search for lump silica, talc, and clay.

United Catalyst, Inc., in joint venture with First Mississippi Gold Corporation, have been exploring for talc in a shear zone in the Precambrian Monk Formation in Pend Oreille County. Results

from several years of drilling have been encouraging, and a plan of operation has been submitted to the U.S. Forest Service for evaluation.

Basic Resources Corporation continues to conduct geological evaluation and drilling at the Rock Top property in Grant County. The company is testing deposits of nonswelling bentonite clays that formed in lakes that developed on the flow surfaces of the Columbia River basalts.

SOME AREAS OF POTENTIAL

Introduction

The potential for discovery and exploitation of industrial mineral deposits in the state is very encouraging. These deposits include barite, clay, dimension stone, dolomite, graphite, limestone, magnesite, pumice, silica, and talc. Excellent road and rail systems, increased industrial growth in the Pacific Northwest, and the reduced shipping time (in relation to other U.S. ports) from the port of Seattle to the Pacific Rim countries enhance the marketability of Washington's industrial minerals. The following is a brief description of a few areas of potential for barite, graphite, magnesite, and limestone and dolomite.

Barite

Approximately 2.1 million tons of barite that has a specific gravity of 3.9 to 4.01 and contains 80 percent BaSO₄ have been developed from the Flagstaff Mountain barite deposit in Stevens County. The open-pit, syngenetic deposit in Devonian metasedimentary rocks was drilled out and permitted, and initial mining by C.E. Combustibles had begun before the downturn in the oil industry resulted in the termination of the operation. Other barite deposits also are located in similar rocks in Stevens County.

Graphite

Flake graphite is present in schist, marble, and gneiss in Okanogan and Ferry Counties. The Boulder Creek deposit in Ferry County occurs in coarse-grained marble with high-grade metamorphic rocks of the Kettle dome. The large-tonnage deposit is reported to contain as much as 10 percent flake graphite (Valentine, 1960). The nearby Renner Lake deposit in similar rock is reported to contain as much as 7.57 percent disseminated flake graphite (Valentine, 1960). In Okanogan County, graphitic schist and gneiss that occur as roof pendants of Eocene granitic rocks (Atwater and others, 1984) were the target of limited production by American Graphite and Metal Corp in the 1940's. According to Valentine (1960), a marble lens with disseminated graphite has also been reported near the site in Haden Creek. A mill at the property ground the graphite to 20 mesh and finer. Additional occurrences of flake graphite in schists are present in Skagit and Chelan Counties; high-quality amorphous graphite is reported to occur in Yakima County (Valentine, 1960).

Limestone and dolomite

Potential for the discovery of high-purity calcium carbonate deposits is very good in the northern tier of Washington. Excellent references on calcium carbonate deposits in the state have been published by the Division of Geology and Earth Resources (Mills, 1962; Danner, 1966), and the reader is referred to those publications.

A high-purity, high-brightness white dolomitic marble occurs

throughout the northern part of the state (Mills, 1962; Danner, 1966). The deposits include large tonnage, contact-metamorphosed, high-purity, coarse-grained dolomite that ranges in age from late Proterozoic to Permian. These include deposits in the Riverside district in Okanogan County, Old Fort Spokane in Lincoln County (Bennett, 1944), along the Columbia River in Stevens County, and on Jim Creek in Pend Oreille County.

Magnesite

Quarries in Stevens County were major U.S. producers of magnesite from 1917 until the cessation of production at the Red Marble quarry in 1968. The deposits, which occur in the northeast-trending, 25-mi-long magnesite belt, are in the upper Proterozoic Stensgar Dolomite of the Deer Trail Group (Campbell and Loofbourn, 1962). The rock was originally mined to produce high-grade, dead-burned magnesite.

Although many of the deposits in the magnesite belt have been mined out, several deposits contain minable reserves. The Turk deposit in the southwest part of the belt has not been commercially exploited and is reported to contain more than 2 million tons of reserves averaging 40 percent magnesia (Bennett, 1943).

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Principal deposits of industrial minerals in Idaho

by Earl H. Bennett, Idaho Geological Survey, Morrill Hall, University of Idaho, Moscow, Idaho 83843; and Samuel W. McNary, Nathan T. Lowe, Terry R. Neumann, Richard L. Rains, Nicholas T. Zilka, Ronald T. Mayerle, Andrew M. Leszczykowski, Jerry E. Olson, and Peter N. Gabby, U.S. Bureau of Mines, Western Field Operations Center, East 360 Third Ave., Spokane, Washington 99202

INTRODUCTION

Idaho is blessed with a wealth of both metallic and nonmetallic minerals. The minerals industry is an important part of the state's economy and has contributed substantially to the state's history. This paper is an introduction to the industrial minerals and rocks that are found in Idaho. There are three sections: the first deals with industrial minerals that are actively mined and processed in Idaho or are under development, the second with minerals that have a potential for production and development, and the third with minerals that are found in the state but are not an economic resource at this time.

Part of this paper is abstracted from a much more complete publication on the state's industrial minerals by the U.S. Bureau of Mines (BOM) entitled "Principal Deposits of Industrial Minerals (Excluding Phosphate) in Idaho." We have added a section on phosphate to our paper, making it a brief review of all industrial minerals in Idaho. Readers are referred to the BOM text for a more elaborate treatment of these commodities.

The value of industrial minerals in Idaho varies considerably from year to year. For example, in 1987, industrial minerals mined in the state were worth about \$91 million or about 27 percent of the \$339 million value of all nonfuel minerals produced. In 1986, the industrials were valued at about \$138 million or about 50 percent of the value for all minerals of \$269 million. Idaho ranks first in the country in garnet production and fourth in pumice production. The state's mines and plants produce about 10 percent of the nation's phosphate, and one plant leads the nation in vanadium production, utilizing a by-product of phosphate processing. As elsewhere, important commodities such as sand and gravel, stone, and cement are major construction materials upon which much of the state is built.

Idaho miners are the highest paid industrial workers in the state, and several counties receive substantial income from taxes and federal lease returns on mining products. Industrial minerals are indeed an important part of our mining industry.

ACTIVE RESOURCES

Phosphate rock, by Nathan T. Lowe

Southeast Idaho is the leading phosphate-producing area in the western United States (Figures 1 and 2), producing about 10 percent of the nation's phosphate products. The value of phosphate production in Idaho was about \$120 million in 1988, an excellent year with all plants running at near capacity. Employment in the phosphate industry is substantial, with FMC, Simplot, NuWest, and Monsanto each employing about 500 in mining and processing.

There are two basic products generated from phosphate mining in Idaho: elemental phosphorus, which has a wide variety of uses (FMC, Monsanto, and Stauffer Chemical), and various grades of phosphoric acid for use in agricultural fertilizers (NuWest and J.R. Simplot). Nationwide, about 10 percent of phosphate production is used to make elemental phosphorus and 90 percent for fertilizer production. All of the mines in Idaho are in the Phosphoria Formation of Permian age and are open-pit operations. About 5 million metric tons of phosphate ore were mined in the state in 1988.

Phosphoric acid is made by mixing sulfuric acid with phosphate ore to make various grades of phosphoric acid. The elemental process uses large electric furnaces to melt the phosphate ore at 2,700 °F and volatilize elemental phosphorus, which is then recovered. Ore grades are controlled to provide about 30 percent

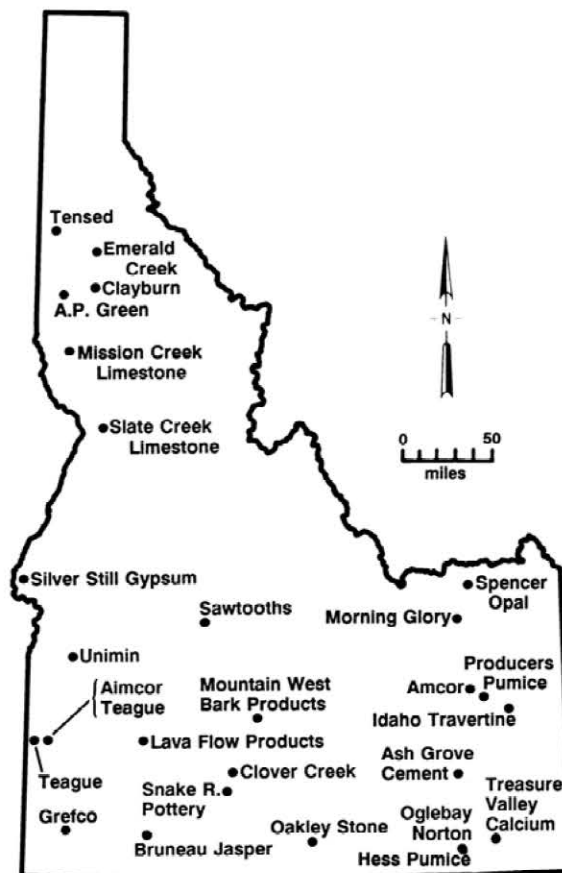


Figure 1. The location of active industrial mineral mines and plants in Idaho.

P₂O₅ for acid (fertilizer) production and 25 percent P₂O₅ for elemental phosphorus production.

Historically, the Waterloo Mine (Montpelier district) is the oldest mine in the Western Phosphate Field, first producing in 1906. The mine remained the only Idaho producer until 1917, when the Western Phosphate Mining and Manufacturing Company developed a mine in Paris Canyon. The Waterloo, which was shut down in 1928, reopened in 1945 as the first open-pit phosphate operation in Idaho. The mine operated intermittently until 1961.

In 1919, Anaconda Copper Mining Company (later to become the Anaconda Company) developed the Conda Mine north of Soda Springs; it became one of the largest underground phosphate mines in the Western Field. The Conda operation was purchased by J.R. Simplot Company in 1959. Ore from the Conda and Gay Mines fed the company's big fertilizer operation at Pocatello. Currently, Simplot obtains ore from the Smoky Canyon Mine near the Idaho-Wyoming border. The ore is slurried at the mine and pumped through an 8-in.-diameter pipeline to a calcining

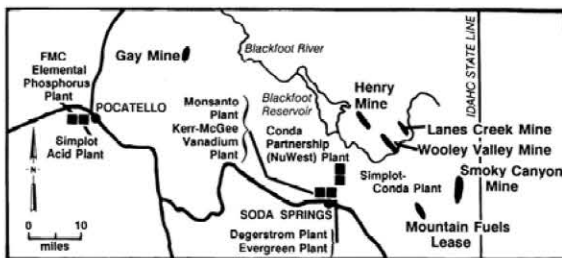


Figure 2. Locations of phosphate mines and plants in southeast Idaho.

plant 22 mi away at Conda. The company plans on adding an additional 61-mi-long pipeline to pump slurried phosphate direct from the mine to Pocatello.

Baker Industries formed the Conda Partnership with Western Cooperative Fertilizer (Calgary, Canada) in 1979. Baker purchased a fertilizer plant at Conda and mines in Dry Valley from El Paso Products, Inc., in 1972. The company operated until 1985, when Baker filed for bankruptcy. The Partnership's operations were closed until 1987, when a new company, Nu-West, purchased Baker's Idaho operation and reopened the fertilizer plant and the Partnership's mines. The company had an excellent year in 1988, its first full year in business.

In 1949, Westvaco built the first elemental phosphorus plant in Idaho at Pocatello. FMC purchased the plant the same year and made it into the largest elemental phosphorus plant in the world. FMC gets ore from the nearly depleted Gay Mine on the Fort Hall Indian Reservation. As noted, Simplot also obtained ore from this mine. FMC will open a new mine in Dry Valley to replace the Gay in 1990. Monsanto built its elemental plant at Soda Springs in 1952. The company mines about 1 million tons of phosphate ore per year from the Henry mine. Stauffer Chemical (a subsidiary of Rhone-Poulenc) ships ore from the Wooley Valley Mine to its elemental plant at Silver Bow, Montana.

Several by-products from Monsanto's elemental plant are used by other companies. Kerr-McGee extracts vanadium from ferro-phosphorus slag. The plant is the largest producer of vanadium in the country. The waste from Kerr-McGee's plant is used by Evergreen Resources, Inc., to make special iron-rich fertilizers. Degerstrom, Inc., is constructing a plant to extract gallium, silver, and other metals from another Monsanto waste called "treater dust."

Pumice and pumicite, by Terry R. Neumann

Idaho was ranked fourth in the Nation for pumice production in 1987. Production came from three commercial operations in southeastern Idaho (Figure 1). No significant production of pumicite (volcanic ash) has taken place in the State.

Hess Pumice Products, Idaho's largest pumice producer, operates the Wrights Creek Mine north of Malad in Oneida County. The company began production in 1958. During the construction boom years of the 1970's, Hess expanded its market, producing up to 50,000 short tons of processed pumice a year. In 1985, the company completed construction on a new \$1.7 million automated pumice processing plant at Malad City. Processed pumice from the plant is sold for use as an abrasive in soaps and cleaning compounds, for industrial abrasive applications, as aggregate in lightweight building blocks, and as a filler. The company, which is one of the Nation's major producers of ground pumice products, has ore reserves in excess of 10 million short tons of crude pumice.

The second largest pumice producer in Idaho is Amcor, Inc., of Idaho Falls. Amcor, previously known as Idaho Pumice Products and Clark Concrete Products, quarried several thousand short tons of pumice in 1987 from its Fan Creek and other claims located near Ammon in Bonneville County. The company mines a red,

scoriaceous material from five pits located along the west flank of the Blackfoot Mountains. The material is trucked to Idaho Falls, where it is crushed, screened, and manufactured into a lightweight building block.

Producers Pumice Company, a subsidiary of Builders Market Place, Inc., of Meridian, Idaho, mines pumice from the Rock Hollow Mine near Ammon (Figure 1.) The open-pit mine produces several thousand short tons of white pumice annually. The pumice is shipped by rail to Meridian, where it is crushed, screened, and manufactured into building block.

Perlite, by Terry R. Neumann

In 1960, Oneida Perlite Corporation began development of the Oneida deposit. Some of the crude perlite was expanded at the company-owned plant in Malad City and was used regionally for plaster aggregate, concrete aggregate, soil conditioner, and insulating material. In the 1970's and early 1980's, the company manufactured expanded perlite under the trade name Perlcor, utilizing the product for industrial fillers and fireproofing and as a filtering medium.

Oglebay Norton Company (Figure 1) purchased the Oneida deposit in December 1986. Since acquisition, Oglebay Norton and its subsidiary, National Perlite, have increased production, shipping bulk perlite to expanding plants throughout the United States and western Canada. At its plant in Malad, the company also processes expanded perlite that is sold locally for horticulture, cryogenic

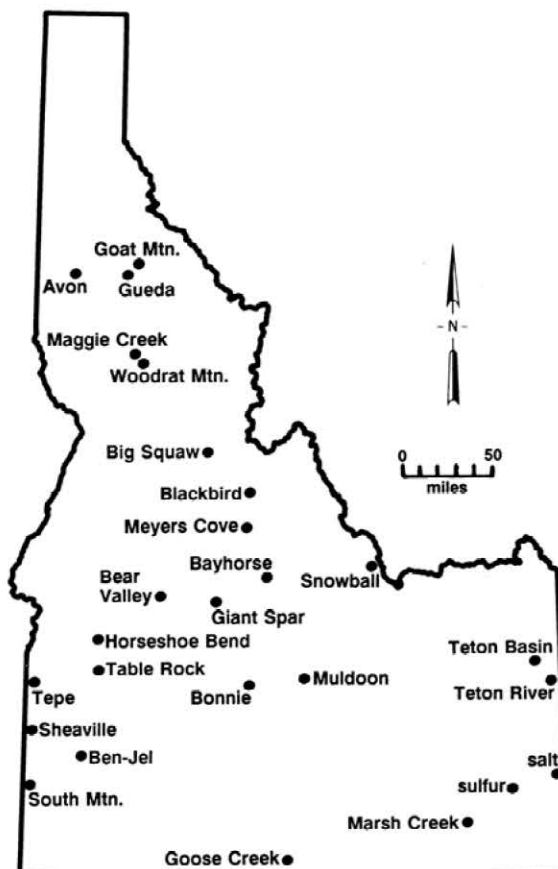


Figure 3. The location of inactive industrial mineral resources in Idaho.

uses, filter aid, loose-fill insulation, and aggregate. National Perlite reports 2.6 million short tons of drill-proven reserves, as well as extensive indicated reserves, at its Oneida deposit, reportedly one of the largest in North America.

A substantial perlite deposit occurs in the Cow Creek basin near Sheaville, Oregon (Figure 3), along the Idaho-Oregon border, but the major portion of the deposit is in Oregon, with only a slight overlap into Idaho. Other known occurrences of perlite in Idaho are on Picket Pin Creek, Ada County; in the Murphy-Silver City area, the Delamar district and near Jordan Creek in Owyhee County; in the Ammon area, Bonneville County; and in the China Hat area, Caribou County.

Garnet (industrial), by Richard L. Rains

Although garnet was discovered in Idaho about 1880, the Idaho garnet industry did not get started until the early 1940's. Two companies, Idaho Garnet Abrasive Company and Garnet Mines, Inc., produced garnet in Benewah County for West Coast markets. In 1979, Emerald Creek Garnet Company bought Idaho Abrasive Company. Emerald Creek (Figure 1) mines garnet from both Emerald and Carpenter Creeks on Federal and privately owned property. The company has six producing mining operations (draglines and washing plants) and two jig plants that wash and concentrate the garnet. From the jig plants, the garnet is hauled by truck to the mill south of Fernwood, where it is dried, crushed, sized, screened, and bagged for shipment. Since 1981, Idaho has been ranked first in the nation in garnet production, and Emerald Creek has been the largest producer of abrasive garnet in the United States.

Clay, by Richard L. Rains

Six companies are currently mining clay in Idaho: two for refractory clay, two for bentonite, and two for common clay. The markets for refractory clay have decreased because of the depressed lumber and aluminum industries. The decline of oil and gas exploration has severely limited the markets for bentonite.

A.P. Green Industries Company (Figure 1), which recently was divested from U.S. Gypsum (USG) Corporation, operates a small refractory brick plant at Troy, Idaho. The plant employs 10 to 12 people year-round and processes about 5,000 short tons of clay per year (about 50 percent of capacity). Clay is mined from pits near Helmer and is hauled by truck to the plant in Troy. High-duty and super-duty bricks are manufactured in more than 100 different shapes. The primary market is the lumber industry, where the bricks are used as liners in burners and driers.

J.R. Simplot Company began mining clay, which it marketed as a paper filler, from the Bovill clay deposit in 1960. Because of the limited market for paper filler in the Pacific Northwest and the high processing costs necessary to meet stringent specifications of the paper manufacturers, Simplot ceased operations in 1974. At present, Clayburn Industry, Ltd., (Figure 1) subleases the Bovill clay deposit from Simplot. Clayburn ships calcined clay to Abbotsford, B.C., Canada, where it is processed into super-duty and 70-percent alumina bricks.

E.J. Wilson and Sons mines 2,000 to 3,000 short tons of bentonite each summer from patented claims near Lidy Hot Springs, Clark County. The bentonite is used as an impervious lining for ponds and water ditches and as a binder for hay pellets, animal feeds, and fertilizers.

Small amounts of bentonite have been mined from the Ben-Jel Mine in Owyhee County. Historically, this bentonite has been used for pond, ditch, and potato cellar linings and oil and gas well drilling muds. Applied Industrial Materials Corporation (AIMCOR) has mined 5,000 short tons for testing in new specialty clay markets.

Interpace Corporation of Mica, Washington, is hauling common clay from the Tensed Mine in Benewah County to Mica, where it is mixed with Washington clay to produce desired colors for structural and facing brick. Because of the uniqueness of the color,

these bricks are shipped throughout the Nation.

Snake River Pottery is mining small amounts of common clay from the Hagerman Valley clay deposit in Twin Falls County. The operation, which employs six people, manufactures custom decorative tile for bathrooms and kitchens.

Silica, by Richard L. Rains

Unimin Corporation (Figure 1), the largest silica sand producer in the United States, operates a plant at Emmett, Gem County, and is the only silica sand producer currently operating in Idaho. The company obtains sand from pits in ancient lake bed deposits. Its sand is marketed mainly in the Pacific Northwest for container glass, foundry molds, sand blasting, filtration, and roofing granules. Gem Silica Company, a predecessor to Unimin Corporation, started operation in 1949, selling various grades of chicken and turkey grits. Later, it marketed blasting sand, primarily to the U.S. Navy.

The two largest quartzite operations in Idaho are the Monsanto Quarry and the Kit Quarry (operated by FMC) (Figure 2). Both Monsanto and FMC are vertically integrated companies and are not currently marketing any metallurgical-grade quartzite. Both companies mine, crush, and size quartzite for use as flux in the recovery process for elemental phosphorus.

A small amount of quartzite is mined near Inkom for manufacturing cement at Ash Grove Cement West (Figure 1). Idaho Quartzite Company is currently trying to market metallurgical-grade quartzite from a deposit south of Oakley, Idaho.

Zeolites, by Nicholas T. Zilka

Domestic exploration for natural zeolites began in the late 1950's, when Union Carbide became interested in alternate sources of, and potential competition against, the zeolites it was synthesizing. In 1962, Union Carbide personnel discovered the Castle Creek deposit near Oreana in Owyhee County. Since then, additional deposits have been identified, but low demand has probably precluded discovery of all deposits.

The only producer, Teague Mineral Products, mines zeolite from a pit on the Idaho-Oregon border (Figure 1) just north of U.S. Highway 95; however, most of its 1987 production (6,700 short tons) came from two pits near its plant at Adrian, Oregon. The company mines clinoptilolite ore, which it crushes, mills, or micronizes to the size required by the end use: anti-caking agents, odor control, fillers in paint and glue, and additives to agricultural products. The company controls the eastern portion of the Castle Creek deposit and is test-marketing samples, especially for pollution abatement. The western portion of the Castle Creek deposit is owned by Double Eagle Petroleum and Mining Company and leased to Applied Industrial Materials Corporation (AIMCOR) (Figure 1). AIMCOR is optimistic about the future of the deposit and is currently conducting market research.

A deposit on the Idaho-Oregon border near Sheaville was initially mined by Occidental Minerals, acquired by Phelps Dodge Corporation in 1983, bought by Tenneco Minerals in 1986, and purchased by Steelhead Resources Ltd. in 1987. Steelhead is evaluating the deposit and identifying markets.

Diatomite, by Ronald T. Mayerle

Idaho does not have any active diatomite producers, and past production from at least nine deposits has been minor. Records are incomplete; however, the State reportedly produced 980 short tons from 1927-1944 and probably about 2,000 additional short tons since then. The bulk of the production apparently came from the Clover Creek deposit (Figure 1). The first production from the deposit, about 1930, consisted of two rail cars that were reportedly shipped to a sugar factory in Utah for probable use as a filter aid. In the mid-1930's, the deposit yielded about 50 to 150 short tons/year for use as insulation. In the 1950's and 1960's, about 100 short tons/year was mined for use as an athletic field

marker. Minor amounts were used for other purposes. Recently, the American Diatomite Company sent 20 short tons to Japan for testing as a component of wallboard. Total production from the deposit to date has been about 2,500 short tons.

Production from the other Idaho deposits has been intermittent and probably totals about 500 short tons. The diatomite was used for insulation, as a filter media for sugar refining, and for other miscellaneous applications. Grefco is evaluating a diatomite deposit in Owyhee County (Figure 1) that is very pure but is far from transportation systems.

Gypsum, by Andrew M. Leszykowski

The existence of gypsum deposits in Idaho has been known since the late 1800's, when deposits were discovered along the Snake River on the Idaho-Oregon border. Other deposits of gypsum are known in Lemhi Valley near Leadore, on Iron Mountain near the old townsite of Mineral, in Dry Lake near Nampa, and in Montpelier Canyon near Montpelier.

The gypsum deposits near the Snake River were claimed in 1912 but were not explored until 1951. No record of mining was found, but the remains of a loading facility were found at the deposit. A small amount of gypsum was probably mined from the deposit by the Weiser Cooperative; however, this deposit is at a stage where no more ore will be produced unless extensive and expensive underground mining operations are undertaken. Gypsum was discovered in 1923 near Iron Mountain (now called Sturgill Mountain), and about 10,000 short tons of gypsum were mined from the deposit from 1971 to 1973. The gypsum, mined by the Weiser Cooperative, was used for local agricultural operations. In 1987, mining resumed at this deposit, and 10,000 short tons of gypsum was produced by the Silver Still Gypsum Company of Weiser (Figure 1). Ore is mined currently on an as-needed basis, and is sold to the Simplot Company for use as a soil additive.

The Snowball (Figure 3), a large gypsum deposit in Lemhi County, was discovered in 1961 and mined by E.J. Wilson and Sons from 1964 to 1977. Between 1964 and 1975, approximately 93,000 short tons of gypsum was sold to the Idaho Portland Cement Company at Inkom. Gypsum for local agriculture (about 24,000 short tons) was sold from 1968 to 1982. Claims comprising the Snowball Mine were patented in 1984, but no further work has been done at the mine.

Limestone, by Jerry E. Olson

Deposits of limestone occur predominantly in the southeast, west-central, and northern parts of Idaho. Since 1892, the first year of recorded limestone production in Idaho, carbonate-bearing rocks have been quarried from pits as far north as Lake Pend Oreille and as far south as the southeast corner of Idaho near Montpelier. Numerous small operations for local use have operated intermittently throughout much of the State.

The only operating limestone quarry of significant size in Idaho today provides material for the Ash Grove West Cement plant at Inkom (Figure 1). The Inkom plant produces over 200,000 short tons of cement per year from about 340,000 short tons of limestone mined from a quarry on site. Smaller limestone operations include Treasure Valley Calcium, which ships to J.R. Simplot's fertilizer plant at Pocatello; the Morning Glory Mine, which produces lime for use as an animal feed supplement; and the Mission Creek quarry, which is operated by the Nez Perce Indians and which produced limestone for Potlatch Corporation's paper plant at Lewiston (Figure 1).

Currently, the largest consumer of limestone in Idaho is the Amalgamated Sugar Company with plants in Twin Falls, Nampa, Rupert, and on the Oregon-Idaho border at Nyssa, Oregon. Collectively, these operations consumed over 230,000 short tons of limestone in 1987. However, all of this lime is imported from Durkee, Oregon.

Dimension stone, by Terry R. Neumann

Stone has been used for building purposes in Idaho since the arrival of the first settlers. The earliest commercial building stone operation in Idaho was at the Table Rock sandstone quarry near Boise. The Boise Stone Company was the first company equipped with saws capable of working large blocks of stone. Sandstone from Table Rock (Figure 3) was used for some of Boise's most prominent early buildings, including the assay office in 1869, and, in later years, the State Capital, St. John's Cathedral, and Boise High School. By the 1920's, sandstone from the Table Rock quarry was used in buildings across the United States and Canada. The Table Rock quarry is still intermittently active, providing small quantities of stone for local use.

By the 1920's and 1930's, the increased popularity of lower cost steel and concrete construction eliminated the need for stone for load-bearing structural use. Today, stone produced in Idaho is used exclusively for decorative purposes, either as a facing veneer stone on the exterior or interior of buildings or as a flagstone. Three areas within southern Idaho produce stone for these purposes.

Idaho Travertine (Figure 1) operates the Fall Creek and Medicine Lodge Creek quarries in southeastern Idaho. The plant began production in 1968 under the name Gem State Stone. Later the operation was run by The Marble Shop, Inc., the nation's largest travertine dimension stone outlet. Idaho Travertine bought the operation in 1988. Since initial production, an average of 70,000 ft³ of travertine has been quarried annually. Travertine, mainly from the Fall Creek quarry, is trucked to Idaho Falls, where it is cut to customer specifications. The company provides facing stone and floor tiles to national and international markets.

Quartzite is quarried by three companies near Oakley (Figure 1) in Cassia County for flagstone and decorative facing stone. Idaho Quartzite Corporation mines quartzite from the Emigrant Canyon quarries; other stone producers in Oakley include Northern Stone Supply and Oakley Valley Stone. The micaceous quartzite, sold under the trade name of Rocky Mountain Quartzite or Oakley Stone, has been mined and sold in significant quantities since 1948.

Two companies, Lava Flow Products and Mountain West Bark, package basaltic scoria for use in gas barbecues and for landscaping and other decorative purposes (Figure 1). Basaltic lava is mined for use as a decorative building stone in a number of locations across south-central and southeastern Idaho.

Gemstones, by Ronald T. Mayerle

Because of the variety and number of locations of natural gemstones in the State, Idaho is known as the Gem State. Garnet (including star garnet, the State gem), opal, aquamarine, quartz crystals, and jasper are the main gemstones; however, numerous other gem minerals have been produced in the past, and still contribute substantially to the gemstone economy of Idaho.

For many years, much of the production of rough gemstones and mineral specimens in Idaho has been by or for rockhounds. Much of the gemstone material (finished or unfinished) and mineral specimens are given as gifts or sold or traded to personal acquaintances, to rock shops, or at gem and mineral shows.

At present, there are a number of producing localities in the State. The five most important are the Spencer opal mine, the Emerald Creek star garnet area, the North Fork and Little North Fork of the Clearwater River (including Dworshak Reservoir), the Sawtooth batholith (aquamarine and smoky quartz), and the Bruneau jasper mines (Figure 1). An important past producer with a potential for future production is the Tepe opal mine, and a possibly important new find is the Gueda sapphire deposit (Figure 3).

A great number and variety of mineral specimens (including ore specimens) have been recovered in Idaho. These include galena, pyrite, anglesite, cerussite, malachite, azurite, agate, fossils, petrified wood, and numerous others. Of special importance was pyromor-

phite from the Bunker Hill lead-zinc-silver mine and other mines in the Coeur d'Alene mining district. About 1980, a number of exceptional, world-class specimens from this mine were sold for a six-figure sum. Important specimens of ilvaite and hedenbergite have come from the South Mountain lead-zinc-copper-silver mines in Owyhee County and vivianite and ludlamite specimens from the Blackbird cobalt mine in Lemhi County (Figure 3).

Sand and gravel and crushed stone (aggregate), by Peter N. Gabby

In 1986, 5,708,000 short tons of construction sand and gravel were removed from 78 pits in Idaho. In 1987, 3,852,000 short tons of crushed stone aggregate from 52 quarries were produced in the State. Mineral aggregate needs in Idaho are dominated by road construction and maintenance.

A survey indicates that Idaho has at least 700 significant sources of aggregate. One hundred ninety are owned or leased by the State Department of Transportation, 170 by the USFS, 250 by county and local highway districts, and 95 by commercial operators. Federal, State, and local government agencies that use aggregates own 320 significant sources.

POTENTIAL RESOURCES

Barite, by Andrew M. Leszykowski

An occurrence of barite (Bonnie Barite Mine, Figure 3) was discovered in the early 1900's in Blaine County, just west of Hailey. Minor production of barite occurred in Idaho from 1922 to 1946. Near the end of World War II, Kaiser Shipyards of Portland, Oregon, proposed using 15,000 to 20,000 short tons of barite from the Bonnie Barite Mine for ship ballast. The war ended before the arrangements were completed. In 1947, initial production of barite from the Bonnie Barite Mine commenced. Barite production from the mine has been sporadic, but 170,000 short tons have been mined for drilling mud. The last production from this mine was in 1982.

The Muldoon Barium Company (Figure 3) produced 2,400 short tons of barite in the early 1950's from its mine at Muldoon, east of Hailey in Blaine County. This barite went to the Atomic Energy Commission at Arco for use in reactor shielding. Except for a bulk sample of 3,000 short tons mined and stockpiled in 1987, this is the only known production from the Muldoon Mine. In 1979, a large barite vein was discovered at the Hoodoo Mine east of Stanley, Idaho, in Custer County.

Coal, by Andrew M. Leszykowski

Minable coal in Idaho occurs primarily in three geographic areas: the Horseshoe Bend area, the Goose Creek Field in Cassia County, and the Teton Coal Field in eastern Idaho (Figure 3). Numerous other coal occurrences are reported in Idaho. Most of these occurrences are not of economic significance because they consist of thin seams of low-grade coal (lignite or subbituminous) or coaly shale.

The Teton Coal Field is in Teton, Bonneville, Bingham, and Caribou Counties in eastern Idaho and includes the Horseshoe Creek, Pine Creek, and Willow-Caribou districts. This area has had the largest coal production in Idaho; an estimated total of 100,000 short tons has been produced from several mines (Mikesell, Boise, Brown Bear, Horseshoe, Idaho, Pintar, Progressive, Blacksmith, Hillman, Driggs, Packsaddle, and Samuels). Most of the production is occurred in the years 1913-1917, 1927-1929, 1931-1932, and 1948-1952. No production is recorded in recent years.

The Teton field has been estimated to contain indicated and inferred coal resources of approximately 14,000,000 short tons in four beds (the Boise, Brown Bear, Horseshoe, and Progressive). Coal in the basin is good-quality subbituminous and bituminous with Btu ratings of 7,000 to 14,000. The coal, which is found

in steeply dipping seams, must be extracted by underground mining methods that are more costly than open-pit methods used in other western coal deposits.

The Goose Creek Coal Field is in southern Cassia County near the juncture of Idaho, Nevada, and Utah. Numerous prospects are found in the area; however, the only known production has been from the Worthington Mine, about 1.5 mi north of the Idaho border, which produced lignite for local consumption.

The Horseshoe Bend area is in Boise County, approximately 30 mi north of Boise. Of the several coal occurrences in the area, only the Henry Mine and the Gaston Mine have produced coal (amount unknown), primarily for local consumption. The Henry Mine operated in 1910 and produced subbituminous coal having a Btu rating of 14,040. In 1938, lignite was mined from a 4-ft-thick bed at the Gaston.

Fluorspar, by Ronald T. Mayerle

Idaho's most important fluorspar localities are the Giant Spar Mine area in the Stanley mining district; the Meyers Cove deposits in the Gravel Range district; the Pacific, Keystone, and Kraken Hill Mines in the Bayhorse district; and the Big Squaw Creek Prospect in the Frank Church River of No Return Wilderness Area (Figure 3). Some of the deposits produced small to moderate amounts of precious and base metals as early as the late 1800's, but the fluorspar was either not recognized or was not considered a potentially economic mineral until World War II, when it was included on the list of strategic and critical minerals.

The first production from a primary fluorspar locality was during or shortly after World War II, when a few truckloads of unknown grade were shipped from the Giant Spar Mine. From 1951 to 1953, 37,432 short tons of ore from the Meyers Cove deposits were treated at a local mill. In 1952 and 1953, the Chalspar Mine in the Bayhorse district produced 475 short tons of metallurgical-grade fluorspar (88 percent CaF_2) and 245 short tons of milling-grade fluorspar (55 percent CaF_2); the milling-grade ore was probably treated at the Meyers Cove mill. Fluorspar mining in this area of Idaho came to a halt in 1953, when the Meyers Cove mill was destroyed by fire. In 1971, after construction of another mill, the Meyers Cove deposits were again mined, but operations ceased after a short time because of milling problems. No fluorspar mines are currently active in Idaho. In Idaho, the six major fluorspar localities, none of which are large, contain an estimated 2 million short tons of contained fluorspar and have potential for discovery of additional significant tonnages.

Kyanite, by Nicholas T. Zilka

Although kyanite occurs at several localities within the State, only the Woodrat Mountain and Goat Mountain-Monumental-Smith Ridge areas in Idaho and Clearwater Counties (Figure 3) contain significant resources. Geologic, beneficiation, and marketing studies by the Bureau in the 1960's indicate that (1) deposits in these areas contain at least 3.2 billion short tons of material averaging 15 percent kyanite; (2) kyanite can be concentrated by a combination of gravity, flotation, and electromagnetic methods; and (3) a western market is needed for economic production. The Woodrat Mountain deposit was explored in the 1960's by Sunshine Mining Company and in the 1970's by Ethyl Corporation. A preliminary cost analysis of the Woodrat Mountain deposit shows that if markets in the western United States or Pacific Rim countries were to expand, the Woodrat deposit, and possibly others, could be mined profitably.

Peat, by Andrew M. Leszykowski

Peat occurrences in Idaho are located in three general areas and consist of reed-sedge and humus-type deposits. Southeastern Idaho deposits occur in small, swampy flats; central Idaho deposits in small, high-alpine basins; and northern Idaho deposits in ponds, lakes, and swampy areas near streams or rivers.

Idaho has no recorded tonnage of peat production or any estimate of reserves. Peat has been mined from two deposits, one on Marsh Creek near Downey in Bannock County and another on the Teton River in Teton County (Figure 3).

The deposits in central Idaho are generally too small to be considered minable, and they are also remote from the urban market areas. Peat deposits in northern Idaho (Kootenai, Bonner, Boundary, and Shoshone Counties) have potential because of their assumed size and proximity to market areas in northern Idaho and eastern Washington.

Blacksands (rare earths), by Earl H. Bennett

With the recent progress made in developing super conductors and microelectronics, there has been a growing interest in rare earth elements (REE's). A number of REE's occur in blacksand placer deposits in Idaho. Most of these deposits are found in alluvial-filled valleys, where blacksands weathered from rocks of the Idaho batholith have accumulated. There are about a dozen deposits in Idaho that are thought to contain significant blacksand reserves. Minerals in the blacksands include monazite, euxenite, columbite, allanite, sphene, garnet, zircon, ilmenite, and magnetite. The monazite and euxenite contain the REE's that are of current interest.

Porter Brothers Corporation began a major operation to reclaim uranium from blacksands in Bear Valley in 1955 (Figure 3). The company built a jig plant and used two bucketline dredges to mine blacksands. The dredge concentrate was treated in a mill at Lowman about 20 mi to the south of the mining operation. Columbite-euxenite and monazite concentrates were produced. The concentrates, containing 90 percent niobium-tantalum pentoxide and uranium, were sold to the U.S. Government. The operation accounted for most of the domestic production of columbite and tantalum in the late 1950's until the operation closed down in 1959 due to cancellation of the government contract.

SUBECONOMIC RESOURCES

Asbestos, by Ronald T. Mayerle

Idaho has no active asbestos producers; past production came only from the Kamiah deposits in the Maggie Creek mining district in Idaho County (Figure 3). The deposits yielded anthophyllite asbestos sporadically from 1910 through 1929. The total production, mostly from surface workings, was small. The asbestos was used for fire brick, pipe and boiler covering, wall plaster, and paint and as a binder in cements and asphalt.

Mica, by Richard L. Rains

Forty-two mica occurrences have been documented in twelve Idaho counties, but records of production exist only for Adams, Idaho, and Latah Counties. Most of the mica mined in Idaho has come from the Avon mining district in Latah County (Figure 3), where in 1888, the first recorded mica production in Idaho was

from the Muscovite Mine. During World War I, mica production was small. It was not until World War II created a large demand that significant amounts of mica were produced in Idaho. The Colonial Mica Corporation, a custom rifting and mica purchasing office, was established in Latah County in 1943. Stimulated by government price supports, Colonial and the U.S. Bureau of Mines produced more than 1.5 million pounds of crude mica from 1943 to 1945, mostly from the Muscovite Mine. When the price supports were dropped in 1945, all of the mica mines shut down. In 1950, the first of several Executive Orders initiated a second government price support program that lasted until 1964. Under this program, several properties in the Avon district produced mica, but again, only the production of the Muscovite Mine was significant. No mica has been produced in Idaho since 1964.

Salt, by Nicholas T. Zilka

Brine from springs along Stump, Tygee, and Crow Creeks near the Idaho-Wyoming border, was evaporated in the early days in troughs over wood fires. The Oneida Salt Works, formed in 1866, sold salt to immigrants traveling west and to local residents. Other similar operations followed. The salt was used for food and for beneficiation (roasting) of precious metal ores. Peak production, 800 short tons, was in 1884. In the late 1880's, development of regional railroad systems made the Idaho deposits uncompetitive. Rock salt was discovered in 1902 at depth beneath the springs (Figure 3), eliminating the cost of processing brine, but market conditions continued to decline. Today, the salt is only used locally for stock.

Sulfur, by Andrew M. Leszczykowski

The existence of elemental sulfur in Idaho has been known since 1872, but no effort was made to delineate the extent or grade of the occurrence. In 1901 and 1902, the Western Sulfur Company of Duluth, Minnesota, erected a plant and mined sulfur from deposits about 4 mi east of Soda Springs (Figure 3). The project failed, and the plant was abandoned and later (1910) dismantled. No record of the tonnage of ore mined or sulfur produced could be found. In 1918, World War I created a demand for sulfur, and the Idaho Sulfur Company reopened the mine. A retorting facility having the capacity to produce 50 million tons of sulfur per day was planned. The plant was to be in full operation by early 1919. The war ended before the plant became operational; the project was abandoned, and no sulfur was produced.

Although several claims have been filed for sulfur, no record could be found for sulfur production from any deposit in Idaho. Most of the claims are in an area 4 mi southeast of Soda Springs.

REFERENCE CITED

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Montana's industrial minerals

by Richard B. Berg, Montana Bureau of Mines and Geology, Montana College of Mineral Science and Technology, Butte, Montana 59701

ABSTRACT

Because of Montana's diverse geology, more than thirty industrial mineral commodities occur in the state. Twelve of these are now being produced, mainly for out-of-state markets, and eight others have been mined in the past. Market and transportation constraints limit the mining of others.

Very pure talc from Archean dolomitic marble is mined at four localities for use in paints, paper, ceramics, plastics, and cosmetics. Chlorite veins in Precambrian quartzofeldspathic gneiss are mined at the only chlorite mine in the U.S. Several million tons of vermiculite has been mined from the Libby deposit, where this mineral formed by weathering of the biotite core of a Jurassic ultramafic body. A Tertiary-age lamprophyre dike at Yogo in central Montana yields blue sapphires; sapphires are also recovered from placers in western Montana. Since 1929, phosphate from the Permian Phosphoria Formation has been mined in the Garrison district.

Barite is mined from veins in metasedimentary rocks of the Belt Supergroup. Travertine from extensive deposits north of Yellowstone National Park is quarried for facing. Marine Cretaceous formations are a source of bentonite now primarily used for engineering applications. Gypsum from the Kibbey Formation of the Mississippian Big Snowy Group is sold to cement plants. Limestone is quarried by two cement manufacturers, one lime manufacturer, and also for use in sugar beet refining. Sand and gravel from fluvial deposits is provided for local markets, and crushed stone for railroad ballast is produced from two quarries.

Fluorspar, silica, kaolinitic clay, brick clay, graphite, mica, optical calcite, and asbestos have been mined in Montana but because of changing market conditions are no longer mined.

A number of other commodities known to occur in Montana are undeveloped either because of lack of markets, transportation constraints, or lack of information on the extent of the deposits. Corundum and sillimanite deposits occur in Archean metamorphic rocks of southwestern Montana. These metamorphic rocks also have contributed garnets to alluvial deposits. Carbonatite bodies in Precambrian rocks in southwestern Montana contain rare earths, and monazite is reported in several placer deposits. Paleozoic formations contain large reserves of high-purity limestone and dolomite. In the subsurface of eastern Montana, Mississippian and Devonian formations contain extensive salt and potash beds. Eocene alkalic igneous rocks in central Montana, some syenitic, are a possible feldspar resource. Tertiary sedimentary rocks in southwestern Montana contain diatomaceous earth and tuffaceous beds suitable for pozzolan. The zeolite minerals clinoptilolite, mordenite, laumontite, and stilbite occur in both Cretaceous and Tertiary formations. Sodium sulfate deposits occur in shallow lakes in northeastern Montana, and similar lakes in central Montana offer the potential for discovery of additional deposits.

Because of continually changing markets, commodities that have not even been considered as having economic potential in the past will be produced in the future.

INTRODUCTION

The purpose of this discussion of 30 industrial mineral commodities is to provide summaries of information on known deposits and in some instances possibilities for exploration for new deposits. The varying degree of coverage of specific commodities is intentional. Those commodities for which recent summary or comprehensive publications are not available are described in more detail. Localities of some of these deposits are shown in Figure 1. References cited in the commodity descriptions will enable the

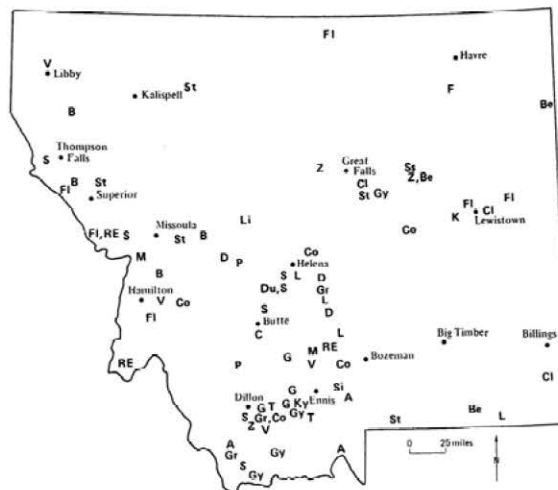


Figure 1. Localities of some industrial mineral commodities in western Montana. Extensive bedded deposits are not shown. A = asbestos; B = barite; Be = bentonite; C = chlorite; Cl = clay; Co = corundum; D = diatomite; Du = dumortierite; F = feldspar; Fl = fluorspar; G = garnet; Gr = graphite; Gy = gypsum; K = kaolinite; Ky = kyanite; L = limestone; Li = lithium; M = mica; P = phosphate; RE = rare-earth elements; S = silica; Si = sillimanite; Ss = sodium sulfate; St = stone; T = talc; V = vermiculite; Z = zeolite.

reader to obtain more detailed information about specific deposits. Two older publications that provide more detailed information on some of these commodities as well as information on metallic mineral resources are Special Publication 28 (Montana Bureau of Mines and U.S. Geological Survey, 1963) and Sahinen and Crowley (1959). Also, Bentley and Mowat (1967) give locality information but no references for 32 nonmetallic commodities in addition to similar information for metalliferous occurrences.

In the following discussion, the industrial mineral commodities are described in alphabetical order, with references listed at the end of the paper.

ASBESTOS

Although currently considered more of a detriment to mineral development than an economic commodity, a brief discussion of asbestos is included, because asbestiform anthophyllite has been mined from one deposit, and attempts were made to produce chrysotile from another. At the Karst deposit 32 mi southwest of Bozeman, irregular veins of fibrous anthophyllite occur in peridotite bodies within Archean gneiss and schist (Perry, 1948, p. 36-39). Anthophyllite fibers typically oriented nearly perpendicular to the vein contacts are as much as 1 ft long. Total production from this mine, which has been inactive since the 1950's, is 1,800 tons.

Attempts have been made to mine and mill chrysotile asbestos from the Cliff Lake deposit in the southern Madison Range 65 mi southwest of Bozeman (Perry, 1948, p. 39, 40). Both chrysotile and massive serpentine occur in Archean dolomitic marble next to a Precambrian gabbro dike. In another area, chrysotile veinlets less than 0.75 in. thick occur in Archean dolomitic marble at the

Anderson deposit 32 mi southwest of Dillon (Sahinen and Crowley, 1959, p. 5).

BARITE

Barite veins that have been mined are confined to metasedimentary rocks of the Proterozoic Belt Supergroup. Quartz and fragments of country rock are the most abundant impurities in these veins, which are typically devoid of metallic minerals. The largest concentration of minable veins is in the Elk Creek-Coloma district 30 mi east of Missoula, where veins occur in the Garnet Range Formation of the Belt Supergroup within 1.2 mi of the exposed contact of the Cretaceous granitoid Garnet stock (Berg, 1988, p. 48-68). The thickest vein, the Elk Creek vein, which is mined from underground workings, reaches a maximum thickness of 27 ft and averages 7 ft.

Barite has also been mined from five other deposits in this same district. Although production figures for the barite mines in the Elk Creek-Coloma district are not available, cumulative production up to 1988 probably was in the range between 150,000 and 200,000 tons (Berg, 1988, p. 56). Another deposit, the Kenelty Mine 28 mi southeast of Libby, produced an estimated 40,000 tons of barite during the years of production from 1978 to 1983 (Berg, 1988, p. 23). Other small producers, now inactive, are the Mullan Mine 25 mi northwest of Superior and the Sheep Creek (Brechtill) and the Burnt Fork Mines, 24 and 27 mi, respectively, south of Missoula.

CHLORITE

Chlorite is mined at the Antler deposit 25 mi southeast of Butte in the Silver Star district. Chlorite veins formed by hydrothermal replacement of Precambrian quartzofeldspathic gneiss and are typically surrounded by envelopes of sericitic alteration (Berg, 1983). The veins consist of the magnesian chlorite clinocllore, with muscovite, zircon, rutile, and limonite in trace concentrations (Berg, 1986, p. 497). When examined in 1982, the thickest vein exposed was 26 ft thick. Chloritic alteration of quartzofeldspathic gneiss is present throughout the southern flank of the Highland Mountains south and west of the Antler Mine, mainly associated with north-west-trending high-angle faults.

CLAYS

Bentonite

Bentonite in Montana has two major sources: (1) Tertiary-age sediments deposited in intermontane basins in the southwestern part, and (2) marine Cretaceous formations exposed on the plains (Berg, 1969). The Tertiary sediments contain bentonite suitable for lining irrigation ditches and similar uses, but they are generally of the low-swelling variety and contain too much sand-size detritus for many applications. Cretaceous formations contain large reserves of good-quality bentonite. Knechtel and Patterson (1956, p. 48) tentatively estimated reserves of 108 million tons in the Montana part of the Hardin district southeast of Billings. Mable bentonite beds in this district are in the Thermopolis Shale, Mowry Shale, Belle Fourche Shale, and Bearpaw Shale. Farther north in the Vananda area 85 mi northeast of Billings, two bentonite beds 3 to 4 ft thick in the Bearpaw Shale have been mined (Berg, 1970). Bentonite has been mined in northern Montana near Glasgow and Malta from what are presumed to be these same two beds for use in drilling mud and for pelletizing taconite iron ore concentrate. The very productive Clay Spur Bed of the Mowry Shale, which extends into southeastern Montana from the Black Hills district, has also been extensively mined (Knechtel and Patterson, 1962, p. 971). The Arrow Creek Bed (also known as the Geyser bed) in the Bootlegger Member of the Blackleaf Formation contains large deposits of bentonite in central Montana east of Great Falls. Samples tested from this and other beds in this area have been

judged unsatisfactory for drilling mud or taconite pelletizing (Great Northern Railway Company Mineral Research and Development Department, 1960). Extensive bentonite deposits approximately 35 mi southeast of Lewistown may be correlative with the Arrow Creek Bed.

Expandable shale

Marine Cretaceous formations also contain shale suitable for expansion to make lightweight aggregate (Berg and others, 1968, p. 68, 69). The Blackleaf Formation was a source of expandable shale in the Great Falls area (Sahinen, 1957). Presently, clay formed by weathering of the LaHood Formation of the Precambrian Belt Supergroup is mined for this purpose from a deposit about 35 mi southeast of Butte and expanded at a plant in Three Forks (Berg and others, 1968, p. 51, 52).

Brick clay

Although Montana no longer has any operating brick plants, there are substantial clay deposits suitable for brick and other structural clay products in the Morrison Formation (Jurassic) and overlying Kootenai Formation (Cretaceous) (Berg and others, 1968, p. 68, 69). Fire clay from kaolinitic beds in the Kootenai Formation has been mined in the area east of Great Falls and used in brick.

Kaolin

The largest known kaolinite deposit in Montana is the Whiteware deposit (unmined) 8 mi northwest of Lewistown in the South Moccasin Mountains. This deposit was formed by hydrothermal alteration of shale and sandstone of Cretaceous or Pennsylvanian age near Tertiary intrusives (Douglass, 1947). Clay from this deposit has been identified as the dickite polytype of kaolinite. The U.S. Bureau of Mines determined by extensive sampling and testing that this clay is suitable for manufacture of whiteware (Roby and Robertson, 1949).

CORUNDUM

Montana is well known to gemologists for its sapphire deposits. The most famous of these is the Yogo deposit 45 m southwest of Lewistown, where the source of the attractive sky-blue sapphires is a Tertiary lamprophyre dike (Clabaugh, 1952, p. 6-34; Dhay, 1988). Sapphires are mined from gravels along the Missouri River northeast of Helena and farther west from gravels in the vicinity of Rock Creek 15 mi southwest of Philipsburg. Sapphires from these deposits, unlike those from the Yogo deposit, show a variety of pale shades of green, blue, and for the Rock Creek sapphires, also yellow and yellowish brown (Zeihen, 1987).

Deposits of corundum that is not of gem quality are less well known. These deposits are relatively thin lenses of corundum-bearing gneiss in Archean metamorphic rocks. Three of these deposits southwest of Bozeman have been investigated by the U.S. Bureau of Mines (Clabaugh and Armstrong, 1950). The largest, the Elk Creek deposit approximately 17 mi southwest of Bozeman, contains several thousand tons of rock with 10 percent corundum.

Farther to the southwest, the Camp Creek corundum deposit is 10 mi southeast of Dillon in the Ruby Range. Corundum gneiss lenses in Archean marble range from 20 to 130 ft in length and from 4 to 20 ft in thickness (Heinrich, 1950, p. 11). Beneficiation tests on a 800-lb sample containing 28 percent corundum conducted by the U.S. Bureau of Mines showed that a concentrate containing 92.5 percent Al_2O_3 can be produced through flotation (Smith and Llewellyn, 1987). The protolith of this corundum gneiss is thought to be an aluminous clay layer that was subsequently metamorphosed during high-grade regional metamorphism (Haartz, 1979).

DIAMONDS

Diatremes in north-central Montana with kimberlitic affinities and, in at least one instance, containing upper mantle xenoliths

have been prospected for diamonds, but with no success. This swarm of late middle Eocene diatremes extends from the vicinity of the Little Rocky Mountains southwestward across the Missouri River (Hearn, 1968; Hearn and Boyd, 1975). The Williams diatreme on the southwestern flank of the Little Rocky Mountains contains dunite and peridotite upper mantle xenoliths, as well as xenocrysts of kimberlite indicator minerals (Hearn and McGee, 1983, p. 9).

DIATOMITE

Pardee (1925, p. 44) reported two occurrences of diatomite in the Townsend Valley. The northern occurrence, north of Beaver Creek approximately 21 mi southeast of Helena, consists of two beds. Each bed is reported to be of chalk-white diatomite about 1 ft thick in Oligocene-age clay and tuff. The second occurrence is about 36 mi southeast of Helena, where Pardee (1925, p. 44) described a 10-ft-thick bed of impure diatomite. A bed of impure diatomite 2 ft thick occurs in the Tertiary Cabbage Patch beds south of the Clark Fork River near Drummond, 45 mi southeast of Missoula (Gwinn, 1961).

DOLOMITE

Four Paleozoic formations contain substantial dolomite deposits. The Middle Cambrian Meagher Limestone is dolomitic in part in southwestern Montana. Some beds of the Upper Cambrian Pilgrim Limestone exposed in southwestern and central Montana are nearly pure dolomite (Perry, 1949, p. 31). The Ordovician Big Horn Dolomite, limited to south-central Montana and ranging in thickness from 250 to 500 ft, is a major potential dolomite source (Balster, 1971, p. 289). The Jefferson Dolomite of Devonian age and exposed in western and central Montana is another potential source. This formation ranges from 200 to 700 ft in thickness in Montana (Balster, 1971, p. 264).

FELDSPARS

The Tertiary alkalic rocks of the central part of the state appear to offer the best potential sources of feldspars for use in ceramics or glass. The Little Rocky Mountains, the Judith Mountains, the North and South Moccasin Mountains, Highwood Mountains, and Bearpaw Mountains all contain syenitic plutonic or hypabyssal igneous rocks. The Rocky Boy stock in the Bearpaw Mountains, 90 mi northeast of Great Falls, contains a variety of alkalic rock types including nepheline-bearing shonkinites and syenites (Pecora, 1942, Figure 2). This stock is exposed over an area of about 12 mi² and may be a potential source of feldspar or nepheline syenite. Syenitic plutons in both the Bearpaw Mountains and the Highwood Mountains 75 mi to the southwest may also have potential for development of feldspar resources.

FLUORSPAR

Fluorspar has been mined from three deposits in western Montana, all close to the Idaho batholith (Cretaceous), which is exposed in the Bitterroot Range along the Idaho-Montana border. The Snowbird and Spar deposits, west and northwest of Missoula, respectively, are in metasedimentary rocks of the Wallace Formation of the Proterozoic Belt Supergroup. At both deposits, fluorite occurs in pods associated with masses of white quartz and calcite (Sahinen, 1962, p. 11-16). The much larger Crystal Mountain deposit, situated in the Sapphire Range 60 mi south of Missoula, is in granite probably related to the Boulder batholith and gneiss presumably formed by metamorphism of rocks of the Belt Supergroup. Other fluorite prospects are reported in the area northwest of Missoula (Com, 1953), and further exploration in this area of western Montana might reveal more deposits.

Fluorite also occurs in hydrothermal veins within and adjacent to the Boulder batholith. These veins are in most instances associated with metalliferous deposits (Sahinen, 1962, p. 16-26). They are typically small, and it is unlikely that fluorite could be economically

recovered except as a coproduct of metal production.

Fluorite occurs in veins and disseminations in alkalic igneous rocks and the adjacent sedimentary rocks exposed in the isolated mountains of central Montana (Ross, 1950; Sahinen, 1962). In the Sweet Grass Hills, South Moccasin Mountains, and Judith Mountains of central and northern Montana, fluorite veins occur in limestone of the Mississippian Madison Group and the adjacent igneous rocks. In the Little Rocky Mountains of north-central Montana, fluorite is disseminated in a porphyritic syenite (Sahinen, 1962, p. 33-34). It is interesting that, in these same mountain ranges, gold deposits are being mined or have been mined in several instances in close association with the fluorite occurrences.

GARNET

Major bedrock garnet occurrences are confined to two geologic environments: grossularite-bearing skarns adjacent to Laramide granitoid plutons in southwestern Montana and Archean metamorphic rocks in southwestern Montana. Of these two environments, the Archean metamorphic rocks and placer deposits derived from them seem to have the greater possibility of economic development. Garnet occurs in amphibolite, hornblende gneiss, quartzofeldspathic gneiss, anthophyllite gneiss, schist, and garnetite in the Archean metamorphic rocks. Relatively widespread amphibolite is an important source of garnet in the placer deposits. The unusual rock garnetite is exposed in the northern end of the Tobacco Root Mountains 35 mi southwest of Butte. This rock consists of 20 to 80 percent pyrospite garnet and 20 to 70 percent quartz (McClain, 1977, p. 1).

The areas of greatest potential for alluvial concentrations of garnet are streams that drain mountain ranges in southwestern Montana, where garnetiferous metamorphic rocks are exposed. The garnetiferous alluvium in Granite Creek in the southern Tobacco Root Mountains has been investigated as a possible source. Farther south in the Greenhorn Range, garnets have been recovered by rockhounds from the gravels along Barton Gulch, which also drains an area of Archean metamorphic rocks. Eluvial concentrations of almandine garnets averaging about 0.25 in. in diameter are reported in the area north of the main road in the Sweetwater Basin 20 mi southeast of Dillon (Heinrich and Rabbit, 1960, p. 33).

GRAPHITE

Lump graphite has been mined from irregular vein-like bodies in Archean gneiss, schist, dolomitic marble, and pegmatite at the Crystal Graphite Mine in the Ruby Range 10 mi southeast of Dillon (Perry, 1948, p. 13-17). Total production of graphite from this mine and from the Bird's Nest claim less than 1 mi northeast is estimated to be 2,350 tons, mainly mined during 1918 and 1919 (Cameron and Weiss, 1960, p. 252, 253). At a prospect on Kate Creek, 35 mi southwest of Dillon, graphite occurs in a fault zone between Paleozoic sedimentary rocks and Archean metamorphic rocks (Perry, 1948, p. 17-20).

A deposit variously reported to contain graphite, amorphous graphite, or fixed carbon is situated north of Indian Creek on the east flank of the Elkhorn Mountains 25 mi southeast of Helena near Townsend. Klepper and others (1971, p. 48) described lignitic shale near the top of the Morrison Formation north of Indian Creek. Possibly these beds of lignitic shale have been metamorphosed by Cretaceous dikes and sills to form graphitic material. In the late 1970's, an effort was made by the Black Diamond Graphite Company to market material from this deposit for refractory use.

GYPSUM

The most extensive gypsum deposits in Montana are in the Great Falls Lewistown area of the west-central part of the State. Gypsum for use in cement manufacture is mined from the Kibbey Formation of the Mississippian Big Snowy Group from a deposit near Raynesford, 32 mi southeast of Great Falls. Perry (1949,

p. 12) reported a thickness of 27 ft for a gypsum bed at this locality. However, he explained that this measurement was on a weathered exposure and may not accurately represent the true thickness. A few miles west near Riceville (24 mi southeast of Great Falls), a gypsum bed averaging 4 to 6 ft has been mined (Perry, 1949, p. 13). This bed is in the Otter Formation, which overlies the Kibbey Formation and also is part of the Big Snowy Group.

The Piper Formation of the Upper Jurassic Ellis Group contains gypsum beds that have been mined in the Lewistown area. West of Lewistown at Hanover, a 7-ft- and a 10-ft-thick bed of gypsum separated by 140 ft of calcareous shale have been mined (Miller, 1959, p. 35). At Heath, which is east of Lewistown, a 13- to 17-ft-thick bed, also in the Piper Formation, was mined for wall board (Perry, 1949, p. 8). The lower 8 to 12 ft of this bed is nearly pure gypsum. In south-central Montana 40 mi southwest of Billings near Bridger, gypsum beds averaging 15 to 20 ft thick near the top of the Triassic Chugwater Formation have been mined (Knappen and Moulton, 1930, p. 67). The Talent Gypsum property located 40 mi southeast of Dillon at an elevation of 9,000 ft within the Snowcrest Range contains indicated ore reserves of 1,400,000 tons that range from 63.8 to 92.4 percent gypsum (Johns, 1980, p. 22,23). Two smaller deposits 40 mi southwest of Dillon, also in the Big Snowy Group, together contain at least 700,000 tons of rock that range from 47 to 93 percent gypsum (Johns, 1980, p. 1). Farther to the east in the Gravelly Range, a 20-ft bed of gypsum occurs in the Jurassic Ellis Formation (Mann, 1954, p. 26). Spring deposits of gypsum are found in the vicinity of this bed.

LIMESTONE

In common with most states, limestone is an abundant mineral commodity in Montana. The Madison Group of Mississippian age is the largest limestone resource in the state. Limestone beds of this group are exposed on the flanks of mountains in central and southwestern Montana and in the Disturbed Belt along the Rocky Mountain front in the northwestern part of the State. The Madison Group is divided into the Lodgepole Formation and the overlying Mission Canyon Formation, which contains higher purity limestone. Much of the Mission Canyon Formation can be classified as high-calcium limestone containing more than 95 percent CaCO_3 , less than 5 percent MgCO_3 , and less than 3 percent other impurities (Chelini, 1965, p. 10). At some localities, unusually pure beds in this formation contain more than 98 percent CaCO_3 (Landreth, 1968, p. 6). The Mission Canyon Formation is up to 900 ft thick in central Montana (Smith and Gilmour, 1980, p. x17). Limestone from the Mission Canyon Formation is quarried near Townsend for lime manufacture and near Warren in south-central Montana for use in sugar beet refining. Limestone has also been quarried near Drummond for sugar beet refining.

Although the CaCO_3 content is lower than in the Mission Canyon Formation, the underlying Lodgepole Formation is an important source of limestone for cement manufacture. Analyses of limestone from the Lodgepole Formation at five localities show a range from 72.8 to 88.2 percent CaCO_3 (Chelini, 1965, p. 19, 37, 38, 44, 47). This formation reaches a maximum thickness of 780 ft in central Montana (Smith and Gilmour, 1980, p. X15).

The Meagher Formation, a Cambrian limestone exposed in central and southwestern Montana, is also a source of high-purity limestone. Limestone from the Meagher Formation formerly quarried for smelter flux at the south end of the Helena Valley contained 93.2 percent CaCO_3 (Perry, 1949, p. 39). Other potential sources of CaCO_3 are the travertine deposits near Lewistown, north of Yellowstone National Park, and southwest of Dillon (Berg, 1974, p. 19, 20).

LITHIUM

Lithium occurs in anomalous concentrations in Oligocene-age

lacustrine sediments exposed in a band 4,200 ft long by 1,000 ft wide near Lincoln 55 mi northeast of Missoula (Brenner-Tourtelot and others, 1978). Some stratigraphic intervals are reported to contain nearly 0.1 percent lithium. Other Oligocene sedimentary rocks from the Helena and Townsend Valleys contain much lower lithium concentrations.

MAGNESITE

Although there are no known major deposits in Montana, magnesite closely associated with talc in Archean dolomitic marble has been identified in at least three localities in southwestern Montana (Berg, 1979, p. 10, 11). Because of the difficulty of distinguishing magnesite from dolomite in the field, one wonders if magnesite may be more abundant in dolomitic marble than has been recognized.

MICA

Pegmatites in the Archean metamorphic rocks of southwestern Montana have yielded small amounts of muscovite mica. The greatest production of about 10 tons was from the Sappington pegmatite west of Three Forks, 45 mi southeast of Butte (Heinrich, 1949, p. 23). Mica production from other pegmatites, mainly during World War II, was much less. The numerous pegmatites in southwestern Montana are small, usually less than 100 ft long and 20 ft thick, and are concordant to foliation of the enclosing gneiss. Some have quartz cores; others are mixtures of quartz, microcline, and plagioclase, with lesser amounts of biotite, muscovite, and sometimes schorl. Muscovite books are up to 5 in. across (Heinrich, 1949, p. 11-25).

A large deposit of muscovite schist produced by the metamorphism of an argillaceous unit in the Belt Supergroup is exposed near the head of McClain Creek in the Bitterroot Range 13 mi southeast of Missoula. Exploratory drilling has shown this deposit to be extensive (Dominick Job, personal communication, 1989). The schist also contains quartz and feldspar.

PHOSPHATE

The Western Phosphate Field encompasses northern Utah, western Wyoming, eastern Idaho, and southwestern Montana, extending as far north as the Elliston district 20 mi northwest of Helena. The Permian Phosphoria Formation has been divided into six members of which the uppermost Retort Phosphatic Shale Member contains the largest phosphate resources (Popoff and Service, 1965, p. 19). This member contains beds of phosphorite and thin-bedded carbonaceous mudstone. The Meade Peak Phosphatic Shale Member, which is stratigraphically lower in the Phosphoria Formation, is also an important phosphate resource. Structural complexities caused by faulting and folding during Laramide time require that phosphorite beds would have to be mined by underground methods in most instances. Popoff and Service (1965, p. 7-13) estimated the phosphate resources contained in beds at least 3 ft thick and at or above the level of the local drainage to be 1.05 billion short tons, with a grade of at least 18 percent P_2O_5 . Of these resources, 93 million tons contain more than 31 percent P_2O_5 (acid grade), 374 million tons contain between 24 and 31 percent P_2O_5 (furnace grade), and the remaining 585 million tons are between 18 and 24 percent P_2O_5 (beneficiation grade). The thickness of most beds that average at least 24 percent P_2O_5 ranges from 3 to 6 ft, and beds that average 18 to 24 percent P_2O_5 are up to 12.4 ft thick. Since 1929, phosphate has been mined in the Garrison district 40 mi northwest of Butte by Cominco American, Inc., for the manufacture of fertilizer. Phosphate was formerly mined underground in the Melrose district 25 mi southwest of Butte and shipped to Stauffer Chemical Company's Victor Chemical Works west of Butte for the manufacture of phosphoric acid and elemental phosphorus. Since the mid-1960's, phosphate mined in an open pit in Idaho has supplied this plant.

POTASH

Potash-bearing beds in the Middle Devonian Prairie Formation have been encountered during oil and gas drilling in northeastern Montana. Analyses by the Montana Bureau of Mines and Geology of core from the salt-bearing interval of this formation at a depth of 9,918 to 10,120 ft from the Farmers Union Central Exchange-Jayhawk well #43X-30 Nelson in NE¼SW¼ sec. 30, T. 3 N., R. 56 E., Sheridan County, showed the material to consist mainly of halite. The thickest sylvite-bearing interval is from a depth of 10,008 to 10,015 ft, where the average content of water-soluble equivalent K₂O is 4.3 weight percent. At a greater depth of 10,048 to 10,050 ft, the equivalent K₂O content is 6.96 weight percent.

At other localities in northeastern Montana, this interval of the Prairie Evaporite Formation contains a greater concentration of sylvite (Reed, personal communication, 1989). However, compared to the large potash deposits mined from this same formation in southern Saskatchewan, the Montana deposits are deeper, thinner, and of lower grade.

PUMICITE

Pumicite occurs in Tertiary sedimentary deposits exposed in the intermontane basins of southwestern Montana. Samples from six pumicite deposits were evaluated by the U.S. Bureau of Mines for suitability as pozzolanic raw material. Two of the samples, one from Big Horn County southeast of Billings and the other from Powell County northwest of Butte, met the minimum requirements for pozzolanic material except that their reactivity with cement alkalies was too low (U.S. Bureau of Mines, 1969, p. 32, 42). The most readily available source of pozzolanic raw material in Montana at the present time is fly ash produced by coal-fired generating plants. Deposits of pumice are not known in Montana.

RARE-EARTH ELEMENTS

Minerals containing rare-earth elements have been reported from a number of Montana localities. In southwestern Montana, carbonatite bodies are exposed in southern Ravalli County, 95 mi south of Missoula, as well as adjacent areas in Idaho. The most abundant rare earths in those bodies that have been explored are cerium and lanthanum (Crowley, 1960, p. 3). Rare-earth minerals from these deposits are monazite, ancylite, bastnasite, and allanite (Heinrich, 1966, p. 364). The rare-earth bearing fluorocarbonate mineral parisite occurs associated with a carbonatite at the Snowbird Mine, a fluorspar deposit 37 mi west of Missoula (Lasmanis, 1977, p. 83-86).

Fergusonite(?) occurs in the Sappington pegmatite, a large pegmatite in Archean metamorphic rocks situated about 40 mi southeast of Butte (Heinrich, 1949, p. 24).

Other potential sources of rare earths are placer deposits in southwestern Montana known to contain concentrations of monazite (Overstreet, 1967, p. 171). Northwest of Great Falls, concentrations of heavy minerals, most notably titaniferous magnetite, in the Virgelle Sandstone Member of the Eagle Formation and the Horsethief Sandstone, both of Cretaceous age, suggest a potential source of rare earths (Overstreet, 1967, p. 170).

SALT

Halite beds occur in the subsurface in eastern Montana on the west flank of the Williston Basin, a structural and stratigraphic basin whose center lies in western North Dakota. The Salt member of the Prairie Formation of the Middle Devonian Elk Point Group consists mainly of halite and is over 200 ft thick in northeastern Montana, where it occurs at a depth of 6,000 to 10,000 ft (Pierce and Rich, 1962, p. 51-56). (See the section on potash for a brief description of potash occurrences in the Prairie Evaporite Formation). Higher in the stratigraphic section, the Charles Formation of Mississippian age contains six salt beds whose cumulative thickness is greater than 300 ft in eastern Montana (Pierce and Rich,

1962, p. 56, 57). The top of the salt beds ranges in depth from 7,000 ft along the Montana-North Dakota border to approximately 2,500 ft at their western limit 90 mi to the west. The Opeche Formation of Permian age also contains a salt bed that extends about 25 mi into eastern Montana (Pierce and Rich, 1962, p. 58). The maximum thickness of this salt bed in eastern Montana is slightly greater than 100 ft.

SAND, GRAVEL, AND CRUSHED STONE

Sand and gravel deposits are abundant in the mountainous western one-third of Montana, where igneous and metamorphic bed rock provide a source of durable material for high-quality sand and gravel. In this area, fluvial deposits close to active rivers and streams provide a good source of sand and gravel. Also, older Quaternary and Tertiary gravel deposits exposed in terraces above the present flood plain provide additional resources (Larrabee and Shride, 1946). Sand and gravel derived from adjacent mountain ranges and forming terrace deposits northwest of Great Falls along the Rocky Mountain Front and also to the southeast are important sources of this commodity. In these areas as well as in eastern Montana, the underlying bed rock of the plains is shale and sandstone of Cretaceous and Tertiary age, which generally do not yield sand and gravel deposits. The only widespread fluvial deposits in eastern Montana associated with an active river are those along the Yellowstone River (Larrabee and Shride, 1946).

North of the Milk River in north-central Montana and north of the Missouri River in northeastern Montana, gravel, sand, and silt with local occurrences of marl and volcanic ash of the Tertiary Flaxville Formation cover a large area (Ross and others, 1955). Quaternary Wiota Gravels, glacial outwash, kame deposits, and eolian sand deposits are also sources of sand and gravel (Colton, 1955, 1963). Scoria formed by the metamorphism and partial melting of beds overlying burned coal in the Tertiary Fort Union Formation of southeastern Montana are used locally for road surfacing.

Crushed stone for railroad ballast is quarried at two localities, both in metasedimentary rocks of the Precambrian Belt Supergroup. Thirteen mi southeast of Missoula along the Clark Fork River, the Bonner Quartzite is quarried at the McQuarrie quarry. Fracturing related to movement along the nearby Clark Fork fault provides for easy quarrying of this quartzite. Quartzite from the Missoula Group is quarried at the Essex quarry, which is located 35 mi northeast of Kalispell near the southern boundary of Glacier National Park.

SILICA

Quartz-cored pegmatites in the Boulder batholith between Butte and Helena are a silica resource. Since 1964, the Basin quarry (now inactive) about 25 mi southwest of Helena near the town of Basin has produced more than 250,000 tons of quartz containing 99.5 percent SiO₂ for metallurgical alloys (Peterson, 1976, p. 93, 94). Chelini (1966) described two other quartz-cored pegmatites in the Boulder batholith south of Helena with purity greater than 99.5 percent SiO₂ and estimated reserves of 500,000 and 275,000 tons. Another quartz-rich pegmatite in the Idaho batholith south of Missoula contains 156,000 tons (Chelini, 1966, p. 12-14). Numerous relatively pure quartz bodies that perhaps resulted from remobilization of quartz from quartzites are present in the Proterozoic metasedimentary rocks of the Belt Supergroup northwest of Missoula. One such occurrence, the Petty Creek deposit, is estimated to contain 960,000 tons of quartz with analyses averaging 99.5 percent SiO₂ (Chelini, 1966, p. 30-32). Farther to the northwest, the Haines Point deposit, also in rocks of the Belt Supergroup, is estimated to contain reserves of at least 100,000 tons of quartz with purity of 99.7 percent SiO₂ (Burlington Northern, 1972, p. 54-57).

The Pennsylvanian Quadrant Formation, mainly a quartzose sandstone which is found throughout southwestern Montana, is

a significant silica resource. Eleven miles southwest of Dillon, sandstone in this formation was quarried at Daly's Spur for smelter flux. Duplicate analyses of sandstone from this quarry indicate 98.9 and 97.5 percent SiO_2 (Carter and others, 1962, p. 21-23). The Detton silica deposit 42 mi south of Dillon is reported to be sufficiently pure for use in glass (personal communication, John Detton, Dillon, Montana, 1989). This deposit also is in the Quadrant Formation. The Tensleep Formation exposed in southern Montana and Wyoming is equivalent to the Quadrant Formation and also is a potential source of silica.

Sandstone of Cretaceous age, although extensive in Montana, generally is feldspathic and thus does not have the high purity desired for most industrial uses. The same is generally true for the quartzite beds in the Belt Supergroup.

SILLIMANITE GROUP REFRACTORIES

Of the three aluminosilicate polymorphs, kyanite, sillimanite, and andalusite, sillimanite is the most abundant in Montana. At reported sillimanite occurrences in Archean metamorphic rocks of southwestern Montana, this mineral occurs in biotite schist, in some instances accompanied by garnet (Heinrich, 1950, p. 20). Sillimanite also occurs in some pegmatites in Archean metamorphic rocks. The Placer Creek sillimanite deposit, 26 mi southwest of Bozeman in the Madison Roadless Area, is in Archean garnet hornblende gneiss. This deposit is estimated to contain 21,000 tons of rock containing 84 percent sillimanite and 2 percent rutile, with an additional inferred resource of 70,000 tons (Simons and others, 1983, p. 5). Kyanite occurs in quartzose pegmatites within Archean gneisses exposed about 13 mi southwest of Ennis. Although kyanite is locally abundant in and adjacent to these pegmatites, where it constitutes as much as 20 percent of the rock, the occurrences are irregular, and the total amount of kyanite may be small (Heinrich, 1948, p. 13).

Andalusite is not known to occur in significant quantities in Montana. Dumortierite, a borosilicate, occurs disseminated in quartz latitic welded tuff of Cretaceous age near Basin about 20 mi southwest of Helena (Ruppel, 1963, p. 96). Potential development of this deposit faces two obstacles: (1) small deposit size, and (2) difficult beneficiation caused by the interlocking of dumortierite grains with other constituents of the rock.

SODIUM SULFATE

In northeastern Montana and western North Dakota, numerous small lakes occupy depressions thought to have formed in ice-marginal channels in glacial till (Witkind, 1959, p. 73). Springs feeding these lakes contribute sodium sulfate, which is concentrated sufficiently in some lakes to form permanent sodium sulfate beds. The largest deposit in Montana is in a small lake southeast of Brush Lake in Sheridan County, where auger drilling by the U.S. Bureau of Mines intersected a bed of mirabilite or glauber's salt ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) a few inches below the surface of the mud in the bottom of the lake. This bed ranges from 3.5 to 5.7 ft in thickness and is estimated to contain 2,710,000 tons of glauber's salt (Binyon, 1952, p. 18, 27).

About 45 mi northeast of Great Falls, a few intermittent lakes lie in the channel occupied by the Missouri River during Wisconsin stage glaciation. Four of these lakes contain significant concentrations of sodium sulfate, which forms a white crust on the mud when the lakes are dry (Sahinen, 1956, p. 5, 6). Further work is needed to determine whether or not permanent sodium sulfate beds occur within the mud on the bottom of these lakes. The largest of these lakes, appropriately named Big Lake, is about 2 mi² in area (Sahinen, 1956, p. 6).

STONE

Although Montana has a wide variety of rock types that are suitable for decorative stone, only a few have been quarried com-

mercially in recent years. The most important of these is travertine from deposits north of Yellowstone National Park, which has been quarried since 1932 for facing. Color of this travertine ranges from white to ochre. Two other large deposits of travertine are present in the state, one southwest of Dillon and the other west of Lewistown (Berg, 1974, p. 20).

Gray granite has been quarried from the Cretaceous-age Boulder batholith in the Butte and Helena areas. Pink granite exposed south of Darby may be suitable for facing but has not been quarried (Berg, 1974, p. 15). Marble, some unusually white, was formed by contact metamorphism next to granitoid plutons in southwestern Montana and also occurs in the Archean sequence exposed in the southwestern part of the state. Slate-like argillite from the Proterozoic Belt Supergroup is produced from a quarry near St. Regis in western Montana. The Flathead Formation, a Cambrian quartzite, has yielded an attractive facing stone from quarries east of Great Falls and from a quarry north of Thompson Falls.

A number of other rock types have been quarried, generally on a small scale or for only a few years. These include green Archean quartzite that contains green chromiferous muscovite, mottled limestone from the Cambrian Meagher Formation, dolomitic siltstone from the Triassic Chugwater Formation, flaggy limestone from the Bear Gulch Limestone Member of the Pennsylvanian Tyler Formation, and Tertiary volcanic rocks (Berg, 1974). Further development of stone deposits depends on aggressive out-of-state marketing and favorable transportation costs.

TALC

In recent years, Montana has led the Nation in value of talc produced. Deposits of high-purity talc, most of which can be mined by open pit methods, occur in Archean metamorphic rocks in the mountain ranges of southwestern Montana (Berg, 1979). Although much still remains to be learned about the origin of these deposits, they appear to be Precambrian in age, their formation controlled in part by structure and in part by host rock lithology. Talc deposits are confined to dolomitic marble (Tysdal and others, 1987, p. A 17). Talc occurrences range in size from thin veinlets and disseminations to large bodies such as the one 95 ft thick at Pfizer's Treasure Chest Mine in the Ruby Range (Olson, 1976, p. 123). Sixteen miles east of Dillon just south of the Treasure Chest Mine, Cyprus Industrial Minerals operates the underground Beaverhead Mine. In the Gravelly Range 18 mi south of Ennis, Cyprus mines talc at the Yellowstone Mine, and just to the west, Montana Talc operates the Johnny Gulch Mine. The greatest concentration of talc occurrences is in the Ruby Range, but talc has also been mined from deposits in the Tobacco Root and Greenhorn Ranges. In 1988, talc production from Montana deposits was estimated to be 339,000 tons (U.S. Bureau of Mines, 1988, p. 4). Talc from Montana deposits is used in paper, paint, ceramics, plastics, and cosmetics. The high purity and lack of asbestiform minerals has enabled Montana talcs to compete effectively in the international market.

VERMICULITE

Only one of the five known vermiculite deposits in Montana has been mined on a large scale. This deposit north of the town of Libby in northwestern Montana has been mined since 1925. The total vermiculite production from the Libby deposit is estimated to be several million tons (Bush, 1976, p. 151, 152). Vermiculite was formed by alteration of a biotite core of a zoned Jurassic ultramafic complex that had intruded metasedimentary rocks of the Belt Supergroup. Alteration of biotite to vermiculite is thought to have been caused by weathering (Boettcher, 1966, p. 293-295).

The Hamilton vermiculite deposit, 45 mi south of Missoula, also was formed by the alteration of biotitic rocks in a pyroxenite body that intruded metasedimentary rocks of the Belt Supergroup (Perry, 1948, p. 28-30). Testing of samples of ore from this deposit

by numerous methods and organizations shows that the content of asbestiform minerals is extremely low and that the average content of actinolite with an aspect ratio greater than 3:1 is 0.028 percent (State of Montana and U.S. Forest Service, 1988, p. 4). Plans are underway to mine this deposit.

The Pony vermiculite deposit is on the north flank of the Tobacco Root Mountains north of the small town of Pony, 40 mi southeast of Butte. The vermiculite at this undeveloped deposit was formed by the alteration of Archean biotite schist interlayered with gneiss (Perry, 1948, p. 32, 33). Because the schist contains quartz, feldspar, and garnet in addition to unaltered biotite, these minerals would have to be separated from the vermiculite. Perry (1948, p. 33) considered the reserves of vermiculite at this deposit to be "extremely large."

At the Elk Creek deposit 13 mi southeast of Dillon, vermiculite is concentrated at the contact between Archean gneiss and an ultramafic body (Desmarais, 1978). Exploratory drilling has indicated reserves of 3.5 million tons of rock containing an average of 11.4 percent vermiculite (Koehler Stout, personal communication, 1989). Several drill holes intercepted rock containing 28 percent vermiculite over a 25-ft cumulative thickness.

Vermiculite is associated with Tertiary syenite pegmatites in the Bearpaw Mountains of north-central Montana (Heinrich, 1949, p. 45, 46). This deposit appears to be much smaller than the others described, and the biotite has not altered sufficiently to produce highly expandable material.

ZEOLITES

Although zeolites have not been mined in Montana, the abundance of Tertiary and Cretaceous volcanic rocks and a number of reported zeolite occurrences suggest the possibility of minable deposits. Pearson (1989, p.8) reported clinoptilolite and mordenite in the Cretaceous-age tuff of Grasshopper Creek. Samples of this tuff collected along Grasshopper Creek 12 mi southwest of Dillon were estimated to contain 60 to more than 90 percent clinoptilolite on the basis of X-ray diffraction analysis. In another southwestern Montana occurrence, a Tertiary tuff from Ryan Canyon 12 mi south of Dillon contains clinoptilolite (Sheppard, 1976, p. 75). Several miles to the north, mordenite and heulandite occur in amygdulites in tuffaceous rocks of Miocene age (Rose, 1972, p. 247).

Lens-like masses of zeolitized tuff 1 to 3 m long and 0.3 to 0.6 m thick occur in the Bootlegger Member of the Cretaceous Blackleaf Formation at the type section northwest of Great Falls (Cobban and others, 1976, p. 34). In the same area, the Vaughn Member, also of the Blackleaf Formation, contains clinoptilolite in a tuffaceous siltstone bed 0.5 m thick (Cobban and others, 1976, p. 29). Near the Dover tunnel 55 mi southeast of Great Falls, the Arrow Creek Bed contains concretionary masses that consist of quartz, clinoptilolite, and calcite. This bed, which is largely bentonitic in this area, is also in the Bootlegger Member of the Blackleaf Formation.

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Industrial minerals in British Columbia: Present producers and further development opportunities

by Z.D. Hora, British Columbia Geological Survey, Ministry of Energy, Mines, and Petroleum Resources, Parliament Buildings, Victoria, B.C. V8V 1X4

INTRODUCTION

Traditionally, the value of industrial minerals produced in British Columbia in any given year comprises between 10 and 15 percent of the combined value of minerals, coal, petroleum, and natural gas. Over the years, a wide variety of industrial minerals has been produced, often with different levels of marketing success. For some products, such as dimension stone and clay or shale products, initial strong demand gradually dissipated; for others such as asbestos and magnesite, new discoveries or new industrial activities created demand and new markets. In some cases, such as fluorite, talc, pyrophyllite, and perlite, wider use has been prevented by the small size, poor quality, or remote location of the deposits. Also, British Columbia, with 2.6 million inhabitants, provides only a limited market, and the industry therefore has to look beyond the provincial borders.

PRESENT AND PAST PRODUCTION

The list of British Columbia industrial minerals with reported past or present production numbers 30 different commodities (Table 1). In 1987 production, 18 different industrial minerals with a total value of \$386 million were reported (Table 2). The main products include asbestos, gypsum, limestone, sulfur, and sand and gravel. The long-time smaller scale producers involve barite, clay and shale, calcium carbonate, dolomite, flagstone, jade, magnetite, and lump silica. There has always been a trend to produce new commodities locally, and this has increased in recent years; as before, some of the new ventures are success stories, or at least survive the initial difficulties to become established on the provincial mining scene, while others wither away. Figure 1 shows the locations of industrial minerals producers and active properties in British Columbia.

Several new mining operations to produce and process B.C. industrial minerals have been started during the past few years. Most of them developed properties that had been known for years and waited for the right economic moment or the right developer. Mountain Minerals Ltd. opened the friable sandstone deposit near Golden to produce glass-grade, foundry, and blasting sand. Baymag Mines Ltd. developed the Mount Brussilof magnesite deposit. Aurum Mines Ltd. started mining perlite near Empire Valley and expanding

Table 1. Industrial minerals in British Columbia: Present and past production record

PRESENT PRODUCTION	PAST PRODUCTION
Asbestos	Alunite
Barite	Bentonite
Building Stone	Chromite
Clay and Shale	Fluorite
Diatomaceous Earth	Hydromagnesite
Dolomite	Magnesium Sulphate
Fuller's Earth	Mica
Gypsum and Anhydrite	Peat
Jade	Phosphate
Limestone	Pozzolan
Magnesite	Pumice
Magnetite	Sodium Carbonate
Perlite	Talc
Pyrophyllite	
Rhodonite	
Sand, Gravel and Crushed Aggregate	
Silica	
Sulphur	

the rock in a new plant in Surrey. Ekaton Resources Ltd. started production of fuller's earth as industrial and domestic absorbent near Red Lake. Clayburn Industries Ltd. is producing diatomaceous earth from Quesnel and pyrophyllite from Princeton. Canroc Ltd. is operating a dimension stone finishing plant in Delta and is processing granite blocks from a quarry near Beaverdell.

Systematic prospecting by Hanna Mining identified a silica resource near Nicholson. The product is processed into ferrosilicon in Wenatchee, Washington. International Marble and Stone Company Ltd. outlined a white limestone deposit near Benson Lake. The quarried rock is processed into filler-grade product in a new plant in Surrey. Rhodonite from a new deposit near Bella Coola is sold for carvings and jewelry by Sea-Rose Mines. Dark bluish-grey diorite from Knight Inlet is processed into monumental stone products by Kellard Marble Inc.

NEW DISCOVERIES

A number of new significant industrial minerals discoveries were made by the industry, prospectors, and government geologists. Some are presently being evaluated for potential development. A major carbonatite plug with niobium values higher than those of the present Canadian producer at St. Honore in Quebec was discovered by Cominco Ltd. at Aley Creek. Another two carbonatites with anomalous values of yttrium and rare earth elements were recently reported from the Kechika River and Wicheeda Lake areas. Rare earth enrichment was discovered in dikes surrounding the main carbonatite plug at Aley Creek and in a fenitized zone at Rock Canyon Creek. Nepheline syenite very similar to that mined in Ontario has been discovered at Trident Mountain. A number of previously unknown rhodonite showings were found by a government geologist during regional mapping of the Cassiar area.

At Lang Bay, a deposit of residual kaolin in weathered Coast plutonic rocks has been discovered by Fargo Resources Ltd. un-

Table 2. Industrial minerals production in British Columbia in 1987

INDUSTRIAL MINERAL	TONNAGE	DOLLARS
Asbestos	97 848	46 938 025
Barite	26 479	787 903
Diatomite	3 300	*165 000
Granules	134 786	2 313 225
Gypsum	587 701	6 231 926
Magnesite	141 394	3 088 139
Magnetite	58 070	2 220 950
Sulphur	505 831	64 885 085
Total		126 465 253
Jade	178.702	984 495
Total		127 449 748
STRUCTURAL MATERIAL	TONNAGE	DOLLARS
Building Stone	391	51 212
Cement	1 312 074	88 181 547
Clay Products		8 376 402
Lime/Limestone	2 063 286	12 389 935
Rock Rubble and Rip Rap	3 590 641	18 230 984
Sand/Gravel	49 259 996	131 316 297
Total		258 546 377

*amount included with Clay Products

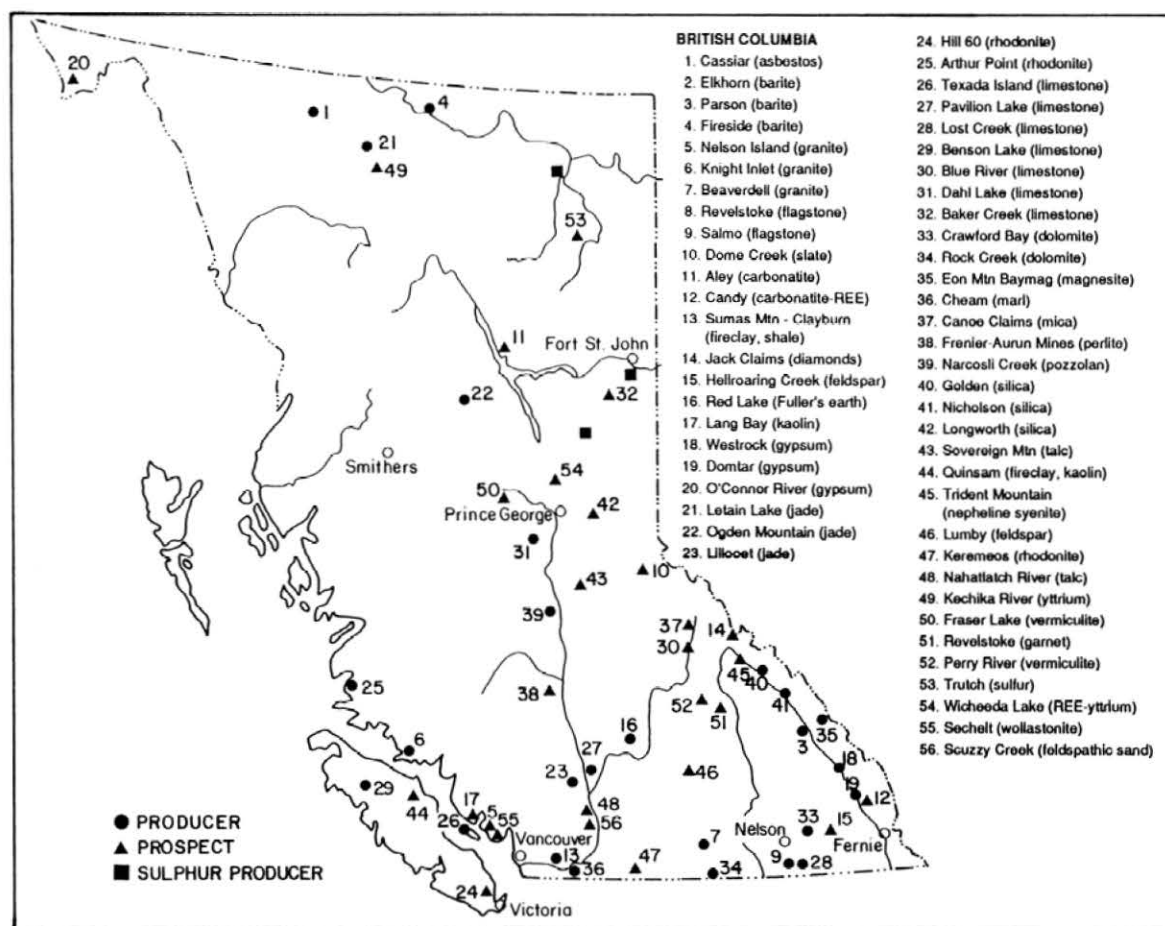


Figure 1. Industrial minerals in British Columbia: Producers and active properties.

derneath Upper Cretaceous sediments. High refractory fireclay was identified at the Quinsam coal deposit near Campbell River. Several deposits of zeolites in altered volcanic ash beds were identified in the Princeton basin, east of Cache Creek, and in the Gang Ranch area. A major intrusive body containing up to 10 percent of vermiculite was reported from the Fort St. James area. Two almandine garnet placers were reported from north and west of Revelstoke. Work by Pacific Geoscience Centre (PGC) of the Geological Survey of Canada has identified large offshore areas with high concentrations of titanium minerals in unconsolidated sediments under Hecate Strait and north of Vancouver Island.

GEOLOGICAL DATABASE

Traditionally, the lone professional staff member of the industrial minerals subsection of the Geological Survey Branch was able to maintain only an observer's role. This situation has changed dramatically since British Columbia signed the Mineral Development Agreement (MDA), which was followed by the Province's commitment to enhance the Branch's base budget. The number of projects undertaken has significantly increased during the last four years, as has the number of published reports. The topics range from office-based compilation and inventory studies on magnesite, silica, kyanite and garnet, talc and pyrophyllite, magnetite, peat, and sulfur, to regional field projects to study gypsum, phosphates, carbonatites and other alkaline ultrabasic rocks, and Tertiary

sedimentary basins. Systematic site-specific commodity-oriented studies involved dimension stone, wollastonite, fluorspar, olivine, and feldspar with nepheline syenite. In proposing individual projects, our strategy has been to seek opportunities to replace imported minerals with a domestic product, to assess the potential for exportable commodities, and to enhance the product value by further processing. The published results clearly indicate that the industrial minerals group of the Branch is taking a leadership role. Besides geological information on individual commodities, occurrences, and favorable host rocks, our results also offer some new conclusions and point to a number of new opportunities for the prospector and the industry.

NEW OPPORTUNITIES

The following are some new geological concepts as they apply to industrial minerals in British Columbia:

Kaolin-fireclay-bentonite-zeolites: Tertiary and Upper Cretaceous basins

Historically this environment has been a source of coal from a number of locations on Vancouver Island and from the Interior, for example, Princeton and Merritt. In one case, bentonite was mined as a by-product of coal mining from a locality near Princeton. Another site (Sumas Mountain) produced refractory and ceramic clays for years, until reserves were depleted.

Our present research and industry activities have identified the presence and significant economic potential of deposits of residual kaolin in basement rocks underlying Cretaceous and Eocene lacustrine sediments. Also, the basal Upper Cretaceous claystones have high kaolin content. These may provide raw materials for the refractory industry. Eocene sediments with deposits of acid volcanic ash are often zeolitized, and locally the zeolite quality has reached commercial grades.

The presence of bentonite in Eocene deposits is much more widespread than previously known and deserves the industry's attention.

Niobium-yttrium-rare earth elements: Ultra-alkaline igneous province in eastern British Columbia

While the presence of this province was suggested by K.L. Currie in 1976, its economic potential had not been realized until recently. Our research and two exploration programs carried out by industry have outlined significant potential for carbonate-hosted deposits of niobium, rare earth elements, and yttrium (Figure 2).

Our project also identified a major deposit of commercial-grade nepheline syenite. Potential for diamondiferous diatremes is still quite speculative, but the petrographic composition of diatremes in B.C. is related to rocks that are known to host diamonds.

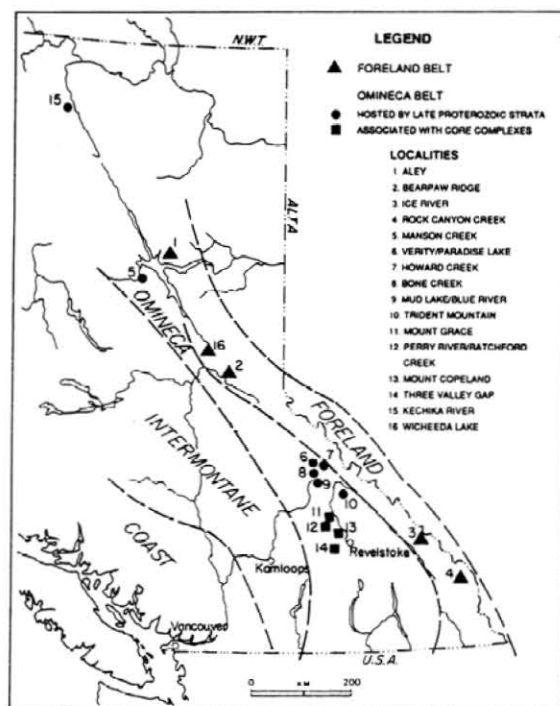


Figure 2. Carbonatite complexes in British Columbia.

Sulfur: Evaporite formations in northeast British Columbia

Major deposits of anhydrite and gypsum are known to be a part of the Devonian-Mississippian and Triassic section east of the Rocky Mountains. There are at least four intersections of native sulfur over a significant length (tens of feet) and a large number of reported sulfur showings in the Devonian-Mississippian sequence reported from oil and gas exploration holes (Figure 3). Native sulfur is also known to be present in the Triassic. In view of dwindling stockpiles of sulfur recovered from sour gas, there is

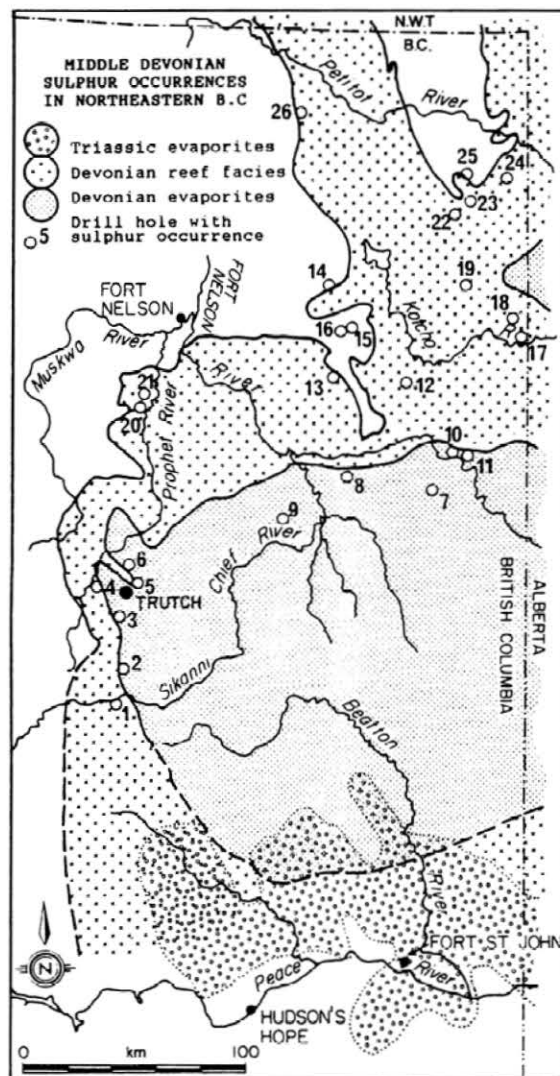


Figure 3. Native sulfur occurrences in northeastern British Columbia.

a major opportunity to investigate Frasch sulfur potential in British Columbia.

Garnet-kyanite-andalusite: Amphibolite-facies rocks in British Columbia

Kyanite, andalusite, and garnet are common components of amphibolite-facies schist and gneisses. A number of locations with high concentrations of garnet or kyanite have been recognized as a result of our compilation study (Figure 4). Two garnet-rich placers associated with primary sources were reported recently from the Revelstoke area. There is excellent potential to find other sources of these abrasive and refractory minerals. Amphibolite rocks are found in the Coast and Omineca crystalline belts.

Talc: Talc occurrences in British Columbia

Our recent study of talc potential in British Columbia identified 38 major showings and 28 occurrences (Figure 5). The majority

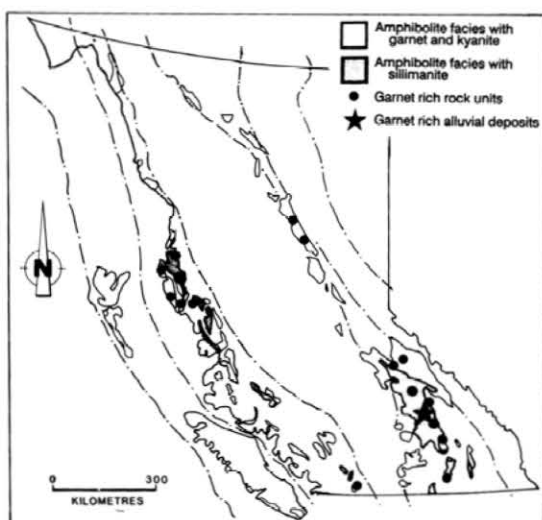


Figure 4. Kyanite and almandine garnet in British Columbia.

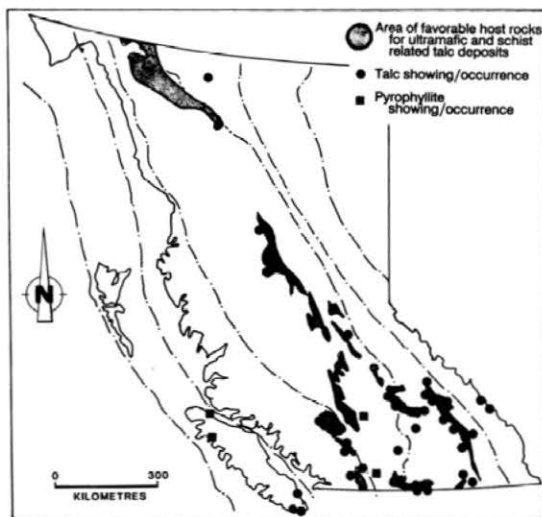


Figure 5. Distribution of talc host rocks units and occurrences in British Columbia.

of occurrences are associated with schists and ultramafics of Mississippian to Triassic and Cambrian to Mississippian formations (Cache Creek, Anarchist, Sylvester, Antler, and Lardeau), all of which are continuous and can be followed over large distances. Two properties that were recently studied in more detail produced commercial quality talc in laboratory-scale investigations. The continuity of geological units hosting talc occurrences, a local market of several tens of thousands tons in the pulp and paper industry (supplied at present from abroad), and a proven possibility to produce a commercial quality product by simple flotation techniques provide excellent incentives for industry to step in and start talc production in British Columbia.

The geology of the dolomite environment of the Rocky Mountains, which hosts two major talc showings now in National Parks, is poorly known. This area deserves attention and should be prospected for high-quality talc deposits.

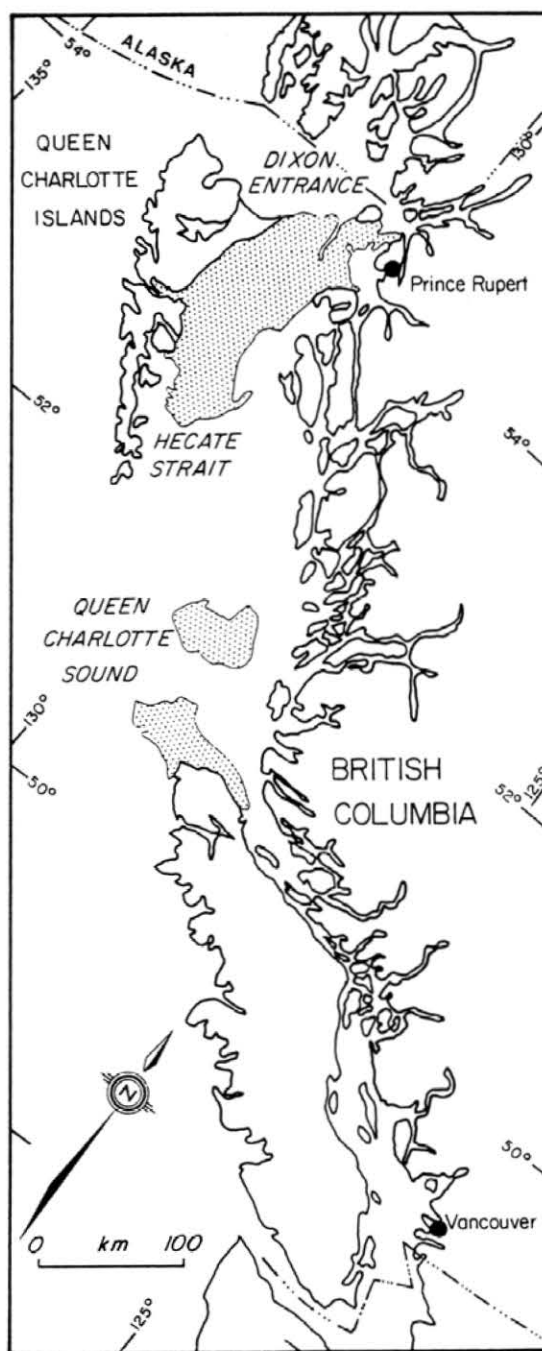


Figure 6. Ilmenite-rich bottom sands in Hecate Strait and Queen Charlotte Sound.

Titanium: Off-shore placer deposits

Recent studies conducted by the Pacific Geoscience Centre have identified three major areas of the inner British Columbia continental shelf with high concentrations of heavy minerals (Figure 6). The

northern margin of Cook Bank, the southwestern margin of Goose Island Bank, and the nearshore area northeast of Graham Island contain up to 18 percent heavy minerals. Significant components of the heavy minerals suite are the titanium minerals ilmenite (5-25 percent) and sphene (5-15 percent); zircon is also present. Shallow drilling into the sea-bottom sediments indicates that heavy mineral enrichment is not only concentrated on the sea floor but continues for at least several meters below it.

Peat: Peat potential of British Columbia

During 1987, the Branch completed a province-wide inventory of peat resources, because deposits of good-quality peat in the Fraser Lowland are mined out. The project concluded that while good sphagnum moss peat in B.C. is not particularly common, there are areas in the northeast and along the north coast where good-quality peat has a minable thickness and should receive some attention from the peat industry.

Other industrial minerals studies

Several site-specific projects were carried out in recent years to investigate the potential for replacing imported industrial minerals by a local product.

A *dimension stone* study confirmed that a number of old abandoned quarries on the coast as well as in the interior have excellent potential to produce marble or granite that would meet industry specifications.

An *olivine* study confirmed that dunite from the Tulameen ultramafic complex can successfully compete with olivine products imported from the state of Washington.

A *feldspar-nepheline syenite* study indicates that at least three of the ten sites studied in 1987 have an excellent chance of filling the 33,000-ton potential market identified by the market study (Figure 7).

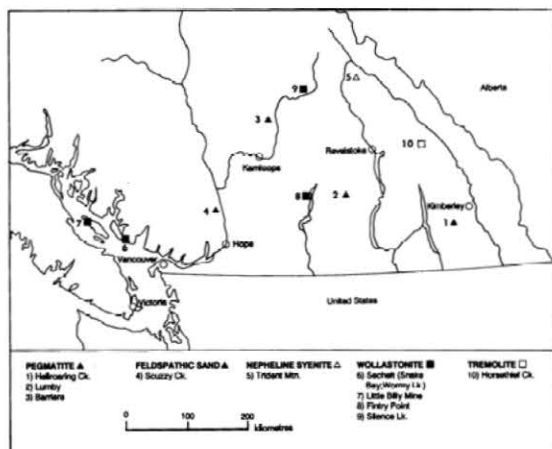


Figure 7. Location of feldspar, nepheline syenite, and wollastonite prospects in British Columbia.

A *magnetite* study identified number of potential alternative sources in all parts of the province. Several genetic types—skarn, magmatic, and iron formation occurrences—are known in British Columbia. Depending on demand and local economics, the industry can choose and develop any of the deposits when the reserves of the present producer are depleted.

A *wollastonite* study confirmed that five prospects are potential deposits capable of supplying western Canada and the Pacific Northwest with acicular products.

A *fluorspar* study classified the known occurrences, assessed the potential of using the regional geochemical survey data as

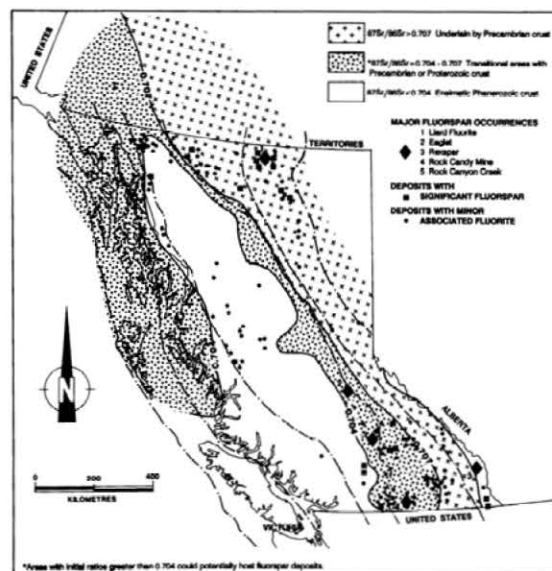


Figure 8. Fluorspar in British Columbia.

an exploration tool for fluorspar, and outlined areas of the province with potential to discover commercial deposits (Figure 8).

TENURE IMPLICATIONS: Bill 66

Historically, industrial minerals in British Columbia have been subject to two tenure systems. Some were classified as minerals, and the tenure was assured by the staking of a mineral claim. Others, like all clays, limestone, dolomite, volcanic ash, or diatomite, were subject to the Lands Act, and the prospector or developer faced many problems securing tenure to a discovery. This lack of secure tenure tended to discourage the development of these commodities. The new Mineral Tenure Act passed its third reading on March 11, 1988, and was proclaimed the following August. Under this new Act, the definition of "mineral" covers, in principal, all industrial minerals. Only fuels, sand and gravel, soil, and peat are excluded from the definition.

ACKNOWLEDGMENTS

In conclusion, I would like to thank a number of my colleagues who did most of the work in developing some of my ideas and doing independent research on individual projects. The main credit, however, goes to the Canada-British Columbia Mineral Development Agreement and to the Geological Survey Branch for providing the funds to reach the conclusions of this paper.

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Overview of the impact on the perlite industry of the IARC classification of crystalline silica as a Group 2A (probable) carcinogen in humans

by James M. Barker and Christopher McKee, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801

ABSTRACT

The International Agency for Research on Cancer (IARC) classified crystalline silica as a Group 2A (probable) carcinogen in humans. Adverse classification by IARC, which is a nonregulatory agency, is very significant because many regulatory bodies must follow or consider its findings. California included IARC findings in its listing of toxic materials under Proposition 65. OSHA considered IARC findings while promulgating its regulations on hazardous air contaminants.

The impact of these scientific and regulatory trends in the mineral industry will be broad. Minerals and materials bearing silica at very low levels will be affected by the IARC threshold of 0.1 percent crystalline silica. The regulatory track should follow that of talc and asbestos, including the emotional aspects. Silica is much more common than talc or asbestos, so, in the final analysis, it may have the farthest reaching impact on industry. Permissible levels set by California and OSHA have usually been lower than industry wants but higher than environmentalists desire. This pragmatic approach will blunt the impact somewhat.

INTRODUCTION

The International Agency for Research on Cancer (IARC) of the World Health Organization published a Group 2A rating (probably carcinogenic in humans) rating for crystalline silica (IARC, 1987a,b). IARC also issued findings on wollastonite, attapulgite, sepiolite, talc, and erionite (Table 1), but this paper will discuss only silica (crystalline and amorphous) and perlite. While IARC is nonregulatory, many government regulatory agencies are bound by its findings. Classification of crystalline silica as a "probable carcinogen" (Class 2A) by IARC triggered requirements to label products containing greater than 0.1-percent crystalline silica and affected regulations in California (Proposition 65) and OSHA (Air Contaminant; Final Rule).

The 0.1-percent crystalline-silica labeling threshold is arbitrary and very low, considering the abundance of silica in the crust of the earth. Therefore, this standard will affect many industrial mineral producers including the perlite industry. Existing analytical techniques were inadequate, so Manville Sales Corporation led the way in developing an X-ray diffraction method to determine 0.1-percent crystalline silica in perlite (Hamilton and Peletis, 1988).

CRYSTALLINE SILICA

The term "silica" refers herein to naturally occurring materials composed of SiO_2 . The two major types are amorphous and crystalline. Additional types of crystalline silica are related to variations in temperature and pressure, but all are SiO_2 . Amorphous silica is noncrystalline but solid silica, which is a colloid, gel, glass, or hydrous cryptocrystalline material (IARC, 1987a, p. 39-40). The most common types of crystalline silica are quartz (common), cristobalite (trace), and tridymite (rare). A common form of amorphous silica is diatomite. Numerous other synonyms for both types of silica occur in chemistry, mineralogy, geology, and industry. Silicon and oxygen are two of the most abundant elements in the crust of the earth (12 percent quartz), leading to many, many forms and a ubiquitous nature. Synthetic forms, such as fused silica, are common (IARC, 1987a, p. 42). The IARC monograph entitled "Silica and Some Silicates" (IARC, 1987a) goes into con-

Table 1. Selected materials classified by carcinogenicity in humans by IARC. Materials are chosen for study by IARC based on some evidence of activity in humans

GROUP 1 (Carcinogenic)

- Arsenic and arsenic compounds
- Asbestos
- Chromium compounds, hexavalent
- Coal gasification
- Coal-tar pitches
- Coal-tars
- Erionite
- Hematite mining, underground, with exposure to radon
- Mineral oils, untreated and mildly treated
- Nickel and nickel compounds
- Shale oils
- Talc containing asbestiform fibers

GROUP 2A (Probably Carcinogenic)

- Beryllium and beryllium compounds
- Cadmium and cadmium compounds
- Silica, crystalline

GROUP 2B (Possibly Carcinogenic)

- Bitumens, extracts of steam-refined and air refined
- Carbon black extracts
- Lead and lead compounds, inorganic

GROUP 3 (Not Classifiable)

- Attapulgite
- Bitumens
- Carbon blacks
- Chromium compounds, trivalent
- Chromium metal
- Ferric oxide
- Hematite
- Lead compounds, organolead
- Mineral oils, highly refined
- Selenium and selenium compounds
- Silica, amorphous
- Talc not containing asbestiform fibers
- Wollastonite

Source: IARC, 1977a, 1977b.

siderable detail on the occurrence, processing, and use of silica in most of its forms. The IARC summary of the evidence for carcinogenicity of silica is in Appendix B.

CALIFORNIA PROPOSITION 65

IARC is a nonregulatory agency whose findings are, however, widely followed. California included minerals from the appropriate IARC list in its group of regulated minerals. California occupies a position similar to IARC because it often leads the way on legislative trends. Passage of Proposition 65 there in 1986 will likely lead to similar proposals nationwide, and most if not all will become law. Illinois is now considering such legislation. Pre-emption by federal statutes may interfere, perhaps not for the better.

Canada has enacted stringent laws on labeling and worker rights. Canada has had labeling regulations in force since October 31, 1988. The regulations are specific to each province, so the regulatory climate is a mixture of conflicting rules. Some provinces require labeling of waste that is to be dumped. The label must be visible during storage, use, or transport. Bulk shipments can have the hauler labeled, but every container need not be labeled. Labels

must be in English and French (keyed to workers' language). Some Canadian companies are labeling everything except distilled water with a "T" for toxic. The worker's right to refuse to work with a toxic material is strong. The worker can neither be replaced nor lose wages. Threshold levels are 1 percent for nuisance dust and 1/10th of 1 percent for carcinogens. The following discussion of Proposition 65 draws heavily on Roberts (1989).

Proposition 65 was a vaguely worded, short proposition. It simply says that the public must be warned if it is knowingly exposed to a substance that poses a significant risk of cancer or birth defects. A toxic substance "known" to the State of California as carcinogenic or to cause birth defects cannot be discharged without a clear and reasonable warning. The proposition is currently being translated into detailed regulations. These regulations are generally intermediate between environmentalist and industrialist desires. Industry, while implementing the law, continues to fight it, particularly in the federal Domestic Policy Council.

California was charged with developing a list of known carcinogens and reproductive toxins, but the need for defining "significant risk" was unspecified in the law. Thus, California is developing these limits. The risk threshold has been set at 10^{-5} , or one excess cancer per 100,000 people. Labeling is mandatory after October 1, 1989, if a company is doing business in California.

The reproductive toxin aspect of Proposition 65 may be unworkable. The law sets the allowable dose at 1,000 times less than the no-observable-effect level (NOEL). This is fixed, unlike the carcinogen dose, and can be changed only by two-thirds vote of the state assembly. At this very low threshold level, some very common products and consumer drugs may require warnings.

OSHA AIR CONTAMINANTS: FINAL RULE

The final regulations concerning airborne perlite and silica were released by OSHA on January 19, 1989, in the Federal Register (OSHA, 1989). Pertinent portions of this lengthy document are in Appendix A, with many acronyms defined in the Glossary. The material in Appendix A is unedited and for reference only; refer to the original before decisions are made. Additional data are in Tables 2 to 11.

OSHA has made the critical distinction between inhalation and ingestion and between respirable and nonrespirable dust. Ingestion has not been shown to be a hazard. Inhalation can be a hazard if the material is small (5 to 10 microns or less). So far, California has not made this distinction but has been petitioned for a waiver by the Perlite Institute. Implementation of the Air Contaminant rules are over a four-year period. The effective date for PEL's is March 1, 1989, as in Table 4 (Z1a). Compliance by a combination of engineering, work practice, and respirators is set for September 1, 1989. Complete compliance by engineering is set for December 31, 1992, unless the methods of compliance have not been published by December 31, 1991, whereupon the compliance date is December 31, 1993. Central to OSHA Rules and Hazard Communications are Material Safety Data Sheets (MSDS), labels, health and safety training, and the worker's right to know. See, for example, OSHA Hazard Communication 1910.1200 (September 23, 1987).

TRACE SILICA DETERMINATION BY X-RAY DIFFRACTION

Sample preparation

Perlite samples were split into about 20-g units. They were ground for three minutes in a tungsten-carbide Tema mill. Grinding is the critical operation in sample preparation. As fine a grind as possible is necessary, but certainly 99 percent greater than 325 mesh is a minimal requirement. Samples were back packed on a glass slide. A special sample holder was fabricated. It was constructed of 1/8-in. hard aluminum with sharp edges and lapped surfaces. Our unit required a 33-mm disk with a 24-mm bore,

GLOSSARY

ACGIH	American Conference of Government Industrial Hygienists
AIHA	American Industrial Hygiene Association
ANPRM	Advanced Notices of Proposal Rulemaking
ANSI	American National Standards Institute
ATSDR	Agency for Toxic Substances and Disease Registry
CAS	Chemical Abstracts Service (Registry Number)
CEGL	Continuous Exposure Guidance Level
CFR	Code of Federal Regulations
CHRIS	Chemical Hazards Response Information System
DL	Detection Limit
DOT	Department of Transportation
EEGL	Emergency Exposure Guidance Level
ETS	Emergency Temporary Standards
HHE	Health Hazard Evaluation
HS	OSHA Health Standard Number
HSDB	Hazardous Substances Data Bank
IARC	International Agency for Research on Cancer
ILO	International Labour Organization
IMIS	Integrated Management Information System
IRIS	Integrated Risk Information System
LD	Lethal Dose
LOAEL	Low Observed Adverse Effect Level
LOEL	Low Observed Effect Level
MAC	Maximum Acceptable Concentration
MSDS	Material Safety Data Sheet
MSHA	Mine Safety and Health Administration
NIOSH	National Institute for Occupational Safety and Health
NOAEL	No Observed Adverse Effect Level
NOEL	No Observed Effect Level
NOES	National Occupational Exposure Survey
NOHS	National Occupational Hazard Survey
NPRM	Notice of Proposed Rulemaking
OCIS	OSHA Computerized Information System
PEL	Permissible Exposure Limit
PNOR	Particulates Not Otherwise Regulated
PRIA	Preliminary Regulatory Impact Analysis
REL	Recommended Exposure Limit
RfD	Reference Dose
RTECS	Registry of Toxic Effects of Chemical Substances
SOCMA	Synthetic Organic Chemical Manufacturers Association
SPGL	Short-term Public Emergency Guidance Level
STEL	Short-term Exposure Limit
TLV	Threshold Limit Value
TLV-C	Threshold Limit Value-Ceiling
TSCA	Toxic Substances Control Act
TWA	Time Weighted Average
WAC	Workday Ambient Air Concentration
WEEL	Workplace Environmental Exposure Limits
WISH	Workers Institute for Safety and Health

but this will vary. A brass piston, 0.004-in. smaller than the bore in the sample holder, is used to pack the sample. The sample holder was placed in a sample spinner (Renault, 1984). The circular holder is easier to pack consistently than one with 90° corners.

Procedure

X-ray diffraction has several benefits over such methods as optical petrography, heavy liquids, solubility, or infrared absorption. The benefits include bulk analysis, insensitivity to material, availability, rapidity, and the ability to detect at the 0.1-percent SiO₂ (crystalline) level.

The samples were analyzed using the parameters in Table 12. Two background positions were measured (26.2° and 27.0°) and subtracted from the total counts to obtain the counts for the quartz peak. Each sample was analyzed three times (Figure 1), and the average of the three values was used in calculations for weight percent quartz and for precision.

A long scan from 60° to 2° two-theta was run first to check for interfering phases such as feldspar, mica, clay, etc. None of the samples had any detectable interfering phases.

Precision at the 0.1-percent crystalline silica level is about

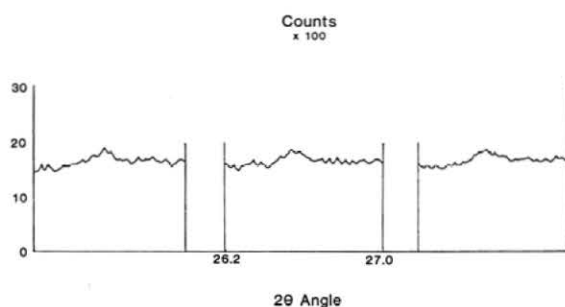


Figure 1. XRD peaks for 0.4% quartz in perlite.

± 30 percent. This is in good agreement with Manville results. Precision increases as crystalline silica content rises, particularly above about the 1-percent level.

The New Mexico Bureau of Mines and Mineral Resources accepts samples on a fee basis. Our base price is \$150 per sample, with volume discounts. Names and addresses of additional laboratories are listed in Appendix C.

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APPENDIX A

Data on perlite and silica abstracted from OSHA Final Regulation (Federal Register, January 19, 1989)

SUBSTANCES FOR WHICH LIMITS ARE BASED ON THE AVOIDANCE OF RESPIRATORY EFFECTS INTRODUCTION

Limits are being established for a total of 35 substances or materials for which exposure has been shown to cause adverse respiratory effects. The chemicals in this group cause acute pulmonary edema, alveolar damage, or chronic respiratory damage through the general mechanisms of cellular damage or fibrosis. At sufficient doses, these effects can be permanent, disabling, and life-threatening.

Table 2. Basis for limits

H.S. No.	Substance Name	CAS Number	Primary Basis for Limits
1310	Perlite	None	Physical Irritation
1352	Silica, amorphous, diatomaceous earth	68855-54-9	Increasing PEL
1353	Silica, amorphous, precipitated or gel	None	Increasing PEL
1354	Silica, crystalline-cristobalite	14464-46-1	Respiratory effects
1355	Silica, crystalline quartz, respirable	14808-60-7	Respiratory effects
1356	Silica, crystalline tridymite	15468-32-3	Respiratory effects
1357	Silica, crystalline tripoli (as quartz dust)	1317-95-9	Respiratory effects
1358	Silica, fused	60676-86-0	Respiratory effects

Some of the materials in this group are composites of naturally occurring minerals, and, for these, the Agency is establishing limits based on the most hazardous component. For several material (coal dust, crystalline tripoli, silica, and graphite), OSHA is requiring the TWA to be measured as the respirable quartz fraction of the dust, because it is exposure to this fraction that presents the greatest risk to exposed workers.

Table C6-1 lists the 35 substances in this group along with the former proposed and final rule PEL's and CAS and HS Numbers. There was no former OSHA PEL for 12 of these substances. For one substance, OSHA is establishing a ceiling limit to replace an existing 8-hour TWA, and for ten substances, a lower TWA and/or STEL are being established. In three instances, OSHA is establishing a STEL to augment its former TWA-PEL's. For nine substances, OSHA is changing only the form in which the limit is being expressed.

Table 3 (C16-1). The ACGIH's limits are higher than the former OSHA PELs

H.S. number/ Chemical name	CAS No.	Current PEL	ACGIH TLV ⁸⁸	Final Rule PEL ⁸
1352 Silica, amorphous-diatomaceous earth (containing less than 1 percent crystalline silica)	68855-54-9	20 upper TWA (6 mg/m ³)	10 mg/m ³ TWA	6 mg/m ³ TWA
1353 Silica, amorphous-precipitate and gel	None	20 upper TWA (6 mg/m ³)	10 mg/m ³ TWA	6 mg/m ³ TWA

* OSHA's TWA limits are for 8-hour exposures; its STELs are for 15 minutes unless otherwise specified; and its ceilings are peaks not to be exceeded for any period of time.

** The ACGIH TWA-TLV is for an 8-hour exposure; its STELs are 15-minute limits not to be exceeded more than 4 times per day with a minimum of 60 minutes between successive STEL exposures; and its ceilings are peaks not to be exceeded for any period of time.

PARTICULATES (NOT OTHERWISE REGULATED)

CAS: None; Chemical Formula: None
H.S. No. 1294

OSHA formerly covered all otherwise unregulated particulates under a single 8-hour TWA PEL of 15 mg/m³ (measured as total particulate) and 5 mg/m³ (measured as the respirable fraction). The ACGIH has a TLV—TWA of 10 mg/m³ (as total dust) for particulates having a quartz content of less than 1 percent. OSHA's proposed total particulate PEL for these physical irritants was 10 mg/m³; NIOSH (Ex. 8-47, Table N4) concurred with the proposed limit. In the final rule, OSHA is retaining its 15-mg/m³ total particulate PEL for particulates that are not specifically identified in the Z tables; OSHA is also retaining its 5-mg/m³ respirable particulate limit for these substances. The Agency has decided to retain its existing limits for particulates that are not specifically identified in the Z tables, because this group of physical irritants consists of substances, both inorganic and organic, for which substance-specific toxicologic data are not available. For those physical irritants for which specific toxicologic data for available, OSHA has separately identified the substance in Table Z-1-A and has promulgated a 10-mg/m³ 8-hour TWA (measured as total particulate) and a 5-mg/m³ 8-hour TWA PEL (measured as the respirable fraction) in the final rule.

The 8-hour TWA limits of 15 mg/m³ (total particulate) and 5 mg/m³ (respirable fraction) apply to all not-otherwise-regulated particulates (i.e., to those irritants that are not specifically identified in the Z tables). For example, OSHA's limits for corn dust, a particulate not identified in the Z tables or otherwise regulated, are 15 mg/m³ (total dust) and 5 mg/m³ (respirable dust). The Agency believes that other particulates that present physical irritant hazards in the workplace should also be regulated under the final rule's generic total particulate limit of 15 mg/m³.

OSHA believes that good industrial hygiene practice requires that exposures to these particulates be controlled in the workplace to or below the 15-mg/m³ level as an 8-hour TWA to protect workers from the broad range of adverse effects associated with exposure to these substances. In the past, these particulates were often called "nuisance" or "inert" substances. These terms are misleading, however, because exposures to these substances in the workplace may cause serious and sometimes disabling effects. Further, good industrial hygiene and public health practice require that workplace exposure to particulates be maintained below the level associated with physical irritation, accidents, and respiratory effects.

Table 4 (Z-1-A). Limits for air contaminants

Substance	Transitional Limits PEL*			Skin designation	TWA		Final Rule Limits** STEL ^C		CEILING		Skin designation
	CAS No.	ppm ^a	mg/m ³ ^b		ppm ^a	mg/m ³ ^b	ppm ^a	mg/m ³ ^b	ppm ^a	mg/m ³ ^b	
Perlite	--	--	--	--	--	--	--	--	--	--	--
Total dust	--	--	15	--	--	15	--	--	--	--	--
Respirable fraction	--	--	5	--	--	5	--	--	--	--	--
Silica, amorphous, precipitated and gel	--	See Table Z-3	--	--	6	--	--	--	--	--	--
Silica, amorphous, diatomaceous earth, containing less than 1% crystalline silica	68855-54-9	See Table Z-3	--	--	6	--	--	--	--	--	--
Silica, crystalline cristobalite (as quartz), respirable dust	14464-46-1	See Table Z-3	--	--	0.05	--	--	--	--	--	--
Silica, crystalline, quartz (as quartz), respirable dust	14808-60-1	See Table Z-3	--	--	0.1	--	--	--	--	--	--
Silica, crystalline tripoli (as quartz), respirable dust	1317-95-9	See Table Z-3	--	--	0.1	--	--	--	--	--	--
Silica, crystalline tridymite (as quartz), respirable dust	15468-32-3	See Table Z-3	--	--	0.05	--	--	--	--	--	--
Silica, fused, respirable dust	60676-86-0	See Table Z-3	--	--	0.1	--	--	--	--	--	--
Silicates (less than 1% crystalline silica)											
Mica (respirable dust)	12001-26-2	See Table Z-3	--	--	3	--	--	--	--	--	--
Soapstone, total dust	--	See Table Z-3	--	--	6	--	--	--	--	--	--
Soapstone, respirable dust	--	See Table Z-3	--	--	3	--	--	--	--	--	--
Talc (containing asbestos): use asbestos limit	--	See Table Z-3	--	--	See 29 CFR 1910.1001						
Talc (containing no asbestos), asbestos, respir- able dust	14807-96-6	See Table Z-3	--	--	2	--	--	--	--	--	--
Tremolite		See Table Z-3	--	--	See 29 CFR 1910.1101						

Several commenters (see, for example, Exs. 3-661, 3-755, 3-1012, 3-1112, and 8-22) submitted comments on OSHA's proposed generic total particulate limit. Most of these participants argued that the proposed reduction in the 8-hour TWA PEL from 15 mg/m³ to 10 mg/m³ was unwarranted because there was, in the opinion of these commenters, no evidence of adverse health effects associated with exposure to these particulates (Exs. 3-755, 3-1012, 3-1112, and 8-22). According to Peter Hernandez of the American Iron and Steel Institute (Ex. 8-22), the effects of such exposures are "short-term and immaterial."

OSHA has responded to these commenters in the final rule by establishing a lower 8-hour TWA total-dust limit of 10 mg/m³ for all particulates having identified health effects in the toxicological literature, and retaining the former 15-mg/m³ total particulate limit for those particulates not specifically linked to health effects other than physical irritation. OSHA finds that good industrial hygiene practice demands and prudent public health policy supports effective workplace control over exposure to all particulates. The effects associated with overexposure to particulates in the workplace constitute material impairments of health and functional capacity and include upper respiratory tract irritation, skin injury, eye irritation, and other forms of physical irritation.

The 15 mg/m³ 8-hour TWA total particulate PEL applies to all particulates not otherwise regulated, not just to inorganic dusts. The OSHA Review Commission interpreted the Agency's former generic dust standard as applying only to mineral dusts, primarily because this limit was entered on the Z tables under the heading "mineral dust." The ACGIH and OSHA both had intended this limit to apply to all particulates, organic and inorganic. Exposure to organic particulates at high levels also causes material health impairment, such as throat, skin, and eye irritation; upper-respiratory-tract problems; and the safety hazards caused by distraction in the workplace.

In the final rule, OSHA establishes an 8-hour TWA limit of 15 mg/m³, measured as total particulate, and retains the 5-mg/m³ limit for respirable

particulates for all particulates not otherwise regulated. The Agency concludes that these limits will protect workers against the significant safety and health risks associated with exposure to excessive concentrations of these substances, which include reduced visibility; deposits in the eyes, ears, and nasal passages; throat and eye irritation; upper-respiratory-tract problems; skin injury; and other forms of physical irritation. The change in terminology from nuisance dusts to particulates not otherwise regulated clarifies OSHA's intent and also more accurately reflects the fact that exposure to all particulates at levels higher than those being established in this final rule causes material impairment of health and functional capacity in workers experiencing these exposures.

PERLITE

CAS: None; Chemical Formula: None
H.S. No. 1310

OSHA formerly regulated perlite under its generic total particulate limit of 15 mg/m³. The ACGIH has a TLV-TWA of 10 mg/m³ for perlite as total dust containing less than 1 percent quartz. The proposed PEL's were 10 mg/m³ (total particulate) and 5 mg/m³ TWA (respirable particulate); however, the final rule retains the 15-mg/m³ TWA PEL for perlite as total particulate containing less than 1 percent quartz. The respirable fraction limit of 5 mg/m³ is also retained. Perlite is a natural volcanic glass; it is essentially an amorphous mineral consisting of fused sodium-potassium-aluminum silicate.

Perlite is reported to have a free-silica content varying from zero to 3 percent (Anderson, Selvig, Bauer and others, 1956, and the Perlite Institute, both as cited in ACGIH 1986/Ex. 1-3, p. 467). In its processed crude and expanded forms, perlite is reported to have a measurable quartz content of 0.4 percent quartz and 0.2 percent cristobalite (Sheckler 1977, as cited in ACGIH 1986/Ex. 1-3, p. 467). There are no published reports of adverse

Table 5. Sampling and analytical methods

H.S. No.	Validated Analyte	Other method	No method	Det method	limit ¹	Comments
1310	Perlite	gravimetric	---	---	0.02 mg/m ³	Same as nuisance particulate TLV
1352	Silica - Amorphous diatomaceous earth (uncalcined)-	grav & ID142	---	---	0.02 mg/m ³	If >1% quartz, use quartz standard
1353	Precipitated silica-					
----	Silica gel-					
----	Silica - Crystalline					
1354	Cristobalite-	OSHA ID142	---	---	0.05 mg/m ³	DL based on 816 L air vol
1355	Quartz-	OSHA ID142	---	---	0.02 mg/m ³	DL based on 480 L air vol
1356	Tridymite-	OSHA ID142	---	---	0.05 mg/m ³	
1357	Tripoli-	OSHA ID142	---	---	0.02 mg/m ³	Quartz analysis
1358	Silica, fused-	OSHA ID142	---	---	0.02 mg/m ³	If >1% quartz, use quartz standard

physiologic effects from exposure to perlite dust. NIOSH, the only commenter on perlite, has not reviewed the evidence for this substance in depth (Ex. 8-47, Table N4).

OSHA finds that perlite is nontoxic when airborne total particulate concentrations are maintained at levels of 15 mg/m³ or below and when its quartz content is limited to a level below 1 percent crystalline silica. For these reasons, the final rule establishes an 8-hour PEL of 15 mg/m³ TWA for total perlite dust containing less than 1 percent quartz and retains the 5-mg/m³ TWA PEL for the respirable fraction of perlite dust. OSHA concludes that these limits protect workers from the significant risk of eye, skin, and other forms of physical irritation.

SILICA, AMORPHOUS-DIATOMACEOUS EARTH

CASL 68855-54-8; Chemical Formula: SiO₂
H.S. No. 1352

OSHA's current limit for amorphous silica is 20 mppcf, which is equivalent to 6 mg/m³ TWA (ACGIH 1984), measured as total dust. The ACGIH has established a limit for this dust (measured as total dust) of 10 mg/m³ (8-hour TLV-TWA). Amorphous silica (diatomaceous earth) is composed of the skeletons of prehistoric plants known as diatoms. These skeletons are largely noncrystalline, although diatomaceous earth can contain varying amounts of crystalline quartz, which has led, in the opinion of the ACGIH (1986/Ex. 1-3, p. 520), to conflicting results in studies of the pulmonary effects of exposure to this colorless to gray, odorless powder.

Cooper and Cralley (1958/Ex. 1-1145) reported "doubtful" linear-nodular changes in the lungs of workers exposed only to amorphous (non-crystalline) silica for five years or more. Other studies (Vigliani and Mottura 1948/Ex. 1-534; Gardner 1942, as cited in ACGIH 1986/Ex. 1-3, p. 520) either found mild silicosis only or no evidence of serious lung pathology in diatomite workers. Kovalevich (1957, as cited in ACGIH 1986/Ex. 1-3, p. 520) reported silicosis in diatomite workers, but intratracheal instillation of diatomaceous earth dust in animals caused evidence of fibrosis (Gardner 1942, as cited in ACGIH 1986/Ex. 1-3, p. 520) and silicosis (Kovalevich 1957, as cited in ACGIH 1986/Ex. 1-3, p. 520). Another study (Tebbens and Beard 1957/Ex. 1-531) exposed guinea pigs to this substance at an average concentration of 60 mg/m³ for 37 to 50 weeks and found both accumulations of dust-laden macrophages and alveolar epithelialization but no fibrosis.

In setting its limit for diatomaceous earth, the ACGIH (1986/Ex. 1-3, p. 520) assumed that this substance itself is either "weakly fibrogenic or nonfibrogenic," and thus that those studies discussed above that report adverse pulmonary effects actually involved exposure to diatomaceous earth having an unmeasured but significant crystalline quartz content. Based on this reasoning, the ACGIH considers amorphous silica (diatomaceous earth) to have low biological activity.

OSHA received few comments on its proposal to retain the 6-mg/m³ PEL for diatomaceous earth. The Synthetic Amorphous Silica and Silicates Industry Association (SASSI) (Ex. 1-630) requested that OSHA revise its entry for "silica, amorphous, diatomaceous earth" to "silica, crystalline, diatomaceous earth" to reflect the fact that diatomaceous earth frequently contains crystalline silica. OSHA intends the PEL for crystalline quartz of 0.1 mg/m³ to apply to diatomaceous earth containing more than 1 percent crystalline silica. For clarification, OSHA has added the designation "con-

taining less than 1 percent crystalline silica" to the entry for diatomaceous earth on Table Z-1-A of the final rule, for which the 6-mg/m³ limit is applicable.

SASSI also suggested that the crystalline silica PEL apply to any silicates containing more than 0.1 percent, rather than 1 percent, crystalline silica because of recent concerns regarding the potential carcinogenicity of silica. As discussed in the section on crystalline silica (see Section VI.C.6), OSHA has not made a final determination on the carcinogenicity of silica; therefore, at this time, OSHA will apply the limits for silicates to those materials containing less than 1 percent silica.

NIOSH (Ex. 8-47) concurred with the 6-mg/m³ TWA PEL for diatomaceous earth, provided the silica content does not exceed 1 percent. Chevron Corporation (Ex. 3-896) also agreed with the proposal of OSHA. Both Chevron (Ex. 3-896) and SASSI (Ex. 3-630) agreed that the former mppcf limit should be revised to a limit expressed as mg/m³, since the use of mppcf units is outdated.

OSHA is retaining an 8-hour TWA of 6 mg/m³ (equivalent to 20 mppcf) for this form of silica. OSHA finds that the health evidence for this substance is not sufficiently persuasive to permit an increase in the limit at the present time. The Agency is revising the units in which its permissible exposure limit for diatomaceous earth is expressed; this change is being made to facilitate the accurate monitoring of employee exposures and does not represent a change in the value of the limit.

Table 6. NIOSH analytical methods for PEL update

H.S. No.	Analyte	Validated Method	Other Method
1310	Perlite	NIOSH 500, 600	
1352	Silica - Amorphous diatomaceous earth (uncalcined)-		NIOSH 7501
	Precipitated silica-		
----	Silica gel-		
----	Silica - Crystalline		
1354	Cristobalite	NIOSH 7500	
1355	Quartz	NIOSH 7500	
1356	Tridymite-	NIOSH 7500	
1357	Tripoli-	NIOSH 7500	

Source: OSHA Final Regs. (Federal Register, Jan. 19, 1989)

SILICA, AMORPHOUS PRECIPITATED AND GEL

CAS: None; Chemical Formula: SiO₂
H.S. No. 1353

OSHA currently has a limit of 20 mppcf (which is equivalent to a limit of 6 mg/m³) for amorphous silica. The ACGIH recommends a TLV-TWA of 10 mg/m³ measured as total dust containing less than 1 percent quartz. OSHA is retaining the current PEL in the final rule but is expressing

Table 7 (C6-1). Exposure limits based on avoidance of respiratory effects

H.S. Number/ Chemical Name	CAS No.	Former PEL	Proposed PEL	Final Rule PEL ^a
1096 Coal dust, @ 5% quartz	None	--	2 mg/m ³ TWAA	2 mg/m ³ TWAA
1097 Coal dust, @ 5% quartz	None	--	0.1 mg/m ³ TWAb	0.1 mg/m ³ TWAb
1191 Graphite, natural, respirable @ 1% quartz	7782-42-5	15 mppcf TWA	2.5 mg/m ³ TWA	2.5 mg/m ³ TWA
1276 Mica, respirable dust containing 1% quartz	12001-26-2	10 mppcf TWA	3 mg/m ³ TWA	3 mg/m ³ TWA
1354 Silica, crystalline cristobalite (as respirable quartz dust)	14464-46-1	1/2 value calcu- lated for quartz	0.05 mg/m ³ TWA	0.05 mg/m ³ TWA
1355 Silica, crystalline quartz, respirable	14808-60-7	10 mg/m ³ ----- % SiO ₂ +2	0.1 mg/m ³ TWA	0.1 mg/m ³ TWA
1356 Silica, crystalline tridymite (as respirable quartz dust)	15468-32-3	1/2 value calcu- lated for quartz	0.5 mg/m ³ TWA	0.05 mg/m ³ TWA
1357 Silica, crystalline tripoli (as respirable quartz dust)	1317-95-9	10 mg/m ³ ----- % SiO ₂ +2	0.1 mg/m ³ TWA	0.1 mg/m ³ TWA
1358 Silica, fused	60676-86-0	10 mg/m ³ ----- % SiO ₂ +2	0.1 mg/m ³ TWA	0.1 mg/m ³ TWA

a For coal dust, respirable fraction less than 5 percent SiO₂.

b For coal dust, respirable fraction more than 5 percent SiO₂.

* OSHA's TWA limits are for 8-hour exposures; its STELs are for 15 minutes unless otherwise specified; and its ceilings are peaks not to be exceeded for any period of time.

this limit in milligrams per cubic meter. NIOSH (Ex. 8-47, Table N1) concurs with the Agency's decision. There are numerous methods of producing precipitated silica; those that apply heat to siliceous products produce airborne dusts that are less toxic than quartz dust because the particles are generally sheathed in a molecular layer of amorphous silica (ACGIH 1986/Ex. 1-3, p. 521).

Studies of laboratory animals have shown no fibrosis after intratracheal and intraperitoneal injection of precipitated silica or silica gel (Klosterkotter 1954/Ex. 1-1156; Klosterkotter 1958/Ex. 1-1039). Schepers and colleagues reported in 1957 that rats exposed for one year and guinea pigs and rabbits exposed for two years to a concentration of 126 mg/m³ of precipitated amorphous silica displayed no pulmonary fibrosis; the effects of exposure were limited to macrophage accumulations and mild proliferation of reticular fibers (Schepers, Durkan, Delahant and others, 1957/Ex. 1-755).

In a study of human exposures to precipitated amorphous silica, Wilson and associates reported no ill effects in 165 workers exposed for an average of 8.6 years (Wilson, Stevens, Lovejoy and others, 1981/Ex. 1-1177).

The ACGIH considers the precipitated and gel forms of amorphous silica to have low biological activity, based on the evidence discussed above. PPG Industries (Ex. 3-1158) commented that an unpublished NIOSH study (Groth, Kommineni, Stettler and others, 1979, as cited by H. E.

Stokinger in Patty's Industrial Hygiene and Toxicology, 3rd rev. ed., vol. 2B, p. 3011-3014) showed that rats, guinea pigs, and monkeys developed accumulations of macrophages in the lungs following exposure to precipitated silica. In addition, the presence of collagen was seen in "very few" monkeys; by comparison, collagen was not seen in any animal exposed to silica gel but was seen in significant amounts in monkeys exposed to fumed silica. PPG remarked that the findings in animals exposed to precipitated silica showed "no evidence for effects * * * which are inconsistent with the ACGIH criteria for nuisance particulates" (Ex. 3-1158). PPG urged OSHA to adopt a 10-mg/m³ PEL for precipitated silica based on this observation. SASSI (Ex. 3-630) also requested that OSHA adopt either a 10-mg/m³ total dust limit or a 5-mg/m³ respirable dust limit for precipitated silica, based on the recommendation of the ASTM E34.16 Committee.

After reviewing these comments, OSHA concludes that the available evidence does not meet the criteria described earlier in this section for determining that an increase in the present PEL is warranted. OSHA notes that, in the study cited by PPG, there was collagen formation only in a few animals exposed to precipitated silica. Furthermore, the report by Wilson and others (1981/Ex. 1-1177) involved only a relatively small number of employees who had been exposed for fewer than 10 years. Accordingly,

Table 8 (C6-2). Summary of dose-response evidence for adverse respiratory effects

H.S. number/ Chemical name	CAS No.	Former PEL	Final rule PEL*	Dose-Response Data		
				Dose/Duration associated with observed effects	Species	Comments
1354 Silica, crystalline cristobalite	14464-46-1	1/2 value for quartz	0.05 mg/m ³ TWA	0.5 mg/m ³ (as total dust) 2.5 years	Dogs	Cellular infiltration of lung and fibrotic nodules in pulmonary lymph nodes.
1355 Silica, crystalline quartz, respirable	14808-60-7	10 mg/m ³ ----- % SiO ₂ +2	0.1 mg/m ³ TWA	0.1 mg/m ³ chronic	Humans	Accelerated loss of pulmonary function over effects of aging alone.
1356 Silica, crystalline tridymite	15468-32-3	1/2 value for quartz	0.05 mg/m ³ TWA	N/A	Rats	Most active forms of free silica when ad- ministered by intra- tracheal injections.
1357 Silica, crystalline tripoli	1317-95-9	10 mg/m ³ ----- % SiO ₂ +2	0.1 mg/m ³ TWA	N/A	Lab Animals	Progressive nodular fibrosis.

*OSHA's TWA limits for 8-hour exposures; its STELs are for 15 minutes unless otherwise specified; and its ceilings are not to be exceeded for any period of time.

N/A = Not available

H.S. Number = OSHA Health Standard number

CAS No. = Chemical Abstract Service registry number

PEL = Permissible exposure limit

TWA = Time weighted average

STEL = Short-term exposure limit

OSHA is retaining its current PEL of 6 mg/m³ (equivalent to 20 mppcf) at the present time. However, to facilitate the accurate monitoring of employee exposures, the Agency is changing the units in which its permissible exposure limit for amorphous silica is expressed.

SILICA, CRYSTALLINE-CRISTOBALITE

CAS: 14464-46-1; Chemical Formula: SiO₂

H.S. No. 1354

The former OSHA PEL for respirable cristobalite was one-half the value calculated from the mass formula for quartz, measured as respirable dust. This limit corresponds to a range of 0.04 to 0.05 mg/m³, measured as silica, for dusts containing 10 to 100 percent quartz. The ACGIH recommends an 8-hour TWA limit of 0.05 mg/m³, measured as respirable silica dust. Although expressed differently, the current ACGIH and former OSHA limit for cristobalite are comparable. The ACGIH's mg/m³ limit, adopted in 1985, does not reflect a reevaluation of cristobalite's toxicity but was adopted merely to simplify the monitoring of cristobalite dust concentrations. The ACGIH limit is based on a study by Gardner (1938, as cited in ACGIH 1986/Ex. 1-3, p. 522) that was confirmed by King, Mohanty, Harrison, and Nagelschmidt (1953/Ex. 1-85). Experimental animals injected with cristobalite showed a more severe response than that produced by quartz, and the fibrosis that followed was diffuse rather than nodular. OSHA proposed, and the final rule establishes, a permissible exposure limit of 0.05 mg/m³ TWA for cristobalite, measured as respirable silica dust. Cristobalite, one of the three major forms of silicon dioxide, is transparent, tasteless, and stable at high temperatures.

The final rule replaces OSHA's former limit for cristobalite, which is expressed, as described above, with a numerically equivalent limit of 0.05 mg/m³. The Agency is establishing this time-weighted average limit to simplify employee exposure monitoring. NIOSH (Ex. 8-47, Table N6A; Tr. p. 3-96 to 3-97) concurred with the selection of this limit but rec-

ommended that cristobalite be designated as a potential human carcinogen. OSHA's discussion of this and other rulemaking issues appears in the following entry describing the record evidence on quartz dust.

SILICA, CRYSTALLINE-QUARTZ

CAS: 14808-60-7; Chemical Formula: None

H.S. No. 1355

The former OSHA limit for silica-containing dusts is a respirable dust limit expressed as the following formula:

$$\frac{(10 \text{ mg/m}^3)}{(\text{percent respirable quartz} + 2)}$$

At one time, the ACGIH also expressed its silica limit in terms of this formula. However, the current ACGIH TLV is 0.1 mg/m³, measured as respirable quartz dust. OSHA proposed, and the final rule establishes, a permissible exposure limit of 0.1 mg/m³ TWA, as respirable quartz. Quartz is a colorless, odorless, noncombustible solid.

The ACGIH does not consider this change in the value of its limit for occupational exposure to silica as significant; instead, the ACGIH made this change to conform its limit for this dust to its TLV's for other dusts. If the former OSHA formula is used to calculate a limit for a dust containing 100 percent quartz, the limit would be 0.98 mg/m³, a value that is not appreciably different from the ACGIH's revised limit of 0.1 mg/m³ for respirable quartz dust. For quartz dusts containing less than 100 percent free silica, the former OSHA formula would yield a limit of, for example, 0.83 mg/m³ for respirable dust containing 10 percent quartz. This result is somewhat more stringent than the ACGIH's TLV of 0.1 mg/m³. For cristobalite and tridymite, the former OSHA formula and the ACGIH limits yield approximately the same results: both are approximately one-half the limit established by these two entities for quartz dust (see the discussions below).

Table 9 (C10-1). Exposure limit based on the avoidance of physical irritation and other effects

H.S. number/ Chemical name	CAS No.	OSHA's Former Generic Total Particulate Limit*	Proposed PEL*	Final Rule PEL for total particulate**; respirable fraction
1310 Perlite	None	15 mg/m ³ TWA	10 mg/m ³ TWA	15 mg/m ³ ; 5 mg/m ³ TWA

Occupational exposure to free silica has been known for many years to produce silicosis, a chronic, disabling lung disease characterized by the formation of silica-containing nodules of scar tissue in the lungs. Simple silicosis, in which the nodules are less than 1 cm in diameter (as measured on chest X-ray films) is generally asymptomatic but can be slowly progressive, even in the absence of continued exposure. Complicated silicosis (i.e., with nodules greater than 1 cm in diameter) is more often associated with disability and can also progress in the absence of continuing exposure.

The health basis underlying the ACGIH's limit for crystalline silica is the work of Russell and others (1929/Ex. 1-156), which suggested that a limit of 10 mppcf would protect workers from the effects of exposure to granite dust; a study by Aver (1969/Ex. 1-129) demonstrated that 10 mppcf of granite dust is approximately equal to 0.1 mg/m³ of respirable quartz dust (ACGIH 1986/Ex. 1-3).

NIOSH has recommended an exposure limit of 0.05 mg/m³ as respirable free silica for all crystalline forms of silica. As applied to cristobalite and tridymite, the NIOSH REL is 0.05 mg/m³, the same as the ACGIH TLV, but NIOSH's 0.05-mg/m³ REL for quartz dust is one-half the value of the ACGIH TLV for quartz dust. To support its more stringent REL for quartz dust, NIOSH cites the work of Hosey, Ashe, and Trasko (1957, as cited in ACGIH 1986/Ex. 1-3, p. 524), which reported that no new cases of silicosis occurred in workers in Vermont granite sheds who were generally exposed to 0.05 mg/m³ or less of granite dust. The recommendation was also partly based on studies by Theriault, Burgess, DiBerardinis and others (1974/Ex. 1-94a); Theriault, Peters, and Fine (1974/Ex. 1-110); and Theriault, Peters, and Johnson (1974/Ex. 1-94b), which found that annual declines in pulmonary function and abnormal chest X-rays occurred among 192 granite shed workers exposed to an average quartz concentration of 0.05 mg/m³. NIOSH noted that the exposure estimates reported in the Theriault and others (1974/Exs. 1-94a, 1-94b, and 1-110) studies failed to account for the higher exposures that probably occurred in the years before exposure sampling was initiated and, therefore, that the Theriault and others (1974) exposure data may have understated average exposure to quartz. Thus, NIOSH believes that the exposures responsible for the declines in pulmonary function were actually above 0.05 mg/m³. The ACGIH (1986/Ex. 1-3) found NIOSH's reasoning unpersuasive, citing a report by Graham, O'Grady and Dubuc (1981/Ex. 1-172), who measured the pulmonary function of the same group of workers studied by Theriault and others (1974/Exs. 1-94a, 1-94b, and 1-110), and found, in contrast to Theriault, that these workers experienced "an overall increase in FVC and FEV" (ACGIH 1986/Ex. 1-3).

Although OSHA did not propose a significant change in the exposure limit, there were several comments that focused on two issues: (1) the adequacy of the proposed 0.1 mg/m³ respirable quartz limit in reducing the risk of silicosis; and (2) recent evidence describing the potential carcinogenicity of silica dust.

With regard to the first issue, Dr. Philip Landrigan of the Mount Sinai School of Medicine, representing the American Public Health Association, testified as follows at the informal hearing:

"Numerous epidemiologic studies have been undertaken in this century, which have established a dose-response relationship between occupational exposure to silica dust and the development of silicosis. These studies have shown clearly that there is a positive dose-response relationship between chronic silica exposure and the development of silicosis.

"The most recent of these reviews which have examined that relationship is presented in the 1986 NIOSH text on occupational respiratory diseases, a most authoritative book in the field, widely read by medical scientists in this country and abroad. The data which were summarized in that chapter indicate quite clearly that the dose-response relationship between silica exposure and silicosis is present in people with lifetime exposure to silica below the current...standard of 100 micrograms per cubic meter. Indeed,

the data suggest that the dose-response relationship extends downward even to levels of exposure below the current NIOSH recommended standard of 50 micrograms per cubic meter.

"And against the authoritative NIOSH review...OSHA has cited one short three-page article...[Graham and others, 1981/Ex. 1-172] to indicate that the dose-response relationship between silica and silicosis does not extend downward to below 100 micrograms per cubic meter (Tr. p. 3-277 to 3-278)."

Several commenters (Exs. 3-678, 3-733, 130, 138, 139, 147, 161, and 126) disagreed with Dr. Landrigan's assessment. For example, Frederick A. Renninger of the National Stone Association (Ex. 139) cited Dr. John Peters, the author of the chapter in the NIOSH reference referred to by Dr. Landrigan. In his chapter, Dr. Peters concluded as follows:

"All of the studies described in this section provide evidence for adverse pulmonary effects at levels of exposure above 10 mppcf or 0.1 mg/m³ of quartz developed silicosis while those with less exposures did not...All the Vermont findings were seen with an average exposure of around 0.05 mg/m³ of quartz. It is possible, however, that since this was the average exposure, individuals whose exposure exceeded this level accounted for the noted effects." (The "no effect" level was probably below 0.05 mg/m³, but the available data did not allow accurate determinations.) (Peters, J. M., "Silicosis," In: Occupational Respiratory Diseases, p. 229, J. S. Merchant, ed. DHHS (NIOSH) Pub. No. 86-102, NIOSH 1986b).

Mr. Renninger also points to the difficulty in equating impinger sampling results that were used in the Vermont granite shed studies, to gravimetric (mg/m³) measures of respirable dust. He cited Dr. Peters as reporting that "gravimetric and impinger sampling are known to be poorly correlated" (Ex. 139, p. 5). Mr. Renninger also pointed out that the conversion between mppcf and mg/m³ measurements for silica will vary with the industry, thus adding another level of uncertainty in interpreting the health data.

OSHA's decision to propose a 0.1-mg/m³ PEL for respirable silica dust, rather than the NIOSH REL of 0.05 mg/m³, was partly based on the report by Dr. William Graham and others (Graham, O'Grady, and Dubuc 1981/Ex. 1-172) discussed above. In a posthearing submission, Dr. Graham discussed the findings of Theriault and co-workers (1974/Exs. 1-94a, 1-94b, and 1-110), which heavily influenced the decision by NIOSH to issue a REL of 0.05 mg/m³ (Ex. 147). Dr. Graham discussed three limitations of the Theriault and others (1974) studies. First, the X-ray films were interpreted by a single reader who was neither certified nor a chest physician; Dr. Peters points out that it is generally accepted that X-ray films must be read by three experienced readers. Second, there was no attempt to study workers hired after 1938 and exposed to low dust levels separately from workers exposed to higher dust levels prior to 1938. Third, there was a group of workers who were judged to have abnormal X-ray findings despite a reported lack of exposure to dust, which raises the question about the accuracy of interpretations.

Dr. Graham also interpreted his own findings of granite shed workers as showing that the loss in pulmonary function predicted to occur among these workers by Theriault and others (1974/Exs. 1-94a, 1-94b, and 1-110) had, in fact, not occurred. One explanation offered by Dr. Graham is the possibility that technical difficulties arose during the Theriault and others (1974) studies in the administration of spirometric tests and may have resulted in spuriously low values for pulmonary function. Dr. Graham discussed a continuation of his own work in which he has found neither pulmonary function losses nor high prevalences of abnormal chest X-rays among granite shed workers who were employed after 1938-1940, when lower dust levels prevailed (Ex. 147, p. 8-9). However, the analysis of quartz content in the dust samples collected has not yet been completed (Ex. 147, p. 8).

In addition to the evidence on the dose-response relationship for silicosis, rulemaking participants discussed at length recent data suggesting that

Table 10. Airborn limits for various silica or silica-bearing minerals and materials (Z-3)		
Substance	mppcf ^e	mg/m ³
SILICA:		
CRYSTALLINE		
QUARTZ (RESPIRABLE)*	250 ^f	10 mg/m ³
QUARTZ (TOTAL DUST)	%SiO ₂ +5	%SiO ₂ +2 30 mg/m ³
CRISTOBALITE*: Use ½ the value calculated from the formula for quartz		
TRIDYMIT*: Use ½ the value calculated from the formula for quartz		
AMORPHOUS, including natural diatomaceous earth*	20	80 mg/m ³
SILICATES (less than 1% crystalline silica):		
Mica*	20	—
Soapstone*	20 ^g	—
Talc (not containing asbestos)*	20	—
Talc (containing asbestos). Use asbestos limit		
Tremolite (see CFR 1910.1101)		
Portland cement*	50	—
GRAPHITE (NATURAL)*	15	—
COAL DUST (respirable fraction less than 5% SiO ₂)		2.4 mg/m ³
For more than 5% SiO ₂ *	—	10 mg/m ³
INERT OR NUISANCE DUST:		
Respirable fraction*	15	5 mg/m ³
Total dust	50	15 mg/m ³
Note: Conversion factors — mmpcfx35.3 — million particles per cubic meter = particles per cc.		
* Substances that are in Table Z-4 in this proposal.		
^e Millions of particles per cubic foot of air, based on impinger samples counted by light-field techniques.		
^f The percentage of crystalline silica in the formula is the amount determined from airborne samples, except in those instances in which other methods have been shown to be applicable.		
^g Both concentration and percent quartz for the application of this limit are to be determined from the fraction passing a size-selector with the following characteristics in Table 11.		
^m containing less than 1% quartz; if 1% quartz, use quartz limit.		
The measurements under this note refer to the use of an AEC (now NRC) instrument. The respirable fraction of coal dust is determined with an MRE: the figure corresponding to that of 2.4 mg/m ³ in the table for coal dust is 4.5 mg/m ³ .		

Table 11. Size-selection characteristics for fraction to be tested against limits set in Table 10

2	90
2.5	75
3.5	50
5.0	25
10	0

Note: Both concentration and percent quartz for the application of limits in Table 10 must be determined from the fraction passing a size selector with the above characteristics.

silica may be carcinogenic (Exs. 147, 161, 194, 138, 3-1159, 3-1060, and 139; Tr. p. 3-94, Tr. p. 7-80, Tr. p. 11-104). NIOSH (Ex. 8-47, Table N6B) believes that the data on silica are such that the Agency should consider a separate 6(b) rulemaking for this substance. Dr. Frank Mirer, Director of the Health and Safety Department of the United Auto Workers,

summarized the evidence on silica's potential carcinogenicity at the hearing.:

"The most prominent study [on the health effects of silica exposure is] by Holland and co-workers* * * [it] provided really clear evidence that silica was carcinogenic in rats by inhalation. Non-malignant pulmonary effects were also observed. There is a considerable line of other work in rats and hamsters, in the development of both lung tumors and lymphatic tumors from exposure to silica.

"In epidemiology, there's ample evidence that crystalline silica is carcinogenic and that it is hazardous at levels below the proposed PEL. The IARC monograph reviewed the data available in 1986 and described a considerable body of evidence. Despite the methodological limitations that were pointed out by IARC, the sheer number and consistency of the findings is most persuasive (Tr. pp. 7-80 to 7-81).

"Studies [exist] of workers in a variety of industries where high exposure of silica-containing dusts have revealed high lung cancer risks. These results include ten positive studies among mine workers, four in ceramics and glass industries, [and] four in the foundry industry. We also bring to your attention at least four additional studies published since the IARC criteria document was completed. These, in particular, we think create an iron-clad case for the problems presented by this material" (Tr. p. 7-80 to 7-81).

Table 12. *Settings for determination of crystalline silica in perlite on a Rigaku diffractometer using the method of Hamilton and Peletis (1988)*

40 kv	
25 mA	
Graphite monochromator	
Scintillation Counter Probe	
slits	
1°	DS
1°	SS
0.15	RS
0.3	MS
Integrated Step Scanning	
0.02°	step
20	seconds/step
26.2°-27.0°	range
Rigaku Geiger flex D/MAX IIA	
Long, fine focus, Cu, x ray tube	

In a posthearing submission by the Refractories Institute, Dr. John Craighead of the University of Vermont reviewed the human and animal data and concluded as follows:

"I find the experimental evidence in animals, suggesting a possible role of silica in the pathogenesis of bronchogenic carcinomas, to be faulty and incomplete. I also conclude that the epidemiological studies in humans provide inadequate evidence to conclude that man is at increased risk of developing carcinoma of the lung as a result of silica dust exposure. My comments in no way exclude from consideration silica as a cause of bronchogenic carcinoma, but only point out the inadequacies of the scientific information and emphasize the need for additional, carefully designed systematic studies" (Ex. 161A, p. 5).

In similar attachments to the Refractories Institute's submission, Dr. Marvin Kushner, Professor of Pathology at the State University of New York at Stony Brook, pointed to the lack of similarity between the pulmonary lesions found in exposed rats and silicosis lesions in humans; he suggested that the carcinomas seen in rats may be due to a "non-specific" effect that is not a direct result of silica inducing malignant transformation (Ex. 161C). Dr. Carl Shy, Professor of Epidemiology at the University of North Carolina, reviewed the epidemiological evidence and concluded that "the role of occupational silica exposure in causing lung cancer remains undetermined" (Ex. 161D, p. 8).

OSHA believes that the issues raised above deserve a careful and thorough scientific evaluation of the literature. The evidence that silica may present a carcinogenic hazard has been developing over the past few years and is continuing to receive considerable attention by investigators. OSHA will continue to monitor with great interest emerging developments in this area. At this time, however, OSHA believes that the record evidence leaves many questions unanswered regarding the need to reduce the PEL for silica. Therefore, in the final rule, OSHA is establishing an 8-hour TWA PEL of 0.1 mg/m³ for quartz measured as the respirable silica fraction. This limit represents no substantial change from OSHA's former formula limit but will simplify sampling procedures, as indicated in the NPRM.

SILICA, CRYSTALLINE-TRIDYMITE

CAS: 15468-32-3; Chemical Formula: SiO₂
H.S. No. 1356

The former OSHA PEL for respirable tridymite was expressed as one-half the value of the mass formula for quartz dust. This formula corresponds to a range of 0.04 to 0.05 mg/m³, measured as silica, for dusts containing 10 to 100 percent tridymite. The Agency proposed, and the final rule establishes, a PEL of 0.05 mg/m³ TWA for tridymite. The ACGIH recommends an 8-hour TWA limit of 0.05 mg/m³, measured as silica dust. The ACGIH limit is based on a study conducted by King, Mohanty, Harrison, and Nagelschmidt (1953/Ex. 1-85) that found tridymite to be the most active of the free silica forms when injected intratracheally into rats. Tridymite is a transparent, tasteless form of free silica.

Although expressed in different units, the current ACGIH and former OSHA limits for tridymite are comparable. The ACGIH's mg/m³ limit, adopted in 1985, does not reflect a reevaluation of tridymite dust concentrations. NIOSH (Ex. 8-47, Table N6A) concurs with the selection of this limit but recommends that tridymite be designated as a potential occupational carcinogen. No other comments were received on tridymite.

OSHA is replacing its former limit for tridymite, which is described above, with a numerically equivalent limit of 0.05 mg/m³, measured as respirable silica dust; the final rule establishes this change to simplify employee exposure monitoring.

SILICA, CRYSTALLINE-TRIPOLI

CAS: 1317-95-9; Chemical Formula: SiO₂
H.S. No. 1357

Tripoli is a colorless microcrystalline form of quartz. Although OSHA's Table Z-2 did not specifically indicate a limit for tripoli, OSHA formerly specified a limit for crystalline quartz based on the formula measured as total respirable dust:

$$\frac{(10 \text{ mg/m}^3)}{(\text{percent SiO}_2 + 2)}$$

Expressed as mg/m³, this limit corresponds to a limit in the range of 0.08 to 0.1 mg/m³ for respirable dust containing from 10 to 100 percent silica. The 8-hour TWA ACGIH limit for tripoli is 0.1 mg/m³, measured as respirable silica dust. This limit was adopted by the ACGIH in 1985 to simplify the monitoring of quartz dust concentrations. Thus, this revision does not represent a reevaluation of toxicity data for tripoli. NIOSH (Ex. 8-47, Table N6B) does not concur with the final rule's limit and recommends a separate 6(b) rulemaking for tripoli, which NIOSH considers a potential occupational carcinogen. (See section above on Crystalline Quartz for OSHA's discussion of the record evidence on the carcinogenicity of silica.) No other comments were received on tripoli.

OSHA is replacing its limit for quartz, which is expressed as the formula presented above, with a numerically equivalent limit of 0.1 mg/m³ TWA as respirable silica dust; the final rule establishes this limit for tripoli.

SILICA, FUSED

CAS: 60676-86-0; Chemical Formula: SiO₂
H.S. No. 1358

Fused silica is a colorless, odorless solid that is a form of quartz. As such, it was formerly covered by OSHA's limit for quartz (Table Z-3). Exposure to fused silica has long been known to cause the fibrogenic lung disease, silicosis. OSHA's former limit for quartz dust was the formula

$$\frac{(10 \text{ mg/m}^3)}{(\text{percent SiO}_2 + 2)}$$

measured as total respirable dust. This limit corresponds to a respirable quartz concentration ranging from 0.08 to 0.1 mg/m³ measured as free silica. The ACGIH recommends an 8-hour TWA limit of 0.1 mg/m³, measured as free silica; the ACGIH adopted this limit in 1985 to simplify the monitoring of quartz dust concentrations. Thus, this revision does not represent a reevaluation of the toxicity data for fused silica. NIOSH (Ex. 8-47, Table N6B) does not concur with the final rule's limit and recommends a separate 6(b) rulemaking for fused silica, which NIOSH considers a potential occupational carcinogen.

OSHA is replacing its limit for fused silica, which is expressed as the formula presented above, with a numerically equivalent limit of 0.1 mg/m³ as total respirable silica dust; the Agency is establishing this limit to simplify employee exposure monitoring.

APPENDIX B SILICA

CRYSTALLINE SILICA (Group 2A) AMORPHOUS SILICA (Group 3)

A. Evidence for carcinogenicity to humans (limited for crystalline silica; inadequate for amorphous silica).

A number of studies have shown that persons diagnosed as having silicosis after occupational exposure to dust containing crystalline silica have an increased risk for dying from lung cancer (IARC, 1987a; Zambon and others, 1987). This increase has been seen among miners, quarry workers,

founding workers, ceramic workers, granite workers, and stone cutters.

Workers in the granite industry have shown increased risks for lung cancer in some studies; the excesses were of the order of 10-30 percent and were not usually statistically significant (IARC, 1987a). An extended follow-up of Finnish granite workers showed 22 lung cancer cases, with 17.1 expected. When allowing for a latency of 15 years, 21 cases were observed, whereas nine were expected (<0.01 ; Poisson distribution). Smoking habits were similar to those of the active Finnish male population, and exposure to radon and asbestos were considered unlikely to have occurred (Koskela and others, 1987). A recent joint Nordic register linkage study, combining lung cancer mortality and incidence data from the cancer registries with census-based records on previous occupation of 20-64-year-old males, showed an elevated risk of lung cancer among stone cutters in Finland and Denmark, but not in Sweden or Norway. Excess risk was also seen for Finnish males in excavation work, whereas no such risk was evident in the other countries (Lyng and others, 1986).

Three epidemiological studies of workers in the ceramics, glass, and refractory brick industries, using different designs, have shown a roughly two-fold increase in mortality from lung cancer. Only one case-referent study took smoking into account (IARC, 1987a). The Nordic register study also found an excess of lung cancer for Danish glass-workers, but workers in the ceramics industry did not have an elevated risk in any of the countries (Lyng and others, 1986a). A U.S. cohort study of pottery workers exposed to silica and talc showed a nonsignificant standardized mortality ratio of 1.37 for workers exposed to high levels of silica dust with no talc exposure (Thomas and Stewart, 1987).

Several studies of metal miners have shown mortality rates from lung cancer some 20-50 percent higher than expected (IARC, 1987a). In the Nordic register study (Lyng and others, 1986), relative risks from 1.0 (Norwegian metal miners) to 5.0 (Finnish nonferrous ore miners) were seen. The largest group was Swedish iron ore miners; their relative risk was 3.2 (85 percent confidence interval, 2.9-3.5), based on 124 observed cases. However, in repeated cohort studies of workers in a gold mine, no excess lung cancer risk was seen (Hessel and others, 1986; IARC, 1987a). The contribution of radon has not, in general, been assessed.

Coal miners appear not to be at increased risk of lung cancer (IARC, 1987a).

Studies of foundry workers have consistently shown moderate increases in mortality from lung cancer (IARC, 1984, 1987a). The Nordic register study also showed lung cancer risk to be elevated for foundry workers in all Nordic countries (Lyng and others, 1986). However, several contaminants other than silica dust occur in the foundry environment, including polycyclic aromatic hydrocarbons.

Epidemiological studies of both exposed populations and silicotics give indications of the carcinogenicity of a working environment contaminated with crystalline silica, particularly in combination with other exposures. In most industries studied, such an effect cannot be separated from those of other concomitant carcinogenic exposures, but in the granite and stone industry the exposure to silica is fairly pure. Few studies provide data on smoking. It is not clear whether the mechanisms of a possible carcinogenic effect of crystalline silica requires a fibrotic process.

No adequate epidemiological study or case report was available to evaluate the carcinogenicity of amorphous silica to humans.

B. Evidence for carcinogenicity to animals (sufficient for crystalline silica; inadequate for amorphous silica).

Various forms and preparations of crystalline silica produced adenocarcinomas and squamous-cell carcinomas of the lung in rats after inhalation or repeated intratracheal instillation. Thoracic and abdominal malignant lymphomas developed in rats after single intrapleural and intraperitoneal injections of suspensions of several types of quartz. Malignant lymphomas developed after intrapleural injection of cristobalite and tridymite. No tumorigenic response was observed in hamsters after repeated intratracheal instillation of quartz dusts or in a mouse-lung adenoma assay with one sample of quartz (IARC, 1987a).

Tests of different preparations of amorphous silica administered by various routes to mice and rats either gave negative results or were inadequate. In two limited tests (one by intraperitoneal injection and one by inhalation) in mice, increased incidences of lymphosarcomas in the abdominal cavity and of lung tumors, respectively, were observed (IARC, 1987a).

C. Other relevant data.

No data were available on the genetic and related effects of silica in humans.

Quartz did not induce micronuclei in mice treated in vivo. In Syrian

hamster embryo cells in vitro, it induced cell transformation and micronuclei; it did not induce sister chromatid exchanges in Chinese hamster cells. Quartz did not inhibit intercellular communication in Chinese hamster cells in vitro. Silica was not mutagenic to bacteria (1987b).

REFERENCES

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- Zambon, P., Simonato, L., Mastrangelo, G., Winkelmann, R., Saia, B., and Crepet, M., 1987, Mortality of workers compensated for silicosis during the period 1959-1963 in the Veneto region of Italy: *Scandinavian Journal of Work Environmental Health*, v. 13, p. 118-123.

APPENDIX C

Laboratories accredited under the Laboratory Accreditation Program of the American Industrial Hygiene Association that accept samples on a fee basis (as of July 11, 1988).

Proficiency testing is an integral part of the American Industrial Hygiene Association's laboratory accreditation program and is fulfilled by the laboratory's participation in the NIOSH Proficiency Analytical Testing Program (PAT). This program presently includes quarterly samples for lead, cadmium, zinc, asbestos, silica, and organic solvents. (The following solvents are provided on a rotating basis: carbon tetrachloride, benzene, cellosolve acetate, trichloroethylene, p-dioxane, toluene, chloroform, 1,2 dichloroethane, methylene chloride, methyl chloroform, methyl ethyl ketone, and 0-xylene.) Accredited laboratories are required to analyze all materials in the PAT Program which they analyze as a part of their routine laboratory operations. The numbers in () indicate analyses in which the laboratory participates: (1) lead, (2) cadmium, (3) zinc; (4) asbestos, (5) silica, (6) organic solvent materials 1-6, (7) All PAT.

Users should check with individual laboratories for current proficiency status if such information is desired.

Source: Journal of the American Industrial Hygienists Association, v. 49, p. A-601 to A-609 (September, 1988).

CALIFORNIA

- EMS Laboratories
211 Pasadena Ave., S. Pasadena, CA 91030, (818) 441-2393 (7)
- Fireman's Fund Risk Management
Environmental Laboratory, 3700 Lakeville Hwy, Petaluma, CA 94952, (800) 227-0765, (800) 227-5889 (7)
- Health Science Associates
Industrial Hygiene Laboratory, 10941 Bloomfield St., Los Alamitos, CA 90720, (213) 430-1031 (7)
- SRI International
Physical Chemistry Laboratory, 333 Ravenswood Ave., Menlo Park, CA 94025, (415) 859-4810 (7)
- Thermal Analytical, Inc.
TMA/Norcal, 2030 Wright Ave., Richmond, CA 94804, (415) 235-2633 (7)

COLORADO

- Adolph Coors Company
Coors Analytical Laboratory, 17750 W. 32nd Ave., Golden, CO 80401, (303) 277-5077 (7)
- Analytica, Inc.
5930 McIntyre St., Golden, CO 80403, (303) 279-2583 (1,2,3,4,5)
- Hager Laboratories, Inc.
11234 E. Caley Ave., Denver, CO 80111, (303) 790-2727 (7)

CONNECTICUT

Aetna Life & Casualty Company
Engineering Industrial Hygiene Laboratory, 151 Farmington Ave., Hartford, CT 06156, (203) 683-3665 (7)
Environmental Health Laboratory
CIGNA Loss Control Services, Inc., 94 Murphy Rd., Hartford, CT 06114, (203) 522-3814 (7)
Hartford Insurance Group
Environmental Sciences Laboratory, Hartford Plaza, Hartford, CT 06115, (203) 547-4557 (7)
Travelers Insurance Company
Engineering Laboratory, 248 C.P. Engineering Lab, Hartford, CT 06103, (203) 277-7533 (7)

FLORIDA

Environmental Science & Engineering, Inc.
P.O. Box ESE, University Station, Gainesville, FL 32602-3053, (904) 968-8476 (1,2,3,6)
Post, Buckley, Schuh & Jernigan, Inc.
Consulting Engineers & Planners, 6635 E. Colonial Dr., Orlando, FL 32807, (407) 277-4443 (1,2,3,5,6)

GEORGIA

Environmental Health Laboratory
CIGNA Loss Control Services, Inc., 1021 Georgia Ave., Macon, GA 31201-6709, (912) 745-4702 (7)

ILLINOIS

American Foundrymen's Society
Lester B. Knight Environmental Services Laboratory, Golf and Wolf Rds., Des Plaines, IL 60016, (312) 824-0181 (1,2,3,5)
Cencon
(CNA Insurance), Env. Hlth. Lab., 333 S. Wabash Ave., 3W, Chicago, IL 60604, (312) 822-6093 (7)
National Loss Control Service Corporation
(Lumbermen's Mutual Casualty Company), Environmental Sciences Laboratory, Rt. 22 and Kemper Ctr., Long Grove, IL 60049, (312) 540-2488

IOWA

University of Iowa
University Hygienic Laboratory, Oakdale Campus, Iowa City, IA 52242, (319) 353-4500 (7)

KANSAS

Wilson Laboratories
P.O. Box 1820, 525 N. 8th St., Salina, KS 67402-1820, (913) 825-7186

MARYLAND

Martin Marietta Corporation
Center for Occup. Health Engrg., 1450 S. Rolling Rd., Baltimore, MD 21227, (301) 247-0700 (7)

MASSACHUSETTS

Arthur D. Little, Inc.
Acorn Park, Cambridge, MA 02140-2390, (617) 864-5770 (7)

MICHIGAN

Clayton Environmental Consultants, Inc.
22345 Roethel Dr., Novi, MI 48050, (313) 344-1770 (7)
IHI-Kemron
32740 Northwestern Hwy., Farmington Hills, MI 48018, (313) 626-2426

MINNESOTA

H.B. Fuller Company
1200 Wolters Blvd., Vadnais Heights, MN 55110, (612) 481-3300 (5,6)
St. Paul Fire & Marine Insurance Company
Environmental Services Analytical Laboratory, 494 Metro Square Bldg., 7th and Roberts Sts., St. Paul, MN 55101, (612) 221-8020 (4)

MISSOURI

St. Louis County Health Department
Environmental Health Laboratory, 801 S. Brentwood Blvd., Clayton, MO 63105, (314) 854-6830 (7)

NEVADA

Reynolds Electrical & Engineering Co.
Industrial Hygiene Laboratory, P.O. Box 98521, M/S 706, Las Vegas, NV 89193-8521, (702) 295-6379 (7)

NEW MEXICO

New Mexico Bureau of Mines and Mineral Resources
(505) 835-5114 (5) NOTE: Not certified.

NEW YORK

Galson Technical Services
Industrial Hygiene Laboratory, 6601 Kirkville Rd., East Syracuse, NY 13057, (315) 432-0506 (7)

PENNSYLVANIA

Freeport Brick Company
Frecc-Col Laboratories, P.O. Box 557, Cotton Rd., Meadville, PA 16335, (814) 724-6242 (7)
Industrial Health Foundation, Inc.
IHF Analytical Laboratory, 34 Penn Cir. West, Pittsburgh, PA 15213, (412) 363-6600 (7)
Pennrun Corporation
150 William Pitt Way, Pittsburgh, PA 15238, (412) 826-5300 (7)

TEXAS

Continental Technical Services
C-Tek Environmental Health Laboratory, 9742 Skillman, Dallas, TX 75243, (214) 343-2025 (7)

UTAH

ASARCO/American Environmental Consultants
Dept. of Environmental Sciences Laboratory, 3422 S. 700 W., Salt Lake City, UT 84119, (801) 262-2459 (1,2,3,4,5)
DataChem, Inc.
960 West Le Vay Dr., Salt Lake City, UT 84123, (801) 266-7700 (7)

VERMONT

Shelburne Laboratories, Inc.
P.O. Box 458, Falls Rd., Shelburne, VT 05482, (802) 985-3379 (4,5)

WASHINGTON

Hanford Environmental Health Foundation/Northwest Health Services
Environmental Health Sciences Laboratory, 805 Goethals Dr., Richland, WA 99352, (509) 943-0802 (7)
University of Washington
Environmental Health Laboratory, F-461 Hlth. Science Bldg., Seattle, WA 98195, (206) 543-4252 (7)

WISCONSIN

Chem-Bio Corporation
Aquasearch Division, 140 E. Ryan Rd., Oak Creek, WI 53154, (414) 764-7005 (7)
Parker Services, Inc.
Environmental Health Division, 1800 N. Point Dr., Stevens Point, WI 54481, (800) 443-9655 (7)
Swanson Environmental
3490 N. 127th St., Brookfield, WI 53005, (414) 783-6111 (1,2,3,5,6)
Wausau Insurance Companies
Environmental Health Laboratory, 2000 Westwood Dr., Wausau, WI 54401, (715) 842-6810 (7)

WYOMING

Wyoming Department of Agriculture
Division of Laboratories, P.O. Box 3228, Rm. 151, Physical Science Bldg., University Station, Laramie, WY 82071, (307) 742-2984 (7)

CANADA

IRSST
505 W. Maisonneuve, 14th Floor, Montreal, ZC, Canada H3A 3C2, (514) 288-1551 (7)
McMaster University
Occupational Health Laboratory, HSC-3H50, 1200 Main St. W., Hamilton, Ontario, Canada L8N 3Z5, (416) 525-9140, Ext. 2336 (7)

SPAIN

MAPFRE
P.O. 36273, 28080 Madrid, Spain 091-638-1011 (7)

Practices and problems of perlite expansion and testing at the New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico

by James M. Barker, New Mexico Bureau of Mines and Mineral Resources, Socorro, New Mexico 87801, and Michael J. Harris, International Process Research Corporation, 5906 McIntyre, Golden, Colorado 80403

ABSTRACT

Techniques of testing perlite require application of both art and science. The modifications made to the Perlite Corporation LVP vertical laboratory furnace include addition of instrumentation, bin vibrators, automatic feeders, and flow regulators. The basic testing sequence consists of expanded density, furnace yield, compacted density, percent sinkers, brightness, and compaction resistance. Filter aids testing includes double-milling and CRC-time determination. These tests are generally slightly modified versions of those specified by the Perlite Institute. This testing sequence is designed as a preliminary evaluation of a perlite's suitability for horticultural or aggregate end uses and a basic measure of filter-aid capability.

INTRODUCTION

The United States is the leading consumer and producer of perlite in the world (Pettifer, 1981). The estimated value of domestic, processed perlite mined in 1988 was about \$16.5 million FOB mine based on production of about 550,000 tons of processed perlite (Meisinger, 1989), with much value added by expansion and processing before sale to end users. Five mines operating in New Mexico during 1988 produced about 85 percent of all domestic crude perlite. In 1988, only four mines were operating in New Mexico (Figure 1), owing to the closing of the Silbrico mine and mill. Perlite is mined in five other western states, expanded in 31 states, and consumed in all states. End use of perlite was 65 percent building construction products and 15 percent filter aids.

In contrast to the ubiquitous nature of perlite products in the U.S. economy, facilities for testing perlite, both unexpanded and expanded, are notably lacking. Many perlite producers, expanders, and consumers do little or no testing of the physical properties of perlite material. Accessible information or data on perlite testing is lacking, apart from the methods and standards published by the Perlite Institute (Perlite Institute, 1984) and several indirectly related tests of the American Society for Testing and Materials (ASTM). The New Mexico Bureau of Mines and Mineral Resources (NMBM&MR) established a perlite testing laboratory in 1984 to remedy this situation and to further the exploitation of domestic perlite resources.

The purpose of this paper is to describe the operation of the perlite expansion furnace and the standard tests performed on perlite material at the NMBM&MR. Interpretation of test results to evaluate commercial viability of a perlite deposit, problems inherent in the furnace operation and test procedures, and difficulties associated with scaling up from laboratory-scale to commercial-scale expansion are discussed.

SAMPLE PREPARATION

Carefully collected and documented perlite samples, at least 2 kg in weight, must be crushed and sized prior to insertion into the vertical expansion furnace. Efficient expansion of perlite particles is highly dependent on their surface-area-to-volume ratio. A narrow, unimodal size distribution is preferred for testing. As needed, charges of crushed material are sieved to desired sizes with U.S. Standard 8-in. sieves using a Tyler RO-TAP or are passed

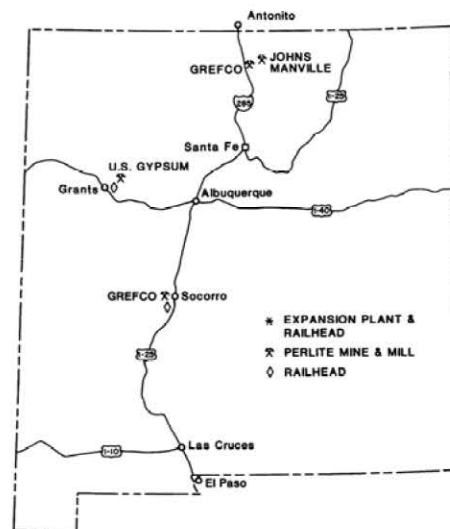


Figure 1. Active perlite mines, mills, expansion plants, and railheads in New Mexico during 1988.

over screens on a Gilson TS-1 testing screen. The small size of the laboratory expansion furnace makes it sensitive to the particle size of the feed material. Expansion is best using the -50+100 mesh fraction, although the -30+50 mesh fraction can also be used. Samples should not be crushed more than two months in advance of testing because some perlite deadens over time after crushing.

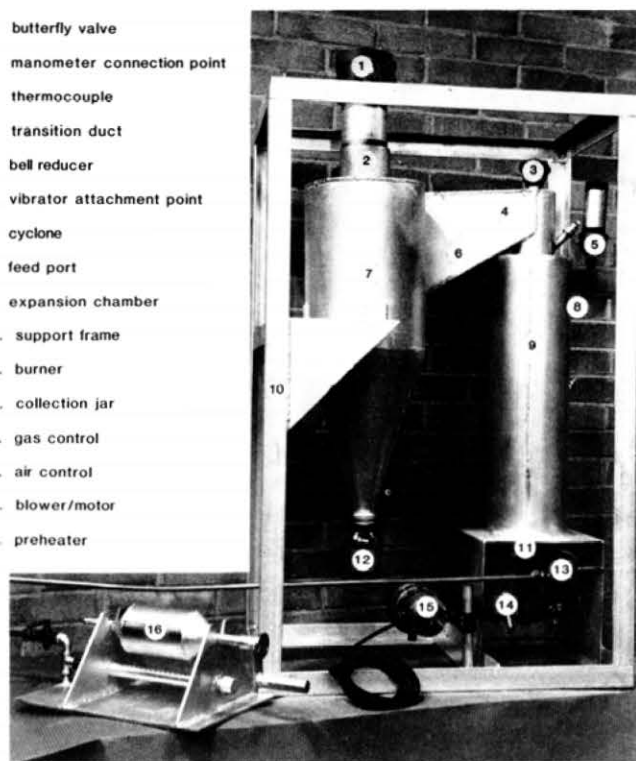
Furnace description

The expansion furnace at the NMBM&MR is a model LVP laboratory furnace manufactured by the Perlite Corporation, Chester, Pennsylvania (Figure 2). The furnace is stationary, has a 4- x 40-in. vertical expansion chamber, and burns natural gas. Several modifications discussed below have been made by the NMBM&MR to the basic furnace design in order to monitor expansion conditions (Table 1).

Because the sample preheater supplied with the furnace is inconvenient and difficult to control, it is not often used. This cylindrical preheater is operated by manually turning it over a flame and then pouring it into the expansion furnace feed port. The fuel input is also set by an uncalibrated valve. For these reasons, it is difficult to control the preheater temperature and to heat the particles uniformly, so results are less reproducible than usually desired (Murdock and Stein, 1950).

The sample feed funnel supplied with the LVP perlite furnace has a 1/8-in. orifice. This orifice is easily clogged when steam exiting the sample inlet pipe contacts the sample in the feed funnel. Clogging inhibits steady and proper feeding of the sample into the furnace. For more accurate, continuously variable feed rates, a Syntrol Model F-TO light-capacity electromagnetic, vibrating-trough feeder has been added to replace the furnace feed funnels.

1. butterfly valve
2. manometer connection point
3. thermocouple
4. transition duct
5. bell reducer
6. vibrator attachment point
7. cyclone
8. feed port
9. expansion chamber
10. support frame
11. burner
12. collection jar
13. gas control
14. air control
15. blower/motor
16. preheater



Source: Perlite Corporation, Chester, Pennsylvania.

Figure 2. Model LVP laboratory vertical perlite expansion furnace with instrument/control board removed and preheater attached.

Furnace operation

Operating the expanding furnace to achieve optimum results is a matter of experience. The controls on the furnace are often dependent upon each other; adjusting one control will cause the other control parameters to become unbalanced.

Figure 3 shows the essential features of the furnace as a schematic representation. The most important feature of the furnace is the area labeled as the expansion zone. The expansion of a perlite particle is directly related to the time the particle spends in the expansion zone and the temperature to which the particle is heated while in that zone. Expansion zone conditions are controlled by (1) the flame temperature, (2) upward velocity of the air thru the expansion tube, (3) the height of the feed port, (4) the particle

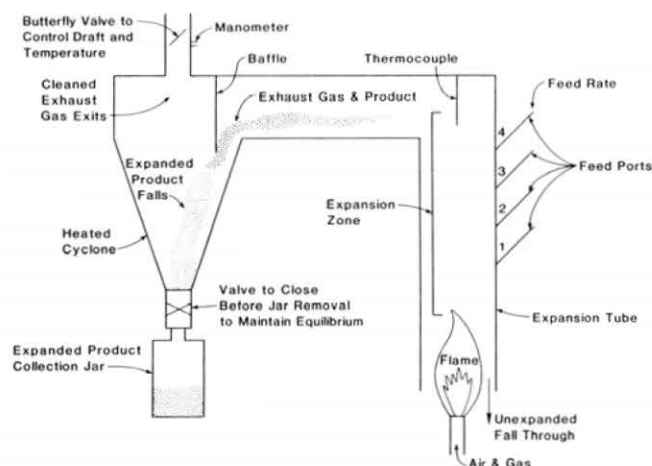


Figure 3. Schematic diagram of a laboratory perlite furnace showing material flow and major control points.

size of the feed material, and (5) back pressure as controlled by the butterfly valve setting.

The factors that affect perlite particle expansion are complexly interrelated (Figure 4). Perlite expansion is a function of composition (especially water content), softening temperature, furnace temperature, and particle residence time in the flame. Perlite can be classified as "lively" or "dead," based upon its water content and softening temperature (Murdock and Stein, 1950). "Dead" perlites have less combined water and higher softening temperatures than "lively" perlites. More heat must penetrate dead perlite particles to achieve good expansion. This can be accomplished by increasing the furnace temperature, increasing the particle residence time in the furnace, or preheating the particle. A study of temperature and expansion time led Stein and Murdock (1955) to conclude that the degree of expansion of a perlite particle is proportional to the temperature achieved in excess of its softening temperature.

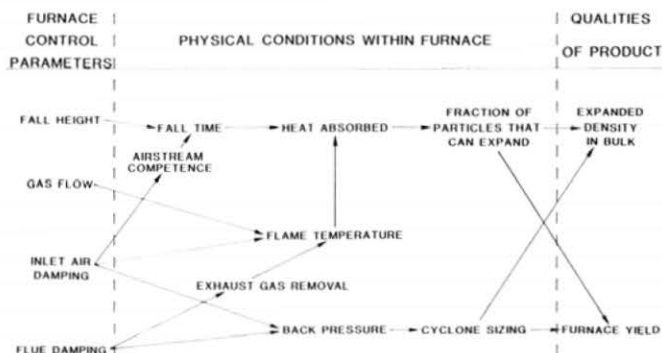


Figure 4. Synergistic interactions between control settings, furnace conditions, and product quality in a perlite expansion furnace.

Because of the multivariate combustion parameters affecting perlite particles, perlite expansion is not an exact science. One-of-a-kind instrumentation and in-house standards are typically used throughout the industry. One of the main sources of variation in the results of expansion and testing is the expansion furnace itself. Our laboratory-scale unit is small and, therefore, very sensitive to even slight changes in combustion parameters. Seemingly minor changes in air, gas, and back pressure can cause major changes in combustion gas velocity and, hence, particle residence time versus softening rate. A major change in gas velocity is often accompanied by only a slight change in furnace temperature. Additional factors affecting perlite expansion include: particle fall-through time (which is itself a complex function directly related to both the particle size and the feed port height), humidity, barometric pressure, and ambient air temperature. Methods used to control or monitor these factors for the NMBM&MR furnace are examined below.

Four feed ports on the side of the expansion chamber allow samples to be fed from different heights above the flame (Figure 3). The particle fall-distance through the flame, and thus the residence time, is controllable by varying the feed port used. Empirical and calculated data suggest that the size range of feed for optimal expansion in the furnace is -30+100 mesh, with the best range at -50+100 mesh. Samples of perlite sized to -50+100 mesh have a high surface-area-to-volume ratio. Heat penetrates them quickly. They need only relatively short residence time and are, therefore, usually fed through the lowest furnace port. Coarser samples can be fed from the higher ports if longer residence time is needed, although samples coarser than 30 mesh do not expand satisfactorily because residence is always too short, even from the highest port.

Furnace yield is the weight percentage of sample residing in the collection jar after expansion relative to the amount of sample fed into the furnace. The furnace yield is, in part, a function of feed rate versus upward airstream velocity in the expansion chamber.

Table 1. List of accessories added to the Perlite Corporation LVP expansion furnace at the NMBM&MR

Device	Maker, Model (Source)	Purpose
Manometer	Dwyer Instruments Durablock 0"-2" H ₂ O	to monitor static pressure of flue to optimize cyclone separation
Vibrating feeder	F.M.C. Syntron F-T0-C	to provide consistent feed rate
Feeder controller	F.M.C. SCK-1-B	to allow continuously variable vibration with reproducible settings
Pneumatic vibrator (weld-on brackets)	Cleveland Vibrator Co. (McMaster-Carr 5.72 8 K31)	to prevent hangup of expanded perlite in transition duct
Air pressure regulator and butterfly valve	available locally	to allow fine control of vibrator rate
Heating tape	Sybron Thermolyne Brisk Heat B1 H101-080, 8', 832 watt Heavy Insulation "Fibrox" (V.W.R. 33737-165)	to maintain cyclone outlet and walls above steam condensation temperature
Controller	Glas-Col Apparatus Co., PL-312 Minitrol (V.W.R. 33797-509)	to adjust heating tape temperature
Insulation	Refractory Products Co. WRP-X-AQ Felt 24" x 36" x 1/2" (McMaster-Carr 93 26K3)	to keep heat within cyclone so steam condensation is minimized
Thermocouple	Omega 115 KF	Digital temperature readout
UV sensor, air and gas pressure sensors		Automatic shutdown for safety

If the feed rate is too high, the capacity of the upward airstream is exceeded, and unexpanded sample falls out the bottom of the expansion chamber. Rapid feed rates can lower furnace temperature, which should be held to within ± 5 to 10°F , and thus retard expansion. A feed rate of 15 g/min typically works best for our furnace compared to the maximum feed rate of 25 g/min recommended by the furnace manufacturer.

The exhaust-air valve, the inlet-air valve, and the gas valve control the airstream velocity in the furnace. The first two are very sensitive and allow significant flexibility in attaining the proper airstream velocity. If the exhaust air valve is opened so that excessive draft is created, the airstream velocity becomes too high, which can lead to poor separation in the cyclone and cause expanded perlite to blow out the exhaust flue. Too low a velocity from excessive exhaust-air valve closure increases fall-through and produces lower furnace yield.

The NMBM&MR has added a heat-proof panel mounted to the front of the furnace frame to hold controls and gauges. The controls are further insulated from furnace heat by sheets of removable ceramic-fiber insulation attached to the back of the heat-proof panel.

Back pressure in the furnace is monitored by a manometer connected about 1.5 in. above the top of the cyclone. The back

pressure generally varies between 0.00 and 0.03 in. of water, with best efficiency usually reached at 0.015 in. of water at our furnace elevation of about 4,700 ft.

Expanded perlite particles tend to "hang up" on the walls of the cyclone and the transition duct leading from the expansion chamber to the cyclone. Hang-up in the cyclone and duct is decreased using a pneumatic vibrator with weld-on brackets, one on each side of the transition duct (Figure 2). After a sample has expanded in the furnace, the pneumatic vibrator is cycled for about one minute to disengage trapped particles. Furnace yield is very sensitive to variation in vibration, so this is kept constant for each sample. Steam generated during expansion condenses on the cyclone walls, adding to the hang-up problem. This problem is minimized by "preheating" the furnace walls using a heat blanket wrapped around the cyclone, by electric heat tapes placed under the ceramic-fiber insulation, and by allowing the furnace to warm up for at least one-half hour prior to perlite expansion.

Before expanding a series of "unknown" samples, an in-house perlite standard from the Grefco El Grande Mine, No Agua, Taos County, New Mexico, is freshly crushed and expanded to ensure that the furnace is working properly for the desired expansion conditions. After the furnace is adjusted relative to the standard's performance, it must be allowed to re-equilibrate before another

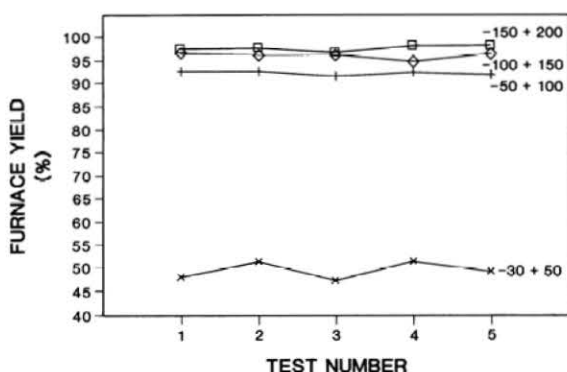


Figure 5. Furnace yield versus particle size of perlite expanded in a vertical furnace at 1,300 °F.

charge of standard is expanded. Once the standard perlite is expanding to its potential, less than 3 lbs/ft³ at 1,300 °F, expansion of the unknown samples can begin. The standard is also usually run following the unknown sample series to monitor changes, if any, in the furnace expansion conditions over time.

The samples are split into 50- to 200-g lots, depending on the anticipated expansion of their volumes and on the testing campaign planned. A minimum of 0.5 l of expanded sample is required for post-expansion testing. Test result variation is minimal in successively fed lots of an individual sample once the furnace has stabilized, so only one lot of each sample need be run. After expanding a sample and vibrating the furnace to purge all material, expanded perlite settles into the collection jar. The collection jar is removed from the cyclone, and any condensation in it is allowed to dissipate before transferring the expanded sample to other containers for further testing.

A gross evaluation of the expansibility of a perlite can be made visually as it feeds through the furnace. Assuming proper airstream velocity within the furnace, perlite with poor expansion remains dense and will fall through the flame, past the burner, then out the furnace bottom. If the furnace heat is too great for a particular perlite, the particles will shatter (over expand), thereby producing abundant fines. Some of these are carried out the exhaust flue, resulting in lower yield and higher expanded density. Some partly expanded perlite will settle into the collection jar and typically looks off-white or gray.

The multiple furnace control parameters that affect perlite particle expansion interact synergistically (Figure 4). The interactions are more complex than available theories and models can predict. As a result, trial-and-error adjustment of the inlet- and exhaust-air

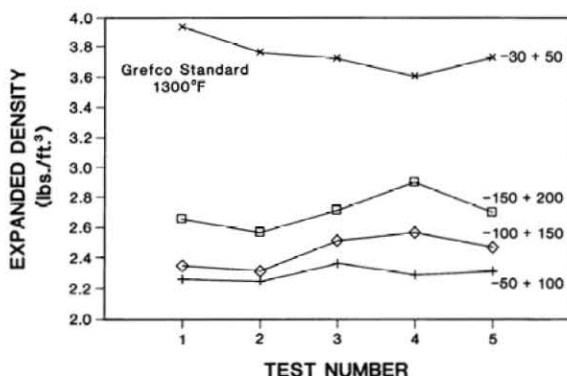


Figure 6. Expanded density versus particle size of perlite expanded in a vertical furnace at 1,300 °F.

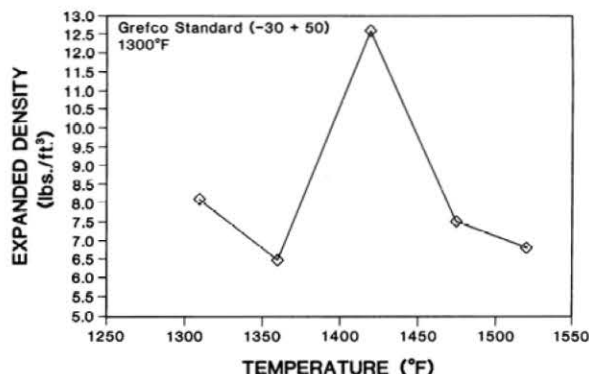


Figure 7. Temperature versus expanded density of perlite sized -30+50 mesh.

valves and the gas setting is done to attain optimum expansion conditions. These controls adjust both the furnace temperature and the air-stream velocity within the furnace. The exhaust-air valve is the most sensitive of the three controls, but an equally critical parameter is the inlet-air damping. Keeping the exhaust-air valve setting constant, if the inlet-air valve is opened, increases air-stream velocity. This leads to increased competence and capacity of the upward airflow and shorter particle residence time in the flame. Closing the valve induces the opposite effects. The gas setting is the least sensitive of the three. Its adjustment essentially mirrors the effects of the inlet-air valve on furnace temperature and airstream velocity.

The optimum expansion temperature is the one at which the density of the expanded perlite is at that desired for a particular perlite end use compared to energy expenditure. Temperatures as low as 950 °F (510 °C) will expand perlite, but temperatures between 1,250 °F and 1,500 °F (677 °C and 816 °C) typically are best in the NMBM&MR furnace. Temperatures above this range are difficult to achieve because boosting the gas flow in an attempt to attain these temperatures often causes the furnace temperature to drop if draft is held constant. The situation where an increase in gas flow yields a temperature drop should be avoided. Increasing the draft to burn excess fuel increases the airstream velocity above its optimum level and causes expanded perlite to be blown out the exhaust flue or unexpanded perlite to short circuit.

Evaluation of furnace performance

Papanastassiou (1978) presented a mathematical model to the Perlite Institute that described perlite expansion behavior in a vertical expanding furnace. This model showed that -30+50 mesh

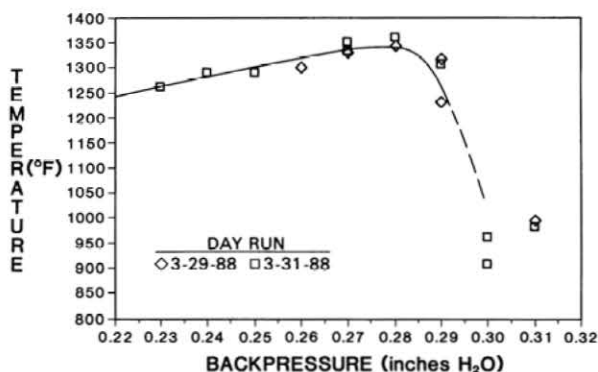


Figure 8. Furnace temperature versus backpressure in a laboratory vertical perlite expansion furnace.

material could be expanded in our furnace but that -50+100 mesh would be the best size fraction for expanding. Experimental results also show this to be the case as shown in Figure 5 (furnace yield) and Figure 6 (expanded density).

The furnace performance as evaluated by furnace yield actually showed the -30+50 mesh fraction to be the poorest performing size fraction. Furnace yields increased as the size fractions being expanded decreased in size. However, the -50+100, +100, +150, and -150+200 mesh fractions all gave furnace yields in the range of 93 to 97 percent.

More revealing is the expanded density as a function of the feed particle size (Figure 6). Again, the -30+50 mesh fraction was the poorest performer, with an expanded density nearly twice that of any of the other fractions. This indicates that the particles were too large to reach the required expanding temperature before they were blown out of the furnace expansion zone. The -50+100 fraction gave the best expanded density results, and the results increased for both the -100+150 and the -150+200 mesh fractions. This increase in the expanded density for the smaller size fractions is taken to indicate that the particles were short circuiting the expanding furnace; they were being blown out of the expansion tube into the cyclone instead of entering into the expansion zone in the furnace.

Increasing temperature as a means of improving the expanded density does not always provide the expected results. Figure 7 summarizes the results of expanding at five different temperatures over a range from 1,300 to 1,525 °F. The lowest expanded density was achieved at a temperature of 1,360 °F, and expansions done at 1,425, 1,475, and 1,525 °F all gave higher values for the expanded density. In fact, the highest density was achieved at 1,425 °F. Obviously, factors other than the expanding temperature control how much the perlite expands.

One of the most important controls on the furnace operation and on the expansion characteristics of the perlite material is the butterfly valve that controls the draft through the exit tube out of the cyclone. This parameter can be quantified as back pressure and is measured with a manometer connected to the exit tube of the cyclone. Results showing how sensitive this control is are shown in Figure 8. The optimum back pressure as expressed by achieving the highest operating temperature was found at about 0.28 in. of water. Opening the butterfly valve from the optimum position (thus decreasing the back pressure) allows the air to flow through the furnace more quickly, allowing diluting air to enter the furnace, which has the effect of lowering the temperature. This is a gradual trend that continues over the range of valve positions to full open. Closing the valve beyond the optimum point causes a sharp decline in temperature. This is caused by increased resistance to air flow through the furnace, which distorts the flame pattern in the furnace. This can be verified visually. With the butterfly valve in a closed position, the flame from the burner can be seen to "spill out" of the bottom of the furnace and play around the outside of the expansion tube. Thus the flame is not directed into the expansion tube, and the temperature of the furnace decreases.

Testing expanded perlite

The Perlite Institute has devised a series of standard tests for perlite evaluation (Perlite Institute, 1984). The standard suite of tests conducted at the NMBM&MR, some of which are modified from Perlite Institute tests, include:

- Loose weight determination of expanded perlite (PI 200-77)
- Determination of furnace yield
- Compacted density (PI 201-77)
- Compaction resistance (PI 306-77)
- Determination of percent nonexpandables in expanded perlite (PI 301-80)
- Determination of relative brightness
- Sieve analysis of expanded perlite, weight basis (PI 115-77)

Many other perlite tests listed in the Perlite Institute test manual (Perlite Institute, 1984) can be performed by the NMBM&MR through special arrangement. A filter aid testing circuit is in place and includes the following tests:

- Double milling
- CRC time
- Wet density
- Sieving of ground perlite

Some comments on each of the standard perlite tests run at the NMBM&MR follow (Table 2). The test procedures will not be discussed in full here, and the reader is referred to the Perlite Institute test manual (Perlite Institute, 1984) and Barker and Hingtgen (1985) or Barker, Hingtgen, and Bowic (1987) for descriptions of the test apparatus, procedures, and calculations.

Table 2. Uses of various densities of expanded perlite

Expanded Density*	End Use
<2.5 or very fine	filter aid, wallboard or cryogenic insulation
~3	filter aid, wallboard, cryogenic insulation; plaster and concrete aggregate if expanded in a horizontal furnace, sometimes if expanded in a vertical furnace
4-11	probable for plaster and concrete aggregate if expanded in a vertical furnace
>11	none

Source: Perlite Corp., Chester, PA * pounds per cubic foot

Expansion and testing of perlite over time unavoidably is done under varying conditions. The Grefco No Agua perlite used to monitor the furnace expansion conditions is also expanded, tested, and used as a commercial standard to which test results of unknown samples are compared. Use of the No Agua perlite as a standard mitigates the above problems to a degree and aids in assessing the commercial viability of unknown samples. For example, the higher the expanded density of an unknown perlite sample compared to the standard, the more energy-intensive the expanded perlite product will be. Test results can also be reduced in a quantitative analysis to the ratio between an unknown sample and the standard to dampen some of the variability. This ratio can be as informative as the actual calculated results.

Scale-up problems abound in designing full-scale plants based on bench-scale expansion tests. No correlation has been demonstrated between laboratory or bench-scale expansion tests using horizontal furnaces and similar tests in commercial plants. Scaling up from vertical furnace laboratory or bench-scale testing to full-scale operation has better correlation, but full-scale testing must be done prior to commitment of resources to investment, mining, or processing of perlite (Kadey, 1983). Our furnace, with a 40-in. tube, cannot readily expand materials coarser than 30-mesh. Thus when we test perlite at sizes used commercially, without preheat, an unacceptably long tube is needed. We are currently working on a custom vibrating feeder that can heat samples to 300 °F, with ability to reach 600 °F a possibility.

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Pozzolans of the Northwest: Natural versus artificial

by Jenny Flechsig, Pozzolan Northwest, Inc., 2448 76th Avenue SE, Suite 222, Mercer Island, Washington 98040

The first use of pozzolans in concrete can be traced back to both the Greeks and Romans, who maintained that certain volcanic deposits, when finely ground and mixed with lime, would yield a mortar that was superior in strength and also would resist the action of either fresh or salt water. For the Greeks, this ingredient was the volcanic tuff from the island of Thera (now named Santorin), while the Romans used the red or purple volcanic tuff found at the Bay of Naples. The variety of earth that was preferable could be found near Pozzoli (or Pozzuoli). Hence this material became known as "pozzolana" and eventually became the designation for the whole class of mineral admixtures.

Pozzolans, according to the American Society for Testing and Materials (ASTM) Standard C-618, are siliceous or siliceous and aluminous materials that in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

Pozzolans can be separated into two categories: natural and artificial. The natural pozzolans are usually of volcanic origin but also include certain diatomaceous earths. The volcanic pozzolans are composed of glassy, incoherent materials or compacted tuffs formed by the deposition of volcanic dust and ash. This volcanic dust and ash undergoes rapid cooling and also extensive chemical alteration in some instances. This new formation produces zeolitic compounds. The pozzolanic properties of these volcanic materials are present due to both the volcanic glass and the altered zeolitic compounds. Zeolites that are found include analcite, chabazite, harschelite, and phillipsite.

The natural pozzolans being used at present in the United States are generally tuffs that contain rhyolitic glass comprising from 50-100 percent of the content, as well as quartz, feldspars, biotite, hornblende, hypersthene, sanidine, calcite, some opal, and montmorillonite-type clays.

The high-silica materials include diatomaceous earths and some siliceous rocks that have lost a lot of their basic oxides.

The diatomaceous earths are made up of the siliceous skeletons of diatoms deposited from silica-bearing waters. Deposits of diatomaceous earths are usually mixed with sand and clay. The main component of the diatomaceous earths is opal, which is amorphous and contains 6-10 percent water. Submicroscopic crystals of beta-cristobalite may also be present.

Artificial pozzolans include burnt clays and shales, burnt gaize, burnt moler, and pulverized fuel ash (fly ash).

The pozzolanic properties of burnt clays were well utilized by the Romans. Bricks and tiles were crushed and added to mortars in place of natural volcanic pozzolans.

Gaize is a sedimentary rock that is quite soft and porous. It is highly siliceous and has been used in the raw form as a pozzolan but is usually burnt prior to mixing with cement in concrete.

Moler can also be used in its raw form as a pozzolan but is much more effective when burnt. Moler comes from a Tertiary-age deposit of diatomaceous earth that contains clay in a large proportion. This deposit of moler is found in Denmark. It is generally used for concrete subjected to sea-water attack.

The fine fly ash produced from the burning of pulverized coal is caught in electrostatic precipitators. The composition and various properties of the fly ash depend not only on the coal that is burned but also the efficiency of the combustion process.

The desire for more rapid hardening, improved durability, reduction in heat evolution, as well as some economy led to the introduction and eventual wide-scale use of pozzolanic cements

in the construction industry today.

To fully examine the role of pozzolans and their history, it is necessary to begin with cement and the actual birth of the concrete construction industry.

Cements are adhesive substances capable of uniting fragments or masses of solid matter to a compact whole. Since this definition is rather vague and encompasses a large range of substances, this paper discusses only the plastic materials that are used to provide adhesion between stones and bricks or other cement products in the construction of engineering works. These cements include hydraulic and portland cements.

The beginning of the construction industry can be traced back to ancient Egyptian buildings. Bricks dried in the sun were layered with moist loam (mud) from the Nile River. As the loam dried, a solid wall was formed. However, this material had no resistance to water, which limited construction to an arid, rainless climate.

The Babylonians and Assyrians layered burnt bricks and alabaster slabs with bitumen. This method was restricted by the occurrence of the natural deposits of bitumen.

The Egyptians also used a mortar between the blocks and slabs of stone in their massive masonry constructions. This mortar was a mixture of sand and a cementitious material that was a product of the calcination or burning of gypsum. This gypsum, which contained calcium carbonate, was basically in an impure state when quarried. Burning was required to decompose the calcium hydroxide. The process of burning at that time was quite uneven and only partially decomposed the calcium carbonate. Ultimately, a mortar that had erratic set times was produced.

Lime was used by both the Greeks and the Romans. Lime was slaked and mixed with sand, gravel, crushed stone, tile, or brick to prepare a mortar that was used between bricks. The structures that were built in this fashion were extremely durable. One example is the Aqueduct at Versailles. The great secret of this durability has been found to be nothing more than thorough mixing and ramming of the mortar.

Pozzolan materials were introduced at this time by the Greeks and Romans. They were convinced that certain volcanic deposits, when finely ground and mixed with lime, would yield a mortar that was superior in strength and would also resist the action of either fresh or salt water.

Some of the mortars would harden as well under water as in air. This was due to the difference in aggregate materials. The Greeks found this special ingredient to be volcanic tuff from the island of Thera (now named Santorin), also known as Santorin earth. This material is still used by modern builders.

The Romans, meanwhile, used the red or purple volcanic tuff found at the Bay of Naples. The variety of earth that was preferable was an ash from Mount Vesuvius that was quarried at Pozzoli (or Pozzuoli), Italy. This material was eventually named "pozzolana" and became the designation for the whole class of mineral admixtures regardless of geologic origin.

A similar type of material to that found near Pozzoli was found in southeastern France and along the Rhine River between Cologne and Coblenz by the Romans as they moved into western Europe. Examples of the ancient structures include the Roman Pantheon, Colosseum, and the Basilica of Constantine. These structures have withstood the test of time not only due to the superior materials used but also because of the quality of workmanship. The Romans were convinced of the extreme importance of thorough mixing and careful ramming of the mortar.

If pozzolana was not available, the Romans found that ground tile, brick, or pottery would serve as a suitable replacement. England,

which was a remote part of the Roman Empire at this time, mainly used ground tiles but also had access to deposits of a material that was similar to pozzolana. This material is known as "trass," a Rhenish volcanic tuff, and is still in use today.

After the Roman times and during the Middle Ages, the quality of mortar construction declined, and the use of concrete in construction was severely limited. After the 14th century, however, excellent mortars were rediscovered.

Roman cement was invented in approximately 1800 A.D. This hydraulic cement was made by the calcination of nodules of argillaceous limestone (septaria) of Tertiary age. This was a quick-setting cement that became quite popular, especially in water environments. Its reign lasted until the development and subsequent use of portland cement in 1850.

A natural cement was developed in France also around 1800 from concretions found near Boulogne as well as at Rosendale and Louisville in the United States. Shortly after, the natural cement industry grew in importance.

The invention of portland cement is most often attributed to Joseph Aspdin, a Leeds builder or brick layer. It is believed, however, that the mixture was so irregular that a poor-quality cement was produced. His first patent is dated October 21, 1824. Evidence that supports Isaac Charles Johnson, who died in 1911, as the developer of quality portland cement is quite strong. The name "portland cement" was given to it due to the similarity in its hardened state to Portland Stone. Its introduction seemed to aid in an increase of concrete in construction but also helped in the demise of other hydraulic cements due to its superior strength, homogeneity, and consistent composition.

Standard specifications were needed as the demand for portland cement increased. Most countries either officially or through voluntary organizations of engineers and consumers or of cement manufacturers developed specifications to ensure quality of the portland cement.

Germany established the first German standard specification in 1877. The British Standard Specification was developed in 1904 by the Engineering Standards Committee. The first ASTM standard was instituted in 1904.

Concrete, which is an artificial conglomerate of gravel or broken stone with sand and lime or cement, can be traced back to the first century B.C. Concrete made with broken tiles was used for pavements, while cement mixed with oil or some organic material was used as a waterproof surface coating. The best concrete was made of broken bricks or volcanic tuffs, lime, and pozzolana.

The most famous of all the Roman structures is the Pantheon. The walls were 20 ft thick and made of tuff and pozzolana concrete covered with a thin layer of brick. The dome was 142.5 ft in diameter and was cast solid in pumice and pozzolana concrete. The conditions at present of not only the Pantheon but other Roman buildings testify to the superiority of the concrete.

In the United States, the first large-scale use of pozzolans was in the construction of the Los Angeles aqueduct in 1910. This used rhyolite tuff, a natural pozzolan.

The use of ground granite in Arrowrock Dam was the next occurrence of pozzolanic concrete, closely followed by Elephant Butte Dam, which contained a ground sandstone. The pozzolanic activity of both the ground granite and sandstone by today's standards are incredibly low; however, the five-year strength was far superior to straight portland cement concrete.

Pozzolans, according to ASTM Standard C-618, are siliceous or siliceous and aluminous materials that in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties (National Sand and Gravel Association and National Ready Mixed Concrete Association, 1985).

During hydration of portland cement, calcium hydroxide is pro-

duced. The excess calcium hydroxide does not add any cementitious properties to the concrete. In fact, it is leached out, leaving a porous, permeable concrete. Pozzolanic materials may be added to the concrete and will actually combine chemically with the excess free lime and produce added strength and impermeability, i.e., more durable concrete. This reaction is due to the presence of amorphous silica, volcanic glass, or aluminous and siliceous compounds produced by the calcination of clays. These substances combine with the calcium hydroxide to form stable, even cementitious materials. In addition, zeolites, also present in pozzolans, may contribute to the reaction.

The pozzolanic reactions proceed at a much slower pace than the normal cement reactions, so the added strength and durability are gained over long periods of time.

Although all pozzolans differ from one another in origin, composition, and mineralogy, the chemical composition must meet certain minimum requirements. Unfortunately, the chemical composition alone is not a measure of the pozzolanic activity. For example, quartz exhibits the necessary composition but is not pozzolanicly active. The material must have an instability due to either a lack or alteration of a crystal structure. However, that, in itself, is not an indication of pozzolanic activity. The reaction with calcium hydroxide must result in the formation of a hard, insoluble compound.

The amount of pozzolans used in concrete vary from less than 5 percent to 40 percent by weight of total cementitious materials. In the United States, the average use is between 15 and 35 percent (Tuthill, 1978).

Probably the largest driving force behind the use of pozzolans as partial replacement for portland cement is economics. Pozzolans are generally less expensive than portland cement. Other advantages of pozzolan-cement concrete include the following:

1. Decreased segregation, bleeding, and water gain.
2. Increased workability.
3. Increase in tensile and compressive strengths.
4. Higher initial heat of hydration and lower ultimate heat of hydration, which leads to a reduction in the heat differential, resulting in turn in decreased cracking.
5. Lower permeability.
6. Increased resistance to sulfates or aggressive waters.
7. Reduction in expansive properties of high-alkali concretes and reactive andesitic aggregates.

It should be understood that not all pozzolanic materials will contribute identically to these benefits. For instance, some pozzolans contain large, angular particles that actually increase the water demand in concrete. This increase in water must be accompanied by the addition of even more portland cement, which increases the cost and ultimately decreases the strength as compared to a control mix of straight portland cement concrete. Longer set and curing times are also noticed with pozzolan-cement concrete. The impermeability and resistance to aggressive waters make pozzolan-cement concrete the obvious choice for underground and underwater structures. Many dams, piers, sewers, and foundations have been constructed with pozzolan-cement concretes for that very reason. Bonneville Dam, which was built in the 1930's, was constructed with pozzolan-cement concrete.

There are two categories of pozzolans: natural and artificial. The natural pozzolans may be further subdivided into two groups: (1) those derived from volcanic rocks in which the amorphous constituent is a glass produced by fusion, and (2) those derived from rocks or earth for which the silica constituent contains opal, either from precipitation of silica from solution or from the remains of organisms. Each type in its natural state may or may not require calcination for use as a pozzolan, depending upon its clay content and/or grinding.

The volcanic pozzolans are composed of glassy, incoherent materials or compacted tuffs formed by the deposition of volcanic

dust and ash. Rhenish trass is an example. It occurs in a rocklike form that is found in the following sequence: a layer of overburden, followed by layers of pumice and sand, followed by layers of tuffstein containing pumice. The remaining layer of tuffstein is quarried and ground. The material remaining is called "trass." It is generally pale yellow to grayish, with a silica content ranging from 46-61 percent. Trass has been used since the end of the seventeenth century and can be found in Roman structures along the valley of the Rhine (Germany).

Volcanic deposits may also be found in a fragmentary, unconsolidated state, as are the Italian pozzolans, like Santorin earth. These are found in open pits and quarries, some of which have been in use for centuries. Santorin earth is a fine, light-gray ash. It is highly variable in composition and pozzolanic quality and generally contains 63-73 percent silica.

The volcanic pozzolans are a mixture of silicates and often contain both glass and crystalline particles. The volcanic ash and dust undergo rapid cooling, which produces increased surface area due to the release of gases. This increased surface area increases the instability and makes the glassy volcanics particularly susceptible to alteration by weathering. Clay minerals or zeolites are the normal products of weathering.

There is also extensive chemical alteration from hydrothermal action. This new formation produces zeolitic compounds. The pozzolanic properties of these volcanic materials are present due to both the volcanic glass and the altered zeolitic compounds. Zeolites that are found include analcite, chabazite, herschelite, and phillipsite.

The Rhenish trass has undergone deterioration due to pressure and exposure to carbon-dioxide bearing waters. Therefore, it now consists of an isotropic mass containing feldspar, leucite, and quartz, with minute traces of augite, hornblende, and mica. The glassy matrix consists of zeolitic compounds including analcite and chabazite or herschelite.

Santorin earth consists of a mixture of pumice, obsidian, and fragments of crystalline feldspars, pyroxenes, and quartz.

The natural pozzolans being used at present in the United States are generally tuffs that contain rhyolitic glass comprising from 50-100 percent of the content, as well as quartz, feldspars, biotite, hornblende, hypersthene, sanidine, calcite, some opal, and montmorillonite-type clays.

Volcanic pozzolans are not widely used in the United States. California is the largest user; however, that use is quite limited. The Los Angeles Aqueduct was constructed with portland cement plus a deeply altered rhyolite tuff. This replacement resulted in a \$700,000 savings over the cost of straight portland cement concrete.

Washington state contains deposits of loose, finely divided pumice or consolidated layers of cemented or agglomerated pumice. Pumice is a porous volcanic rock that consists mainly of rhyolitic glass. Feldspar and quartz are the main constituents. This raw pumice was used in the construction of Priest River Dam. A savings of 30 percent was accrued on that project due to the replacement of a portion of portland cement by pumice. Hungry Horse Dam also utilized uncalcined, natural pumice. The savings on that project was about 50 percent of the cost of portland cement, even with the added cost associated with importing the pozzolan from Chicago.

Heat treatment or calcining is ineffective in enhancing the pozzolanic activity of the volcanic glass and often harms the structure of the glass. It does, however, remove excess water.

The high-silica materials include diatomaceous earths and some siliceous rocks that have ultimately lost a lot of their basic oxides.

The diatomaceous earths are made up of the siliceous skeletons of diatoms (silica-secreting algae) deposited from silica-bearing waters. Deposits of diatomaceous earths are usually mixed with sand and clay. As a group, the diatomaceous earths are the most reactive with lime of all the natural pozzolans. The main component

of the diatomaceous earths is opal, which is amorphous and contains 6-10 percent water. Submicroscopic crystals of beta-cristobalite, an unstable silica mineral, may also be present. Although opal has inherent pozzolanic activity, some effects may be improved by calcination. The largest known deposit of diatomaceous earths is located in California.

Artificial pozzolans include burnt clays and shales, burnt gaize, burnt moler, and pulverized fuel ash or fly ash. The first three materials mentioned are actually found in nature as natural pozzolans, but the pozzolanic activity is significantly increased due to alteration by the burning, or calcination, of the material. Therefore, for the purpose of this paper we shall consider these under the "artificial pozzolan" category.

The pozzolanic properties of burnt clays and shales were well utilized by the Romans. Since both clays and shales occur more frequently than the natural volcanic pozzolans, many times these were used as substitutes.

Raw materials deemed suitable must be highly argillaceous, since pozzolanic activity increases with clay content. Clays of kaolinitic or montmorillonite-type with high alumina contents are preferred. The optimum temperature for calcination ranges between 1,300 °F and 1,475 °F. Anything much above the upper temperature causes the activity to decrease. Montmorillonite-type clays require a slightly lower temperature for calcination. This product is then ground to cement fineness.

Water demand for concretes containing calcined clay is quite a bit less than for those containing diatomaceous earths or volcanic pozzolans, although it is still more than for straight cement concrete. Due to this additional water, the drying shrinkage is usually less when calcined clays are used. Heat of hydration is also reduced with calcined clays.

A lime-surkhi mortar has been used in India for quite awhile. This mortar consists of grinding lime mixed with crushed bricks or burnt clays and placing this mixture in a mortar mill. This mortar is then frequently used in underwater structures such as dams.

Gaize is a sedimentary rock that is quite soft and porous. It is highly siliceous and has been used in the raw form as a pozzolan but is usually burned prior to mixing with cement in concrete. The concrete produced by the addition of gaize is quite resistant to sea-water attack.

Moler can also be used in its raw form as a pozzolan but is much more effective when burned. Moler is found in a Tertiary-age deposit of diatomaceous earth that contains clay in a large abundance. Moler is found in a deposit on the islands west of Limfjord, Denmark. It, too, is often used for concrete subjected to sea-water attack. Since moler is a diatomaceous earth, the water demand is incredibly high. However, with calcination at 1,450 °F, both water demand and subsequent drying shrinkage are reduced dramatically.

Fly ash is a by-product of burning finely ground coal in electricity-generating power plants. It is captured by electrostatic precipitators or bag houses. Pozzolan Northwest, a processor and distributor of fly ash in the western United States, goes one step further in this process, by running the fly ash through a classifier to divide the particles by size, which in turn assures consistency of the product.

The composition and various properties of the fly ash depend not only on the coal that is burned but also the efficiency of the combustion process.

Fly ash particles are glassy and spherical in shape. Due to this spherical shape, a ball-bearing effect is created. This allows for a reduction in water content while still producing an extremely flowable mix.

Carbon content and fineness of fly ash are closely related. Generally speaking, the higher the carbon content, the higher the fineness. While the higher fineness would tend to increase the strength

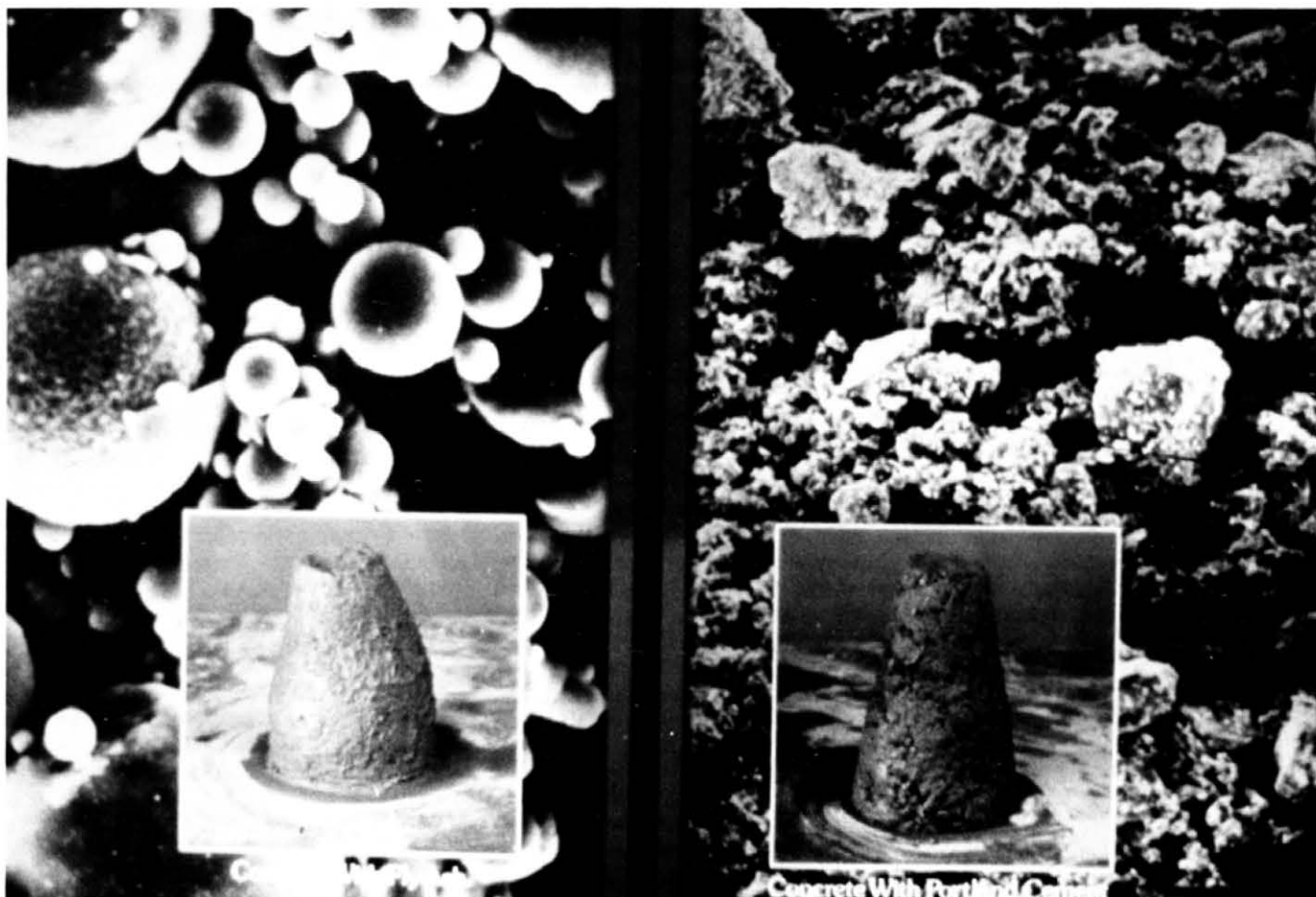


Figure 1. Slump comparison of concrete with fly ash and concrete with portland cement.

of the concrete, the high carbon content reduces the strength significantly. Pozzolan Northwest is known for maintaining very strict standards for carbon content and fineness. In fact, its specifications are much more strict than those of American Society of Testing and Materials.

There are two types of fly ash available: Type F and Type C. Type F is the most common. It is produced by the burning of either anthracite, bituminous, or sub-bituminous coal. Type F is low in lime content and generally has a larger combined silica, alumina, and iron content than Type C. Type F is the single most effective moderator of heat gain during the curing stage for concrete. It is considered an ideal replacement for a portion of cement in mass concrete and in high-strength mixes.

Type C fly ash is the product of burning lignite or sub-bituminous coal. Due to the nature of the coal, the ash produced is slightly higher in lime content. This increased lime gives Type C a self-hardening characteristic. Therefore, it has the added feature of possessing cementitious as well as pozzolanic properties.

Type C fly ash is very useful in "performance" concretes, prestressed, or other early-strength designs, as well as architectural concrete. It is also used frequently in soil stabilization due to the excess lime contents.

Fly ash is quite similar in chemical composition to cement. This means there is nothing foreign going into the concrete mix. Fly ash merely combines with the excess calcium hydroxide (free lime) to produce additional amounts of calcium silicate hydrate, which leaves a more durable concrete product. As mentioned previously, fly ash contains tiny glass spheres that dramatically improve the workability of the concrete without additional water needed. The slump test in Figure 1 shows the improved cohesion of the fly ash concrete mix.

Many of the natural pozzolans have very angular particles, as opposed to the spherical particles of fly ash.

Fly ash can compensate for the fines, which are often absent in sands, increasing ease of pumping, placing, and finishing.

The face of America is raising through concrete buildings built with fly ash concrete. We at Pozzolan Northwest constantly consult with all levels of the construction industry to solve the problems of the West by producing and distributing a high-quality fly ash, thereby allowing the creation of superior concrete.

In summary, the desire for more rapid hardening, improved durability, reduction in heat evolution, as well as economy has helped lead to the introduction, development, and wide-scale use of pozzolanic concretes in the construction industry today.

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Rare earth resources: Comparisons of the geology of existing and potential resources

by Stephen B. Castor, Nevada Bureau of Mines and Geology, University of Nevada-Reno, Reno, Nevada 89557-0088

ABSTRACT

The rare earths, which include the lanthanides and yttrium, are lithophile elements that invariably occur together. Natural deposits of rare earth elements are generally enriched in light lanthanides or in yttrium and heavy lanthanides. Although prices and consumption have increased steadily over recent years, near-term rare earth production capacity as a whole will probably exceed demand. However, new uses for yttrium have increased interest in heavy lanthanide/yttrium deposits.

Currently, rare earth production is dominated by light lanthanides extracted from carbonatite at Mountain Pass in California and from iron ore at Bayan Obo in China. These deposits are apparently the same age and have compositions indicative of alkaline igneous origin. Placer monazite, mainly from Australia, is a third major source of light lanthanides.

Yttrium and heavy lanthanides are presently recovered in small amounts from light lanthanide raw materials, Malaysian tin placers, Canadian uranium ore, and rare earth-enriched clay in China. Zirconia deposits in apatitic alkaline rocks in North America, Greenland, Brazil, Saudi Arabia, Australia, and the USSR are potential yttrium and heavy rare earth sources. Development of large resources of mixed light and heavy rare earths in carbonatite in Australia and Brazil and in a monazite/xenotime placer in Australia has been delayed by metallurgical problems.

INTRODUCTION

Deposits of rare earth elements, which include the lanthanide elements ($Z = 57$ through 71) and yttrium ($Z = 39$), have been subjected to increased scrutiny in recent years. Rare earth commodities have seen relatively steady price increases (Figure 1) as well as production increases since the 1960's, when markets were created in response to new technologies.

The lanthanide elements have traditionally been divided into two groups: the light rare earths, lanthanum through europium; and the heavy rare earths, gadolinium through lutetium. Although yttrium is the lightest rare earth element, it is usually grouped with the heavy rare earths to which it is chemically and physically similar.

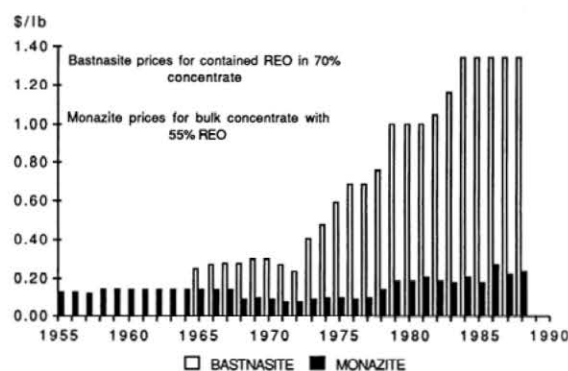


Figure 1. Rare earth oxide (REO) prices in dollars per pound for bastnasite and monazite. Data gathered from *Engineering and Mining Journal* (1965-1972, 1983-1984), *U.S. Bureau of Mines Minerals Yearbook* (1955-1974), *Industrial Minerals* (1975-1988), and *O'Driscoll* (1988).

The rare earths are lithophile elements that invariably occur together naturally because they are all trivalent (except for cerium and europium in some environments) and have similar ionic radii (Figure 2). Such chemical and physical differences that do exist within the rare earth group are caused by small differences in ionic radius, leading to the segregation of the rare earths into deposits enriched in either heavy or light lanthanides. The natural actinides uranium and thorium generally occur in rare earth deposits, and most lode deposits are radioactive. Other lithophile elements that cluster around the rare earths on Figure 2, such as scandium, zirconium, and barium, are commonly associated with lode deposits of rare earths.

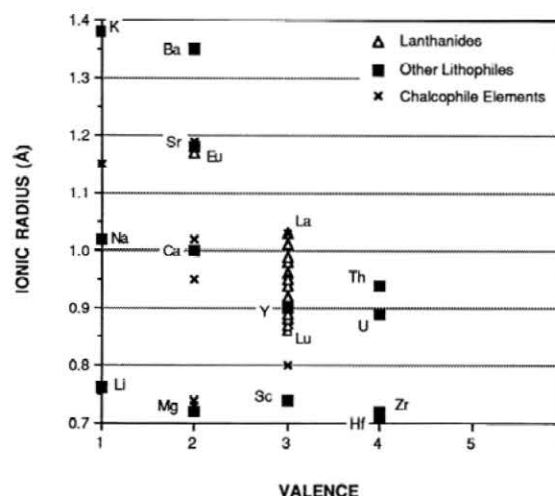


Figure 2. Ionic radii of lanthanide elements plotted against valence compared with similar plots for other elements. Ionic radius data are from Shannon and Prewitt (1976). The most common valence is shown for all elements except europium, for which points are shown for both +2 and +3 valence. Ionic radii are all for 6-fold coordination.

USES OF RARE EARTH ELEMENTS

Traditional rare earth uses in mischmetal and lighter flints have declined as a percentage of the overall market from nearly 100 percent before 1950 to about 30 percent in the 1980's. At present, the glass industry uses the most rare earth by weight, mainly cerium oxide as a decolorizing additive and an abrasive. Cerium is also in demand for use in automotive catalytic converters. Sales of lanthanum-rich mixed rare earth compounds for use in petroleum refining peaked in 1984, declining substantially since then due to changes in the types of crude oil consumed and types of gasoline produced.

Beginning in the 1960's, color television manufacture spurred demand for high-value rare earth phosphors based on yttrium, europium, gadolinium, and terbium. More recently, increased production of rare earth phosphors has resulted from their use for color control in fluorescent lighting. In addition to its use in phosphors, yttrium has found increased use in zirconia ceramic.

Table 1. Rare earth distribution (percent by weight of total REO) in minerals and ore types worldwide. Compiled from following sources: Mountain Pass, USA (bastnasite concentrate)—this paper; Bayan Obo, China (ore)—Yuzhuo and others (1983); eastern Australia (monazite), western Australia (monazite), and Malaysia (xenotime)—Hedrick (1988); Jiangxi, China (ore)—O'Driscoll (1988); Kipawa, Canada (eudialite)—Fryer and Edgar (1977); Strange Lake, Canada (rock)—this paper; Saudi Arabia (rock)—Drysdall and others (1984)

Element	Light Lanthanide Deposits					Yttrium and Heavy Lanthanide Element Deposits				
	MTN PASS	BAYAN OBO	E. AUST.	W. AUST.	FLORIDA	MALAYSIA	JIANGXI	KIPAWA	STRANGE L.	SAUDI
La	32.97	24.50	20.20	23.90	17.47	0.50	24.60	8.30	5.40	0.05
Ce	49.89	50.50	45.30	46.03	43.73	5.00	1.60	15.80	14.70	0.40
Pr	4.15	5.50	5.40	5.05	4.98	0.70	4.80	1.80	4.80	0.02
Nd	11.47	16.50	18.30	17.38	17.47	2.20	17.20	7.10	1.60	0.16
Sm	0.93	1.20	4.60	2.53	4.87	1.90	3.60	2.30	2.10	0.32
Eu	0.12	0.20	0.10	0.05	0.16	0.20	1.10	0.40	0.10	0.02
Gd	0.25	0.50	2.00	1.49	6.56	4.00	5.20	3.10	2.10	1.20
Tb	0.02	0.20	0.20	0.04	0.26	1.00	0.70		0.20	
Dy	0.04	0.20	1.15	0.69	0.90	8.70	4.40	5.60	8.50	8.19
Ho	0.004	0.03	0.05	0.05	0.11	2.10	0.50		1.70	2.40
Er	0.006	0.06	0.40	0.21	0.04	5.40	2.40	4.80	5.10	9.43
Tm	0.002	0.01		0.01	0.03	0.90	0.30		0.70	
Yb	0.002	0.10	0.20	0.12	0.21	6.20	2.10	5.80	4.20	13.37
Lu		0.10		0.04	0.03	0.40		0.80	0.40	1.82
Y	0.15	0.40	2.10	2.41	3.18	60.80	31.10	44.00	48.20	62.59
Total	100.00	100.00	100.00	100.00	100.00	100.00	99.60	99.80	99.80	99.97

In the 1970's, the introduction of high-strength cobalt-samarium permanent magnets, particularly for use in small electric motors, created a dynamic new rare earth market. During the 1980's, demand for samarium has often exceeded supply.

Volumetrically, minor markets for rare earth elements include the use of yttrium and gadolinium garnets for laser production; yttrium, praseodymium, and lanthanum in electronics; cerium and praseodymium in ceramics; and lanthanum in microwave technology.

Proposed future uses have recently sponsored increased awareness of potential profits in rare earth raw materials. Superconducting substances produced from oxide mixtures of lanthanum or yttrium with barium and copper have been in the spotlight since 1986. However, volume markets for these substances await further technological breakthroughs. Neodymium-iron-boron permanent magnets show promise as lower-cost substitutes for some uses of cobalt-samarium magnets, but volume production has not yet been initiated. New methods have been devised to use lanthanum in hydrogen-based cryogenics, potentially a large market area.

RARE EARTH DEPOSITS

In a practical sense, rare earth deposits are best separated into two types: (1) those dominated by the light lanthanide elements, and (2) those that mostly contain yttrium and the heavy lanthanides. Although these two types of deposits occur in somewhat similar geologic environments, and a few deposits contain mixtures of both groups of elements, market potentials for the two types are sufficiently different to justify separate discussion. Table 1 shows lanthanide and yttrium distributions in ore and exploited minerals for examples of the two types of deposits.

Light lanthanide deposits

Traditionally, rare earth production has come from light lanthanide deposits. Prior to the 1950's, rare earth elements were mainly used in mischmetal, a mixed light lanthanide metallurgic component. Significant use of individual lanthanide compounds was dominated by light lanthanides until the mid 1960's, when yttrium and some heavy lanthanides found use in phosphors.

At present, hard-rock light lanthanide deposits in the USA and China account for about 60 percent of the world's rare earths

(Figure 3). Most of the remaining production is from monazite placers in Australia, Brazil, Malaysia, and India (Figure 4).

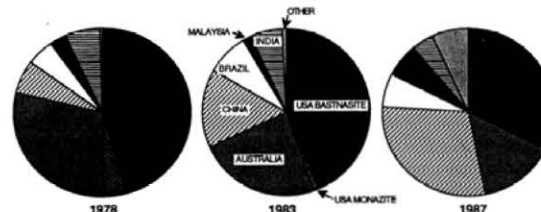


Figure 3. Relative production of rare earths by country for 1978, 1983, and 1987. Compiled using data from Griffiths (1984), O'Driscoll (1988), and Hedrick (1988).

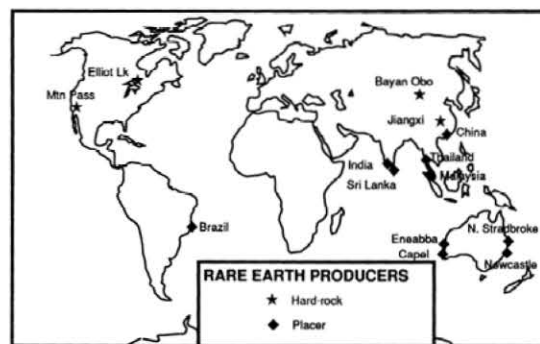


Figure 4. Locations of rare earth raw material producers.

Mountain Pass, USA: The Mountain Pass deposit, which has been in production continuously since 1954, is the only deposit mined exclusively for rare earths. It is owned and operated by Molycorp, Inc., a subsidiary of Unocal. In 1987, proven and probable reserves totalled 32 million short tons, with an average grade of 8.9-percent rare earth oxide (REO) based on a 5-percent cutoff

grade. Bastnasite, a lanthanide fluorocarbonate containing about 70 percent REO, is concentrated by flotation from carbonatite ore typically containing about 65 percent calcite and/or dolomite, 20 to 25 percent barite, and 10 to 15 percent bastnasite. Two basic ore types are distinguished at Mountain Pass: sovite and beforite, with carbonate mineralogies dominated by calcite and dolomite, respectively. Other gangue minerals that may be present in significant amounts are strontianite, celestite, quartz, and talc. Minor amounts of hematite are ubiquitous, and magnetite is rare. Galena is locally abundant, but other sulfide minerals are rare. The lanthanide minerals parisite, synchisite, ancylite, sahalamite, hydroxylbastnasite, monazite, florencite, allanite, and cerite also occur at Mountain Pass, generally as minor phases.

The Mountain Pass carbonatite orebody, which is about 1.4 Ga (DeWitt and others, 1987), is a moderately dipping tabular intrusion (Figure 5) cutting granulite grade gneiss. It is associated with 1.4-Ga ultrapotassic alkaline plutons of similar size and orientation, as well as abundant carbonatite and ultrapotassic dikes. The Mountain Pass carbonatite/alkaline district is part of a narrow, north-trending zone of ultrapotassic alkaline igneous rocks at least 130 km long (Castor and others, 1989). Alteration associated with carbonatite intrusion and lanthanide mineralization at Mountain Pass includes distinctive "fertilization" consisting of carbonate, red potash feldspar, and blue-grey magnesioriebeckite introduced into gneiss and ultrapotassic rocks. In addition, chlorite and phlogopite are common alteration products.

The mineralogy and chemistry of the Mountain Pass orebody, in addition to its tabular shape and association with ultrapotassic alkaline plutons, serve to distinguish it from the more common niobium- and phosphorus-rich circular carbonatite and nepheline or nepheline syenite systems. With the exception of carbonatite at Kangankunde, Tanzania, the Mountain Pass ore is the only carbonatite containing significant amounts of bastnasite as a primary phase (A.N. Mariano, personal communication, 1988).

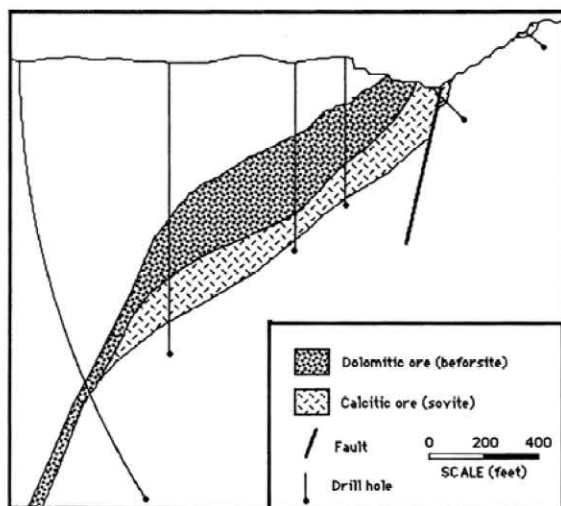


Figure 5. Cross section of the Mountain Pass orebody showing the two dominant ore types.

Bayan Obo, China: At Bayan Obo, Inner Mongolia, China, iron ore mined since 1957 became an important source of light lanthanides in the 1980's. Development of the rare earth potential at Bayan Obo catapulted China from a relatively minor producer in 1978 to an approximately equal position with the USA in 1987 (Figure 3). In the 1960's, concentrates containing only 30 percent REO were produced; it was not until the 1970's that 60 percent

REO concentrates were available from Bayan Obo (Griffiths, 1984).

The Bayan Obo rare earth resource is 36 million metric tons of REO (O'Driscoll, 1988), more than ten times the Mountain Pass reserves. The average grade of the Bayan Obo resource is about 5 percent REO, mainly in monazite and bastnasite that are present in approximately equal amounts (Qiu Yuzhuo, personal communication, 1985). Rare earth concentrates are produced by processing tailings from iron oxide beneficiation. The ore, which contains 32 to 35 percent iron as hematite, magnetite, and martite, is crushed at Bayan Obo and hauled 95 mi south to Baotou for beneficiation (Argall, 1980). A production increase from 290,000 tons to 950,000 tons per year of ore is planned for 1990 (O'Driscoll, 1988); however, recent political developments may have a negative impact on rare earth exports from China.

Iron ore at Bayan Obo is mined from two sites: the Main pit, which exploits an orebody roughly elliptical in plan and measuring about 2,700 ft by 4,000 ft, and the East orebody, which is also 4,000 ft long but "U" shaped in plan, with the limbs of the "U" about 600 ft wide (Argall, 1980). Both orebodies occur in Proterozoic dolomite, adjacent to its contact with overlying black slate along an east-trending syncline and dip moderately to steeply south (Figure 6). Undeveloped bodies of iron/rare earth ore occur in the same setting more than 10 mi west of the Main pit.

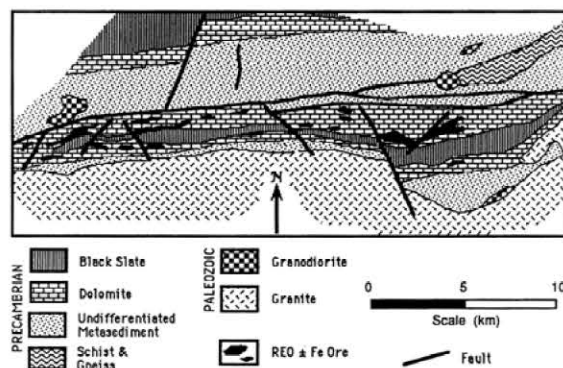


Figure 6. Geologic map of the Bayan Obo area, China, adapted from Meng Qingrun, 1982.

In addition to iron oxide, the ore at Bayan Obo contains more than 20 rare earth minerals and a number of niobium minerals (Hou and others, 1987). Niobium comprises more than 0.1 percent of the Main and East orebodies, mainly occurring as eschynite and fergusonite. Major gangue minerals are dolomite, fluorite, aegerine, riebeckite, apatite, barite, biotite, phlogopite, pyrite, and rutile.

Qui and others (1983) classified the Bayan Obo ore as banded iron formation and compared it with Precambrian iron formations elsewhere in China. Based on its geochemistry, Bai and Yuan (1985) suggested that it is "marine volcano-sedimentary carbonatite" that was formed during syndimentary effusion of carbonatite magma. Chao and others (1989) and Drew and others (1989) believe that the ore was formed by replacement of dolomite by hydrothermal fluids related to unexposed Precambrian alkaline and/or carbonatite plutonism and was subjected to later hydrothermal remobilization. It may be significant that dates on monazites representing the earliest stage of mineralization suggest a 1.4-Ga age like that of the Mountain Pass orebody (Qui and others, 1983; Chao and others, 1989).

Placer monazite deposits: The third most important source of light lanthanides in the world is by-product monazite from titanite/zircon paleobeach placers in western Australia. Prior to 1985, Australia was the second most important source of rare earths, but its market share has since declined (Figure 3). However, if expansion plans described by O'Driscoll (1988) come to fruition,

Australian monazite production should double in the early 1990's. Construction of a new rare earth processing facility in Western Australia by Rhone-Poulenc, Inc., that is scheduled to begin production in 1990, along with a recent surge in zirconia demand, should spur near-term increases in Australian monazite production.

Placer rutile/zircon/ilmenite deposits at Eneabba on Australia's west coast north of Perth were brought into production in the late 1970's, beginning the transfer of dominance of Australia's titania/zircon placer mining from the east coast. In recent years, Eneabba has accounted for more than half of Australia's monazite production. Heavy minerals comprise about 5 percent of the sand mined. Monazite, which makes up about 3 percent of the heavy mineral concentrates produced at Eneabba, is beneficiated by magnetic and electrostatic methods to yield a 58 percent REO product (Griffiths, 1984). The heavy mineral sands, which lie 100 ft or more above present sea level, were deposited in late Tertiary or early Pleistocene time (Lissiman and Oxenford, 1975). Archean metamorphic rocks in the interior provided heavy minerals to Mesozoic sedimentary rocks that were reworked to form the deposits. Parallel high-grade zones within the deposits mark strandline accumulations on progressively lower wave-cut benches.

At Capel, south of Perth, ilmenite/zircon paleobeach deposits have been mined since the mid-1950's. The deposits occur along a strike length of about 30 mi in Pleistocene to Recent sands up to 250 ft above the present sea level (Welch and others, 1975). The source and setting are similar to those described for Eneabba. Although the average heavy mineral grade of the Capel area deposits is somewhat higher than at Eneabba, monazite content is lower, at about 0.2 percent of concentrated products. Monazite concentrates produced in the Capel area contain slightly more than 60 percent REO.

Less than ten percent of Australia's monazite is produced from east coast titania/zircon placers. Rutile and zircon are the main mineral products from these operations, which exploit Pleistocene paleoplacers.

Placer operations in other countries produce by-product monazite from paleobeach deposits. In order of decreasing production, these countries are Malaysia, India, Brazil, Thailand, China, USA, and Sri Lanka. In Malaysia, monazite is produced as a by-product of tin mining, and production rates are dependent on tin prices, which have been relatively low in recent years. In Brazil and India, monazite production from titania/zircon placering is government controlled, and both countries have plants that process monazite concentrate into rare earth products. Indian monazite production is expected to double in the near future (O'Driscoll, 1988). Production of monazite from the Green Cove Springs placer deposit in Florida has been a minor contributor to total USA production, and none was produced in 1987 (Figure 3).

Heavy rare earth deposits

Although some yttrium and heavy lanthanides are produced from the light rare earth deposits discussed above, the supply from these deposits is not adequate to meet world demand, particularly for yttrium. At present, three sources provide a rare earth mix consisting predominantly of yttrium and heavy lanthanides.

Xenotime placers: Xenotime, a phosphate mineral that contains about 60 percent yttrium and heavy rare earths, is a minor constituent of some monazite placer deposits. The Malaysian tin placers are the most important source of xenotime, with production capacity at about 120 metric tons per year of yttrium concentrates containing a minimum of 30 percent yttrium oxide. Some Australian titania/zircon/monazite placers also produce minor amounts of xenotime.

Elliot Lake, Canada: In 1986, production of yttrium began as a by-product of uranium recovery from Precambrian conglomerate ore at Elliot Lake in Ontario, Canada. The ore mineral is brannerite, a complex oxide of uranium, thorium, and rare earth

elements. Although this new plant has a yearly capacity of 150 tons of yttrium oxide, production has been considerably below that figure.

Jiangxi, China: Beginning in 1987, yttrium has been produced from rare earth-rich clay in Jiangxi Province, China. According to O'Driscoll (1988), the mill feed contains 92 percent total rare earth oxide. As percentages of total rare earths, the ore contains over 30 percent yttrium oxide along with about 10 percent total heavy lanthanides (see Table 1).

Potential yttrium and heavy lanthanide sources

In the 1980's, active exploration for deposits of yttrium and heavy lanthanides has been promoted by new ceramic markets and the expansion of phosphor markets. For the most part, the focus has been on deposits with high yttrium content.

Agpaitic syenite and/or granite or rhyolite complexes with large masses of rock rich in zirconia, yttrium, and heavy lanthanides, with or without high beryllium, niobium, and fluorine contents have been in the spotlight lately. Recent high zirconia demand has added some impetus to evaluation of such deposits. Although deposits as old as 2.8 Ga and as young as 60 Ma are known, most are 1.2 to 1.3 Ga and occur in a northeasterly belt extending across North America from New Mexico to Labrador, through Greenland, and onto the Kola Peninsula, USSR (Figure 7).

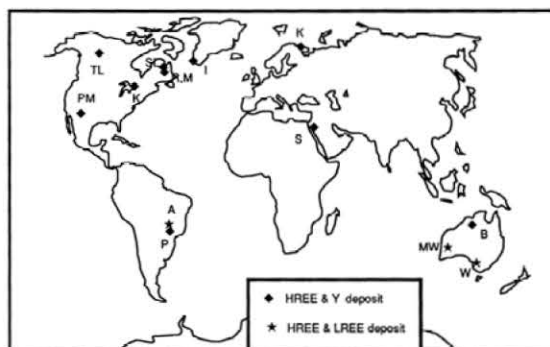


Figure 7. Potential heavy rare earth (HREE) and mixed heavy and light rare earth (HREE & LREE) deposits: B = Brockman, Australia, tuff; K = Khibina, USSR, eudialite; KR = Kipawa River, Canada, eudialite; I = Ilmaussaq, Greenland, eudialite; PM = Pajarito Mountain, USA, eudialite; R.M. = Redwine complex and Mann 1 prospect, Canada, eudialite; S = Saudi Arabia, peralkaline granites and syenites; SL = Stange Lake, Canada, gadolinite in syenite; TL = Thor Lake, Canada, Be in syenite; A = Araxa, Brazil, Nb carbonatite; MW = Mount Weld, Australia, carbonatite; W = WIM 150 prospect, Australia, paleoplacer.

Eudialite deposits: In 1989, Molycorp, Inc., announced the discovery of an orebody containing about 3 million tons of eudialite syenite containing 1.3 percent zirconia and 0.18 percent yttria at Pajarito Mountain, New Mexico. It is believed that production costs for extraction of zirconia, yttria, and heavy lanthanides from this deposit will be low, because eudialite is soluble in dilute acid, and heap-leach processing similar to that utilized for some low-grade gold deposits may be used (J.O. Landreth, personal communication, 1989).

The Pajarito Mountain deposit, which is within the Mescalero Apache Reservation, is part of an agpaitic syenite complex exposed over an area of about 2 mi by 1 mi (Kelley, 1968). Syenite containing up to 20 percent eudialite and 5 percent fluorite with perthite, quartz, riebeckite, and aegerine occurs in an area of about 0.2 mi²

(Woolley, 1987). K-Ar dates on the Pajarito Mountain syenite complex indicate a 1.2-Ga age.

Other North American eudialite syenite/granite occurrences are at Kipawa Lake, Quebec; in the Red Wine complex, Labrador; and at the Mann I prospect, Labrador. Eudialite from Kipawa contains 1.6 percent yttria, 1.7 percent light lanthanides, and 0.8 percent heavy lanthanides (Fryer and Edgar, 1977). Rb/Sr isochron data on the Red Wine complex yielded a 1.3-Ga initial age (Woolley, 1987).

At Ilmaussaq, in Greenland, eudialite-rich agpaitic syenites (lujavrites and kakorkaites) are being evaluated as zirconia-yttria-heavy lanthanide sources. Announced grade for potential targets is 1.5 percent zirconia and 0.12 percent yttria. The alkaline complex that contains the deposits is a roughly oval mass about 10 mi by 4 mi. Data on the size of the deposits have not been released, but eudialite-rich rock at Ilmaussaq is known to occur in layers up to 30 ft thick (Sorenson, 1974). Rocks from Ilmaussaq have been dated at 1.2 Ga (Woolley, 1987).

On the Kola Peninsula, USSR, a 1.2-Ga syenite complexes at Khibina and Lovozero is known to contain large amounts of eudialite-bearing rock (Gerasimovsky and others, 1974). Rare earth elements are said to be produced from apatite deposits in the Lovozero alkaline complex, but data on grade, production, and reserves are not available.

At Pocos de Caldas, Brazil, a circular agpaitic syenite complex 20 mi in diameter has produced zirconia from baddeleyite and uranium from laterized syenite. Eudialite is said to occur in places within this complex, but data on tonnage and rare earth grade are not available. The Pocos de Caldas complex is much younger than the eudialite occurrences listed above, having yielded 53- to 90-Ma dates (Woolley, 1987).

Other yttrium/zirconia deposits in alkaline rocks: The Brockman deposit near Falls Creek in northern Australia is being evaluated as a source of yttrium and other rare elements. Announced reserves are 9 million tons at 1.3 percent zirconia, 0.15 percent yttria, 0.12 percent heavy lanthanides, 0.4 percent niobium, and 0.03 percent tantalum. The zirconia phase is very fine-grained zirconolite in a metamorphosed rhyolite tuff. No information has been released on rare earth mineralogy.

At Thor Lake in the Northwest Territories, Canada, a 2.1-Ga circular alkaline complex 20 mi in diameter contains a beryllium orebody with zirconium, yttrium, and lanthanide credits. Reserves are said to consist of about 2 million short tons of ore with 0.9 percent beryllia and 0.2 percent yttria. Underground development at Thor Lake has been initiated to develop the beryllium resource.

Several bodies of peralkaline granite and syenite that contain significant amounts of yttrium have been discovered in Saudi Arabia (Drysall and others, 1984). The highest grade occurrence contains 0.5 percent yttria along with 0.3 percent lanthanides and consists of about 6 million metric tons of rock. The largest, at 440 million metric tons, carries 0.13 percent yttria and less than 0.1 percent lanthanides. The rare earth mineralogy of these deposits is variable but includes xenotime, monazite, and bastnasite. Zirconium, present as zircon, exceeds 1.5 percent in some deposits.

At Strange Lake in Labrador, a 1.3-Ga circular agpaitic syenite and granite complex 5 mi in diameter contains a large amount of rock with 1.6 percent zirconia, 0.3 percent yttria, and significant lanthanide, niobium, and beryllium contents. The most abundant rare earth phase in this rock is gadolinite (A.N. Mariano, personal communication, 1989). Because of its remoteness, it is unlikely that this deposit will be developed in the near future.

Potential mixed light and heavy lanthanide deposits

Three large deposits with potential for production of light and heavy lanthanides as well as yttrium have been evaluated, but metallurgical problems have so far precluded their development. Two are carbonatites, and one is a monazite-xenotime placer.

The Mount Weld deposit, located in the southwestern Australian interior, is in the laterized cap of a large circular carbonatite. Drilling of this carbonatite has established the existence of a yttrium/lanthanide/tantalum resource containing significant volumes of rock with 0.2 to 0.5 percent yttria. Unweathered carbonatite intercepted at depths of 10 to 130 m contains rare earths, phosphorus, and niobium in amounts that are normal for carbonatites associated with nepheline syenites. The rich yttrium and lanthanide deposits at Mount Weld are thought to have been derived during long-term laterization by protracted leaching and redeposition of rare earths and other elements by groundwater and mainly consist of secondary monazite and the hydrous yttrio-phosphate churchite (Lottermoser, 1988). Although the Mount Weld deposit is a large, high-grade rare earth resource, metallurgical problems have precluded its development at this time; however, development of associated apatite as a source of phosphate fertilizer is likely.

At Araxa, Brazil, niobium is mined from a thick laterized cap overlying a circular 90-Ma carbonatite and glimmerite complex about 3 mi in diameter. In addition to the niobium resource, estimated to be 460 million tons at 2.5 percent Nb₂O₅, 0.8 million tons of laterite containing 13.5 percent REO have been proven to a depth of 50 ft (Sad and Torres, 1978), and much larger reserves are likely. As at Mount Weld, the rare earth minerals are secondary phosphates not currently amenable to beneficiation.

Near Horsheim in southeastern Australia, a large titanite/zircon paleoplacer deposit containing significant amounts of monazite and xenotime was discovered in 1987. This property, known as the WIM 150 deposit, contains a billion metric tons of sand with an average heavy mineral content of about 3 percent. Initial plans call for dredge mining of 20 million metric tons of sand per year, with projected yields of 12,000 metric tons of monazite and 2,000 to 3,000 metric tons of xenotime per year (O'Driscoll, 1988). Recovery may be a problem at WIM 150, because most of the monazite and xenotime in the deposit will pass 200 mesh.

SUMMARY

The world's light rare earth production comes mostly from the Mountain Pass carbonatite, USA; the Bayan Obo iron deposit, China; and placers in Australia, Malaysia, India, and Brazil. World light rare earth production is expected to increase substantially in the early 1990's. With the possible exception of samarium, near-term light rare earth production capacity will probably exceed demand.

Demand for yttrium, which mostly comes from deposits enriched in heavy rare earths, appears to be increasing more quickly than the world supply. Potential future yttrium and heavy rare earth sources are deposits in agpaitic igneous rocks in North America, Greenland, Russia, Australia, and Brazil; a xenotime-bearing placer in Australia; and carbonatites containing secondary enrichments of mixed light and heavy rare earths in Brazil and Australia.

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Pacific Northwest zeolite update

by David A. Holmes, Meridian Minerals Company, 5613 DTC Parkway, Englewood, Colorado 80111

ABSTRACT

Natural zeolites occur as altered Tertiary silicic ash-fall tuffs in all five Pacific Northwest states and have become a viable commodity in eastern Oregon, southwestern Idaho, and south-central Wyoming. Of the more than 30 naturally-occurring zeolite minerals, five have significant economic potential, including chabazite, clinoptilolite, erionite, mordenite, and phillipsite. All five economic species occur in the Pacific Northwest.

Recent exploration programs have proven and characterized economic zeolite resources in ten zeolite districts. Clinoptilolite is the most common zeolite mineral and the only one currently being produced in the Pacific Northwest. Major economic clinoptilolite deposits include Sheaville and Chrisman Hill, Oregon-Idaho; Harney Basin and Succor Creek, Oregon; Castle Creek and Bear River, Idaho; and Washakie Basin, Wyoming. Potentially economic chabazite deposits are located at Durkee and Harney Basin, Oregon, and Beaver Rim, Wyoming. Major erionite deposits occur in the "Rome Beds" and in the Harney Basin sediments, Oregon. High-quality mordenite resources constitute the white tuff beds of the "Crooked Creek" member of the "Rome Beds," Oregon. Phillipsite occurs in possible economic concentrations in the Harney Basin, Oregon.

There are only two active natural zeolite producers in the region: Teague Mineral Products mines clinoptilolite at the XY (Castle Creek) and Chrisman Hill, Idaho, and Succor Creek, Oregon, deposits to supply its processing plant in Adrian, Oregon, in making a wide range of agricultural and industrial products. The Norton Company mines a small tonnage of clinoptilolite annually for internal supply to its molecular sieve manufacturing facility in Ohio. Several other small companies are working to develop additional regional clinoptilolite sources.

Regional economic zeolite deposits were formed during alter-

ation or diagenesis of Tertiary ash-fall tuffs by the reaction of vitric material with percolating water, both in open hydrologic systems and in closed-system alkaline or saline playa environments. The high quality of the Sheaville and Chrisman Hill and possibly the XY (Castle Creek) deposits appears enhanced by overprint of local hydrothermal alteration.

Clinoptilolite will remain the principal economic natural zeolite mineral produced in the region and will expand gradually in North American and overseas industrial product markets. Agricultural applications will be limited by transport restraints to regional markets.

INTRODUCTION

Sheppard (1976) presented a classic zeolite paper entitled "Zeolites in Sedimentary Deposits of the Northwestern United States—Potential Industrial Minerals," at the Eleventh Forum on Industrial Minerals in Kalispell, Montana, in July 1975. This paper was subsequently published in the Montana Bureau of Mines and Geology Special Publication 74. Sheppard's paper represents an enduring foundation for natural zeolite studies in the Pacific Northwest, and there is little need to restate the basic information or to relist the numerous occurrences presented in his study (see Figure 1).

This paper is an up-date of Sheppard's study, describing exploration work and commercial development that have taken place on Pacific Northwest zeolites since 1979. Relatively few new zeolite discoveries have been made in the region in this interval.

Major efforts by several large mining corporations on commercial development of the Pacific Northwest natural zeolites during 1974-1983 failed, and the regional zeolite industry is now in the hands of smaller entrepreneurial companies operating or exploring principally in the Owyhee region of Oregon and Idaho.

More than thirty distinct species of natural zeolite minerals

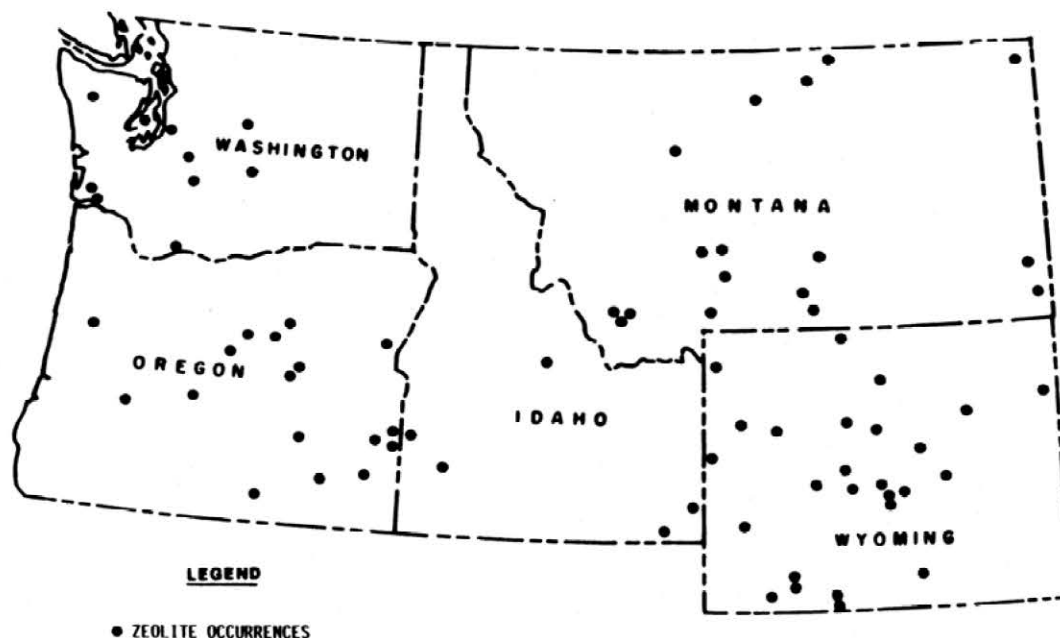


Figure 1. Pacific Northwest natural zeolite occurrences (after Sheppard, 1976).

are recognized. Numerous zeolites have also been synthesized, but few match natural counterparts. There are no synthetic zeolite counterparts to match the five principal economic natural zeolite minerals (clinoptilolite, chabazite, mordenite, erionite, and phillipsite). Synthetic zeolites are generally incompatible with low pH (acid) environments, in contrast with the ability of clinoptilolite and mordenite to survive and function in solutions with a pH as low as 3.0.

Natural zeolites occur as authigenic silicate minerals in a variety of sedimentary rocks and depositional environments. Table 1 lists common modes of geologic occurrence of natural zeolites. Virtually all of the economic or potentially commercial natural zeolite deposits in the Pacific Northwest occur in zeolitized tuffs or tuffaceous sediments. The amorphous volcanic glass in tuffaceous host rocks is an ideal starting material to yield natural zeolite minerals in an authigenic setting. Natural zeolites also occur as major fine-grained mineral constituents in low-grade metamorphic rocks and in various sedimentary rocks. The finer grained zeolites do not appeal to most mineral collectors, but if they have large reserves and yield high-quality products, they may offer economic potential for many industrial and agricultural applications. Natural zeolites commonly occur as fillings in cavities and fractures in igneous rocks, particularly basalts. Most of the large, attractive zeolite specimens in museum collections have been obtained from sources in igneous rocks (Sheppard, 1979).

PROPERTIES OF NATURAL ZEOLITES

Natural zeolites may show considerable range in chemical composition, including variation in water content, cation content, and Si:Al ratio. Compositional variation is reflected as well in variation of the physical properties of specific zeolites, which logically is reflected in relative performance of zeolite products in commercial use. Such characteristics as brightness, cation exchange capacity, and gas adsorption capacity may vary greatly for individual zeolite mineral species from place to place.

Zeolite occurrences in sedimentary rocks commonly include some intermixed natural zeolite minerals, particularly those formed in closed alkaline lake or playa settings. This may cause serious problems in mining and processing for commercial use, as the physical properties will vary widely with the variation in the relative content of the different zeolite minerals. Most attractive zeolite deposits are either monomineralic or contain preferably no more than two zeolite minerals in a relatively constant ratio relationship.

Table 1. Types of natural zeolite occurrences

• SALINE/ALKALINE LAKES (CLOSED HYDROLOGIC SYSTEM)
• OPEN HYDROLOGIC SYSTEM
• HYDROTHERMAL ALTERATION
• BURIAL METAMORPHIC
• DEEP SEA SEDIMENTS
• SOILS AND LAND SURFACES

Table 2. Currently economic natural zeolite minerals

• CLINOPTILOLITE
• CHABAZITE
• ERIONITE
• MORDENITE
• PHILLIPSITE

The wide diversity of applications and potential applications of natural zeolites is due to a unique set of properties, including reversible dehydration, cation exchange, adsorption, and molecular sieving. The major properties of natural and synthetic zeolites are discussed in detail in Breck (1974).

Most economic zeolites are too fine grained to identify in hand specimen and have an actual zeolite mineral content in the range of 60 percent to 85 percent. Few have purity above 85 percent. The other constituents are commonly clay minerals, quartz, feldspar, amorphous silica, and unaltered ash and mafic minerals. X-ray powder diffraction (XRD) analysis of samples is the common technique used to identify zeolite minerals. This method also permits a semiquantitative estimate of the abundance of zeolite and associated minerals in the samples. Scanning electron microscopy (SEM) is also useful in studying the relative zeolite mineral content, crystal size and shape, paragenesis, and presence of any deleterious contaminants, i.e., fibrous minerals. Ammonia cation exchange capacity analysis is a commonly used technique to screen zeolites and to conduct mining quality control, particularly for clinoptilolite. Depending on the mineralogy and specifications of the zeolite products to be made and their ultimate end uses, a variety of other physical tests may be employed, such as gas adsorption capacity, gas separation characteristics, brightness, color, specific metals cation exchange capacity (e.g., cesium, silver, and copper), viscosity in solutions, etc. The ultimate test for any natural zeolite product is the quality of its performance for an end use function, and preliminary or periodic end-use testing may be done to both develop new products and ensure that sustained production is yielding effective product materials. In actual commercial practice, XRD and SEM analysis are rarely done for mining or processing quality control, and a producer relies on one or more physical tests and/or on very specific end-use related tests to achieve quality assurance.

Table 3. Companies involved with zeolites in the Pacific Northwest

COME AND GONE
• KENNEDY MINERALS
• UNION CARBIDE
• SHELL OIL
• FILTROL
• ANACONDA MINERALS
• OCCIDENTAL MINERALS
• IMC
• ROCKY MOUNTAIN ENERGY
• PHELPS DODGE ZEOLITES
• TENNECO SPECIALTY MINERALS
ACTIVE PRODUCERS/NEAR-PRODUCERS
• TEAGUE MINERAL PRODUCTS
• NORTON COMPANY
• STEELHEAD SPECIALTY MINERALS
• U.S. ZEOLITES
ACTIVE-OTHER
• EAST-WEST MINERALS
• DOUBLE EAGLE MINING
• AIMCOR
• U.S. ENERGY
• TOM SHARPS & PARTNERS

ZEOLITE MINERALS WITH COMMERCIAL POTENTIAL

Zeolite minerals have been recognized in many different sedimentary rocks and depositional environments since the discovery of phillipsite in deep sea sediments in 1891. Sheppard (1976) reports that only eight different zeolites, including analcime, chabazite, clinoptilolite, erionite, heulandite, laumontite, mordenite, and phillipsite commonly occur in the sedimentary rocks of the Pacific Northwest. Analcime and clinoptilolite are by far the most commonly reported.

In light of current markets, five of the natural zeolites, including chabazite, clinoptilolite, erionite, mordenite, and phillipsite, have strongly established economic potential (see Table 2). The balance lack definable characteristics of economic interest and are not currently sought. Continuing research and future market development will inevitably find new uses and establish economic potential for other zeolite minerals.

Chabazite has a generally blocky crystal shape and particular value for gas separation, natural gas clean-up, and catalysis applications. Commercial quality chabazite is relatively scarce and is currently mined in North America only from a very thin bed in shallow Pliocene sediments near Bowie, Arizona. Figure 2 indicates chabazite occurrences in the Pacific Northwest.

Clinoptilolite is the most versatile, as well as most common, of the economic zeolite minerals. It has wide and varying uses in ion exchange, adsorption, and, to a lesser extent, molecular sieving and catalysis applications. Clinoptilolite's tabular crystal shape and especially strong affinity for ammonia make it a particularly attractive mineral for removal and control of any kind of ammonia waste, e.g., cat litter, large animal deodorant, sewage waste clean-up, industrial waste stream clean-up, and aquacultural use. Regional clinoptilolite occurrences are shown in Figure 3.

Erionite has strong economic potential for gas separation, natural gas clean-up, and catalytic and selected ion exchange applications but is a fibrous mineral with suspected carcinogenic characteristics. This has inhibited product research and commercial use of an otherwise promising zeolite mineral (see Figure 4).

Mordenite is also a fibrous mineral but has not been identified as a potential carcinogen. It has excellent gas separation characteristics, particularly for separating nitrogen and oxygen, as in blast furnace air feed and similar applications (see Figure 5).

Phillipsite has attractive ion exchange and sorption characteristics but is relatively rare in the Pacific Northwest and has not been pursued locally as a strong potential ore mineral. Major phillipsite deposits at Lake Tecopa, California, and near Naples, Italy, are capable of producing large tonnages of fairly low-cost phillipsite products that would compete formidably with Oregon sources (see Figure 6).

The relative commercial quality of any zeolite mineral may vary considerably from deposit to deposit, so the quality of one individual deposit in Oregon may surpass or be considerably less than one elsewhere. For example, Oregon chabazites have not been found to have the same high-quality levels of gas separation efficiency as the Bowie chabazite mined from a 6-in.-thick bed near Bowie, Arizona. On the other hand, clinoptilolites in the Shea Bed and XY deposits in Oregon and Idaho, respectively, have superior quality for many commercial applications compared to other clinoptilolite deposits.

HISTORY OF PACIFIC NORTHWEST COMMERCIAL ZEOLITE INTEREST

The occurrence of economic concentrations of natural zeolites was not known in the Pacific Northwest until 1958, with the exception of the mining of lightweight dimension stone blocks of soft erionite at several locations in eastern Oregon. Table 3 lists the companies that are or have been active in natural zeolite exploration and development since 1958.

The submittal of a sample of erionite from Rome, Oregon, by Kennedy Minerals Company of Los Angeles to Union Carbide Corporation for mineralogic identification and the discovery of clinoptilolite in tuffaceous sediments by Professor L.B. Sand of the University of Utah led Linde Division geologist Richard H. Olson to conduct reconnaissance studies for natural zeolites in eastern Oregon. On his initial trip to Rome, Oregon, to verify the erionite discovery and assist Kennedy Minerals Company in claims staking, Olson also identified a major clinoptilolite occurrence in a roadcut on US Highway 95, several miles north of the village of Sheaville.

Studies by Bradley (1928), Bramlette (1933), Coombs (1954), and others had established by the late 1950's (1) that volcanic glass may alter to natural zeolite minerals, and (2) that thick tuffaceous units in Tertiary sedimentary sequences in the western U.S. and elsewhere may include potentially economic concentrations of natural zeolite minerals. The identification of the Rome erionite sample was one of several events that triggered the intensive wave of exploration by Union Carbide Corporation, a leading molecular sieve producer, to find new zeolite sources—or at least to tie up any natural sources that might compete with its more expensive synthetic cousins. The Union Carbide program was active in the Pacific Northwest during 1958-1962 and then was phased out as the company directed its efforts toward development of the Bowie chabazite deposit, Arizona. Shell Development Company also conducted a zeolite exploration program during 1961-1964, discovering the Rome mordenite and other zeolite occurrences in eastern Oregon. Most of the major regional zeolite deposits were discovered during these programs by the two companies, particularly Union Carbide. Neither company showed particular interest in clinoptilolite, regarding it only as a fair desiccant and lacking the adsorption properties attractive for use in petroleum refining and natural gas clean-up. The early period of western zeolites exploration has been well documented by Mumpton (1984).

Four other notable geological investigators identified important clinoptilolite occurrences during this early period. Glen Teague prospected the Owyhee region intensely, later gaining land control over many of the important clinoptilolite deposits and eventually setting up an operation for mining and processing clinoptilolite. Hay (1963) identified clinoptilolite/heulandite in the John Day Formation in central Oregon during studies with the University of California at Berkeley, which led to government investigation of the John Day Formation as a possible source of clinoptilolite for nuclear waste treatment, specifically the removal of cesium and strontium isotopes from radioactive fluids. Regis and Sand (1966) jointly studied zeolite deposits in the Pacific Northwest and subsequently staked several mining claims covering some Sheaville district clinoptilolites for the Norton Company in 1964. Norton Chemical produces several thousand tons of clinoptilolite annually from pits in the Sheaville district, Oregon, for internal supply to its molecular sieve manufacturing facilities.

A second wave of major business interest in zeolites led to intense corporate exploration and market development during 1974-1983. Anaconda Minerals Corporation and Occidental Minerals Corporation launched extensive programs to acquire and develop zeolite deposit positions to yield products reaching the full spectrum of zeolite commodity uses. Rocky Mountain Energy Company, a subsidiary of Union Pacific Railroad, mounted a major effort to develop major clinoptilolite sources on its lands overlying the Washakie Basin, Wyoming, and Mountain Green, Utah, clinoptilolite deposits. Numerous smaller companies also gained control of scattered deposits during this period, and a few reached production and survive today.

During the mineral industry depression of the early 1980's, all three listed companies were closed down by their parent corporations and dropped their zeolite programs. Anaconda Minerals sold its zeolite holdings to East-West Minerals, Ltd., an Australian



Figure 2. Chabazite occurrences in the Pacific Northwest.



Figure 5. Mordenite occurrences in the Pacific Northwest.

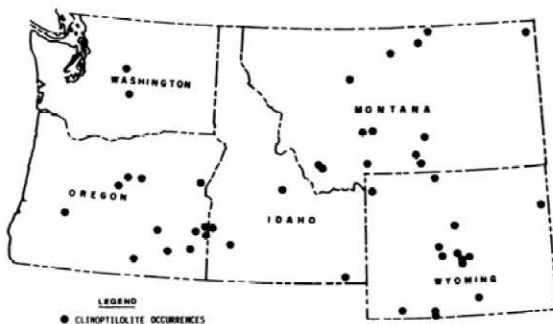


Figure 3. Clinoptilolite occurrences in the Pacific Northwest.



Figure 6. Phillipsite occurrences in the Pacific Northwest.



Figure 4. Erionite occurrences in the Pacific Northwest.



Figure 7. Economic activity in Pacific Northwest zeolites.

mining company. East-West built a crushing/screening plant near the Eastgate mordenite-clinoptilolite deposit east of Fallon, Nevada, and limited its sales to products from this plant and a small crushing/screening facility near the Ash Meadows, Nevada, clinoptilolite deposit. Occidental Minerals Corporation sold its zeolite package to Western Nuclear, Inc., a subsidiary of the Phelps Dodge Corporation in 1982. Under the name of PDZ Corporation, they concentrated on sales into selected consumer products markets (mostly as deodorants) supplied from their Mud Hills clinoptilolite deposit in southern California. In 1985, Phelps Dodge sold the zeolite business unit to Tenneco Minerals, who subsequently sold it to Steelhead Resources, Inc., a small Spokane-based industrial mineral producer. Steelhead continued the consumer products production and sales from the Mud Hills site and may initiate clinoptilolite production from eastern Oregon deposits to reach additional domestic and foreign industrial and agricultural markets.

Teague Mineral Products began processing and sales of bentonite products from its plant in Adrian, Oregon, in the early 1970's.

As bentonite production gradually rose, Teague added clinoptilolite products and is presently selling them into both regional and export industrial and agricultural markets. Teague has achieved market penetration that the departed large corporate works were on the verge of capturing.

Double Eagle Mining and Petroleum Company staked early claims over the Castle Creek clinoptilolite occurrence south of Bruneau, Owyhee County, Idaho. Teague Mineral Products later staked other nearby zeolite occurrences in the Castle Creek basin, entering a joint venture for its development with IMC Minerals. IMC emerged with control of the known reserves, and Teague again staked more claims on this high-quality clinoptilolite horizon, naming the new resources the "XY" zeolite deposit. AIMCOR later bought out the IMC interest and currently controls the former IMC mining claims and a lease on the Double Eagle property, mining bentonite from these lands as raw material for its processing plant in Caldwell, Idaho.

The Rocky Mountain Energy effort in Washakie Basin, Wy-

oming, to develop large reserves of clinoptilolite in the "Robin's Egg Blue" bed began in the late 1970's. The company later entered a joint venture with IMC Corporation to pursue principally agricultural applications and markets. The venture terminated when Rocky Mountain Energy discontinued its mineral program to concentrate on oil and gas exploration, and IMC sold off minerals operations to Colorado investors with little interest in pursuing zeolite market development. Several small interests, including U.S. Zeolites, Inc., of Golden, Colorado, and Thomas Sharps, former industrial minerals geologist with Rocky Mountain Energy, are working to prove minable reserves and to sell clinoptilolite for limited commodity uses, initially the cat litter additive market.

U.S. Energy Corporation, a small Wyoming minerals and oil and gas company, fielded a zeolite venture to develop markets for clinoptilolite from claims originally staked to develop uranium reserves for agricultural and aquacultural applications as well as any other market it could sell into.

Various other prospecting efforts have attempted to develop clinoptilolite properties in the last 20 years. Typical ventures included development projects on the Bear Creek clinoptilolites near Preston, Idaho; in the Challis Volcanics near Deep Creek, Idaho; on altered rhyolitic tuffs near Prineville, Oregon; and on soft, erratically zeolitized Pliocene tuffs near Marsing, Idaho. These efforts failed due to inability (1) to develop saleable clinoptilolite products; and/or (2) to penetrate existing, competitive domestic clinoptilolite markets.

REGIONAL ECONOMIC ZEOLITE OCCURRENCES

As economic natural zeolite deposits of the Pacific Northwest occur primarily as altered Tertiary tuffaceous and pyroclastic rocks, they are limited to those areas within the five states where silicic tuffaceous sediments occur in thick Tertiary volcanic sequences. Such widespread Tertiary rocks occur extensively east of the Cascade Range, most notably in eastern Oregon, southwestern Idaho, and central Wyoming. Figure 7 shows the locations of regional natural zeolite deposits that are currently producing or under development and the principal zeolite mineral species occurring in each.

Idaho

Economic zeolites in southwestern Idaho occur in the Sucker Creek Formation extending eastward into Owyhee County from large clinoptilolite occurrences in Malheur County, Oregon, and in the Snake River Plain Pliocene volcanic sedimentary sequence between the Snake River and the mountains to the south. Thick beds of zeolitized Eocene Salt Lake Formation tuffs in southeastern Idaho also present significant economic potential for clinoptilolite. Clinoptilolite occurs in tuffs and tuffaceous sandstone in the Germer Tuffaceous Member of the Challis Volcanics of Eocene or Oligocene age but have supported limited commercial interest.

Bear River clinoptilolite: Thick beds of green zeolitized tuff in the Eocene Salt Lake Formation are widespread in Franklin County, southeastern Idaho. Selected localities have large resources

of clinoptilolite equivalent in age and physical character to the huge Mountain Green clinoptilolite deposit located east of Provo, Utah. The Bear River zeolites are lower quality than major Owyhee Region sources but may have potential for local agricultural markets.

Castle Creek district: A soft, fine-grained ash-fall tuff unit within the Pliocene Chalk Hills Formation is altered to fine white clinoptilolite in the Castle Creek drainage in Owyhee County. Double Eagle Mining and Petroleum Corporation located mining claims on the Castle Creek clinoptilolite deposit several miles south of Bruneau. Its subsequent drilling and trenching program developed resources of very high-quality clinoptilolite, partly covered by a thick layer of Pleistocene sand and gravels. Continued bulk sampling and testing have established that the material is of high quality, particularly for low abrasion and high brightness uses such as paper filler, but the property is not yet operating.

Subsequent exploration by Teague Mineral Products developed additional resources of high-quality clinoptilolite in extensions of the Castle Creek Bed to the east and southeast, incorporating IMC as a partner in the exploration and development of this ground. IMC sold its participating business unit to AIMCOR, who gained control of the drilled reserves of clinoptilolite and associated white bentonite on the property. Teague Mineral Products later extended its prospecting program, finding more and higher quality clinoptilolite beds to the southeast and staked this ground as the "Z-Chem" or "XY" property, covering probably the highest quality clinoptilolite of the district.

The Castle Creek district has large resources of promising high-quality clinoptilolite in a favorable mining setting. Figure 8 is a photographic view across the Z-Chem deposit (lighter colored beds in mid-photo) toward a distant limestone-capped ridge. Figure 9 is an SEM image of typical XY clinoptilolite.

Chrisman Hill deposit: A thick massive to thin-bedded white zeolitized tuff bed occurs within the Sucker Creek Formation about 19 mi north of Jordan Valley, Oregon. The deposit consists of high-quality, white to light-gray clinoptilolite very similar in appearance and quality to the Sheaville deposit 7 mi to the south. Thickness of the zeolitized zone is 60 ft, with millions of tons of reserves potential. The deposit partially straddles the Idaho-Oregon border and is permitted and mined by Teague Mineral Products on the Idaho side for supply to its processing plant in Adrian, Oregon. The Chrisman Hill clinoptilolite lies on a weak hydrothermal alteration trend, and the zeolitized zone shows evidence of alteration as well as obliteration of sedimentary structures.

Upper Succor Creek clinoptilolite: Attractive, thick, high-quality clinoptilolite beds occur within the Sucker Creek Formation, extending into Idaho in the upper Succor Creek drainage from adjacent Malheur County, Oregon. The Sheaville deposit along Succor Creek has been partially drilled and developed and represents known reserves of commercial-grade clinoptilolite available for production. This deposit is described in greater detail under "Oregon" below. Additional massive white clinoptilolite occurrences upstream from the Sheaville site have not been thoroughly explored.



Figure 8. View looking easterly across XY clinoptilolite deposit, Owyhee County, Idaho. Light-colored beds across middle of photograph are XY/Z-Chem clinoptilolite unit.



Figure 9. SEM image of XY clinoptilolite, Idaho.

Montana

Some scattered occurrences of clinoptilolite-heulandite, analcime, mordenite, laumontite, and stilbite are reported by Sheppard (1976), Berg (1969), and others in Cretaceous to Eocene bentonite, lignite, and tuffaceous sandstone and siltstone in the sedimentary rocks of the eastern plains of Montana, but none have significant economic potential.

Weakly zeolitized volcanoclastic rocks of Cretaceous age in Park and Gallatin Counties contain a suite of natural zeolites (clinoptilolite, mordenite, laumontite, and stilbite) generally representative of a low-grade metamorphic setting. They also offer no apparent commercial potential.

Several clinoptilolite occurrences are known in weakly zeolitized Tertiary tuffaceous sediments in the intermontane basins of Beaverhead, Park, and Chouteau Counties and offer economic potential for local agricultural and waste water clean-up projects within the state. Anaconda Minerals considered development of local clinoptilolite sources for clean-up of mine waters in the Butte-Anaconda area in the late 1970's.

Oregon

Current zeolite development and production are limited to Tertiary silicic tuffs in eastern Oregon.

Divide clinoptilolite: White to light-gray zeolitized tuffs are exposed along a drainage divide over a strike length of 1.1 mi at a site northwest of Jordan Valley, Malheur County. This unit averages 28 ft in thickness and occurs within a sequence of Miocene tuffaceous siltstone and bentonite of the Sucker Creek Formation. Clinoptilolite is the predominant zeolite mineral, with traces of erionite and interbeds of siltstone and bentonite. The total zeolite content ranges from 40 to 65 percent and the CEC less than 1.2 meq ammonia.

Durkee chabazite: The Durkee zeolite deposits are located in a small Tertiary basin of late Miocene age near Durkee in Baker County. The basin underlies 120 km², of which 18 km² contains diagenetically formed zeolites and authigenic feldspar. Economic zeolite minerals include chabazite, erionite, and clinoptilolite, with minor analcime, mordenite, and phillipsite. The authigenic zeolites were derived from siliceous tuffs deposited in a late Miocene saline/alkaline lake near the site of Durkee and formed diagenetically at low pressure and temperature. The zeolitized air-fall and reworked tuffs and one ash-flow tuff are interbedded with diatomite, mudstone, sandstone, siltstone, and conglomerate. Detailed studies have been carried out on this deposit by the U.S. Geological Survey (Sheppard and Gude, 1969, 1980; Gude and Sheppard, 1978, 1986).

Exploration by Anaconda Minerals, Occidental Minerals Corporation, and the Filtrol Corporation defined promising target areas for possible large-tonnage chabazite zones, but their exploration results remain unknown.

Harney Basin zeolites: Zeolitized tuffaceous zones in the shallow Pliocene beds of the Harney-Malheur Basin comprise huge resources of clinoptilolite, with lesser occurrence of erionite, chabazite, phillipsite, and mordenite on the basin margins. The principal mineralized area underlies roughly 8 mi² about 25 mi south of Burns, Harney County.

Zeolitized coarse to fine-grained ash-fall tuffs and reworked zeolitized tuffaceous sediments of lacustrine and fluvial origin occur within the partially eroded Tertiary basin fill. These were mapped as unit Tst, or early to middle Pliocene sedimentary rocks, by Green and others (1972). Two members have been identified within this sedimentary sequence in the center basin facies. The upper member is composed chiefly of a poorly stratified and poorly sorted mixture of pumice, scoria, other lithic fragments, plagioclase, and glass shards in a clay matrix. Several thin basalt flows and dikes crop out within this member. The lower member consists mostly of relatively clean coarse to fine, altered ash-fall tuff beds

of interfingering lacustrine and fluvial origin. It is the most favorable host rock for zeolitization.

Figure 10 is an idealized stratigraphic section for the center of the Pliocene basin showing the two members, a thick zeolitized tuff sequence including the massive clinoptilolite bed 60 ft or more thick, underlain by a thin-bedded zeolitic tuff bed, and finally a basal lapilli zeolitic tuff bed that is present over much of the basin as a marker unit. Laterally toward the margins of the basin, the clinoptilolite grades into thinner beds of erionite, chabazite, and phillipsite. Figure 11 is an SEM image of mixed chabazite (60 percent) and clinoptilolite (40 percent) in a sample collected near the interface of the center clinoptilolite zone and the marginal zeolites. The zeolite deposits of the Harney Basin formed as a result of diagenetic alteration of ash-fall tuffs and reworked tuffaceous fluvial sediments within a closed hydrologic basin.

Potential clinoptilolite resources of the Harney Basin deposit are huge, although the overall quality is lower than the major deposits of the Owyhee region, and trace amounts of erionite are commonly present. The lapilli tuff unit is locally altered to mordenite. Erionite resources appear large but scattered within thinner beds in lacustrine and fluvial sediments on the margins of the basin. The chabazite resource potential is largely unknown, due to limited drilling information. Phillipsite resources are poorly defined and scattered through marginal areas.

John Day zeolites: Thick beds of zeolitized tuffs occur within the Eocene John Day Formation in central Oregon. Clinoptilolite is the dominant zeolite mineral within this open-system setting, but overall quality of the zeolite is lower than the major deposits of the Owyhee Region to the southeast. Early studies of this clinoptilolite as a possible source for nuclear waste treatment at Hanford, Washington, and other sites have spurred continuing interest in this district.

Rome zeolites: The Rome zeolite district offers large potential resources of high-quality erionite, mordenite, and mixed mordenite-clinoptilolite. It is located about 37 mi westerly of Jordan Valley, Malheur County, in the vicinity of the Owyhee River and Crooked Creek in a region of fairly gentle Tertiary volcanic desert uplands dissected by steep-walled canyons.

The zeolites occur within several zeolitized tuffaceous members of the "Rome Beds," a Pliocene fluvio-lacustrine sequence (see the idealized stratigraphic section in Figure 12). The formation dips several degrees northeasterly in the Rome Cliffs area and

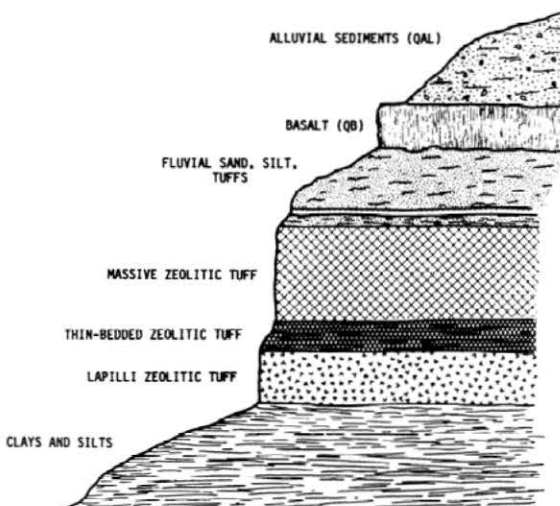


Figure 10. Harney Basin zeolite beds, Oregon (after Anaconda Minerals).



Figure 11. SEM image of Harney Basin mixed chabazite/clinoptilolite with minor montmorillonite, Oregon.

is about 400 ft thick. Two zeolitized tuffaceous beds comprising the upper member in the poorly sorted fluvial upper Rome Beds offer significant commercial promise. Each bed is about 10 ft thick and contains 50 to 70 percent erionite. The two beds are slightly harder than the surrounding unconsolidated sediments, form resistant ridge-tops and mesas, and are informally called the "Billboard Erionite" in the steep-walled "Rome Cliffs" badlands area several miles north of the village of Rome. Figure 13 is an SEM image of the typical Billboard Erionite.

The lower "Crooked Creek" zeolitic member ranges from 14 to 23 ft thick and consists of two light-gray fine-grained ash-fall tuffs, separated by a prominent thin orange or yellow sandy tuff bed known as the "Orange Layer." It crops out within the Crooked Creek drainage area in the southwest portion of the Pliocene basin. Both lower and upper gray units are predominantly mordenite, with some mixed mordenite-clinoptilolite, especially in the lower bed. Figure 14 is a view of the Crooked Creek Member. Figure 15 is an SEM image of clinoptilolite from the Crooked Creek Member.

Thick sandy and silty erionite beds also occur in small dimension stone quarries near the U.S. highway 95 crossing of Crooked Creek. These beds are locally over 60 ft thick and contain 40 to 70 percent erionite. Blocks of the soft but weather-resistant erionite were sawed in these quarries (see Figure 16) for use in local house and building construction.

The Rome district has large resources of erionite, mordenite, and mordenite-clinoptilolite.

Sheaville district: The Sheaville zeolite district encompasses at least 4 square mi where the westward-flowing Succor Creek crosses and dissects the Oregon-Idaho state border and the axis of a north-south-trending anticline, respectively. The area lies 12 mi north of Jordan Valley, Malheur County, and lies between U.S. Highway 95 and the state border.

The Sheaville clinoptilolite sequence occurs in the Miocene Succor Creek Formation, a continental lacustrine formation with interbedded tuffs, zeolitized tuffs, bentonite, and carbonaceous siltstones. Basalt dikes and flows intrude and are intercalated within this formation, respectively.

At least five thick massive beds of white to light-gray, highly zeolitized tuff crop out in this area. Figure 17 is an east-west cross section (looking south) showing the relative position of the principal beds. Figure 18 is a view across the zeolite exposures on the north side of Succor Creek.

Clinoptilolite is the predominant zeolite mineral, with trace mordenite reported in XRD analyses and in SEM images. The zeolitized tuff beds are interbedded with bentonites and carbonaceous siltstones. Zeolitization is most intense near the axis of the north-south anticline. Several large breccia pipes are present in the zeolitized area and are composed of volcanic and older rocks from greater depths. The more intensely altered zeolitic rocks appear to have a hydrothermal alteration overprint on the open-system clinoptilolite occurrence. The altered rock is massive, and sedimentary structures are largely obliterated. The quality of the clinoptilolite may be

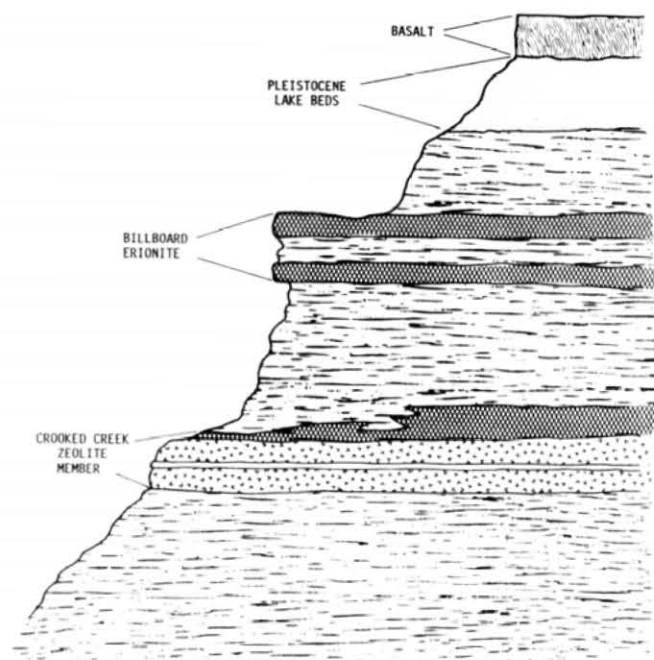


Figure 12. Rome zeolite beds, Oregon.



Figure 13. SEM image of erionite from "Billboard Cliffs" area, Rome district, Oregon. Letter "E" indicates typical acicular erionite crystal.



Figure 14. View of Crooked Creek Member, Rome Beds, Rome district, Oregon.

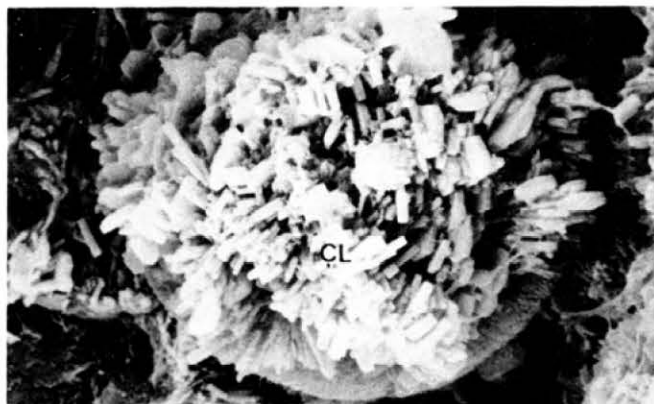


Figure 15. SEM image of clinoptilolite from Crooked Creek Member, Rome Beds, Rome district, Oregon. Letters "CL" indicate clinoptilolite.

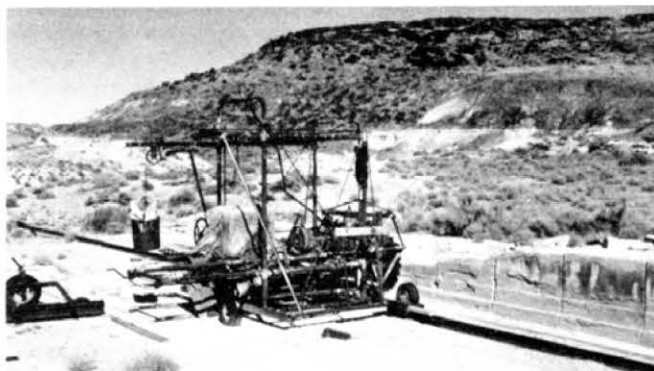


Figure 16. View of rock-cutting saw in erionite rock quarry, Rome district, Oregon.

consistent over tens of feet vertically as well as considerable distances laterally.

Past geologic study as well as production activity by Norton Chemicals, Inc., has been confined to the "Sheaville Bed" on the western flank of the anticline. This bed is well exposed less than a quarter of a mile east of U.S. Highway 95, close to the western edge of the zeolitized area.

The "Shea Bed" is the thickest zeolite unit in the district and the lowest zeolite bed on the south side of Succor Creek. It ranges in thickness from 16 to 66 ft and is composed of highly zeolitized white to light-gray massive clinoptilolite. Occidental Minerals Corporation drilled out the reserves of this unit during 1977-1981 and opened a large test pit near the anticline axis in 1982. Figure 19 is an SEM image of high-quality clinoptilolite from the present Steelhead pit area.

The Sheaville district has large reserves of high-quality clinoptilolite in a favorable mining setting. Steelhead Resources Company currently holds the dominant land position in the district and plans to reopen the pit to initiate regional clinoptilolite production.

Succor Creek deposits: Scattered bodies of white to light-gray, massive and sandy zeolitized tuffs occur within the Miocene Sucker Creek Formation along the lower stretches of Succor Creek, both within and downstream from Succor Creek State Park. Clinoptilolite is the predominant zeolite mineral, with content ranging from 30 to 70 percent. These occurrences show no evidence of hydrothermal alteration and are generally of lower quality than the Sheaville and Chrisman Hill deposits of comparable age. Zeolite thickness ranges up to 80 ft. Teague Mineral Products operates one open-pit mine in the Succor Creek area to extract lower quality material for agricultural and similar uses.

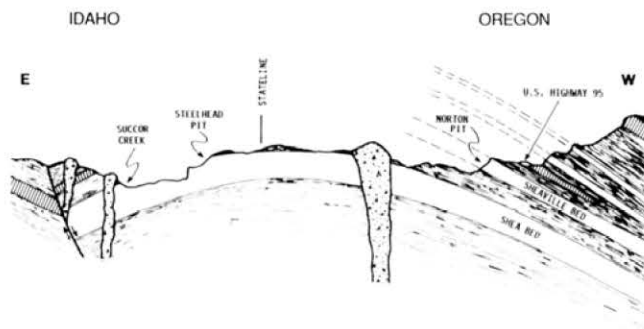


Figure 17. Simplified east-west cross-section across Sheaville zeolite district, Idaho-Oregon (looking south).



Figure 18. View looking northeasterly across Sheaville zeolite district from Oregon into Idaho. Note Succor Creek, in foreground, flowing to the west (left).

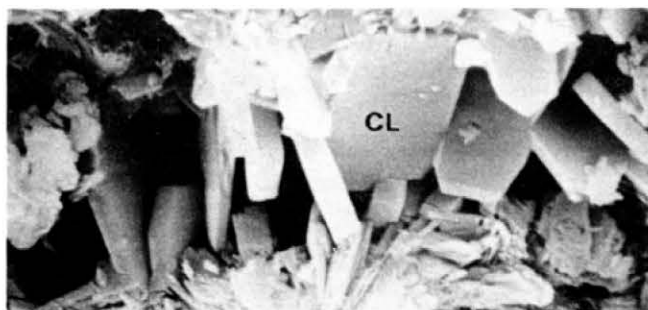


Figure 19. SEM image of clinoptilolite from Shea Bed, Sheaville district, Oregon. Letters "CL" indicate large, tabular clinoptilolite crystal.

Washington

Natural zeolites are reported by Sheppard (1976) at ten localities in the state of Washington. Five occurrences are within marine sedimentary rocks in western Washington and range in age from Eocene to Miocene. These zeolites occur principally in tuffaceous siltstones and as fine-grained matrix in marine sandstones. None have any apparent economic potential. Three occurrences in thick Oligocene volcanoclastic and ash-flow sections in the southern Cascade Range contain heulandite, laumontite, wairakite, and analcime; however, none of these offer worthwhile economic potential. Clinoptilolite-laumontite reported in the Paleocene Swauk Formation in Chelan County as a product of low-grade metamorphism of volcanic rocks has no commercial potential. Clinoptilolite reported within the Miocene Ellensburg Formation on the east flanks of the Cascade Range offers notable exploration promise.

No significant zeolite production is reported from Washington state, but Tertiary tuffaceous sediments in central Washington may host low-quality clinoptilolite deposits suitable for pozzolans, soil conditioning, and comparable uses.

Wyoming

Occurrences of clinoptilolite, heulandite, and analcime are reported in the Cretaceous- and Triassic-age sedimentary rocks of Wyoming, but none exhibit quality and grade adequate to support economic potential.

Promising natural zeolite occurrences are reported in Tertiary tuffaceous rocks in the state by Surdam (1972), Boles and Surdam (1971), Van Houten (1964), and others.

Persistent exploration effort by commercial interests has defined major economic deposits of clinoptilolite in two Tertiary basins. Large resources of clinoptilolite have been identified in fine-grained zeolitized ash-fall tuffs of the Lancy Shale Member of the Green River Formation in the broad Washakie Synclinal Basin in Sweetwater County. Several beds of zeolitized ash-fall tuff within the Wagon Bed Formation of Eocene age in Fremont County have been drilled, defining significant bodies of high-quality clinoptilolite with lesser chabazite, erionite, phillipsite, and analcime. Other promising Tertiary zeolitized tuff occurrences include the Independence Rock clinoptilolite, the Moonstone Peak clinoptilolite-erionite-phillipsite, and the Split Rock clinoptilolite occurrences in Natrona County (Surdam, 1972); the Saratoga clinoptilolite-phillipsite in Carbon County (Surdam, 1972); Riverton clinoptilolite in Fremont County (Surdam, 1972); and Lysite Mountain clinoptilolite-analcime-erionite-mordenite in Hot Springs County (Surdam, 1972).

Washakie Basin: The Washakie Basin clinoptilolite was discovered and originally described by Roehler (1972, 1973), who identified the mineral in the Robins Egg Blue (REB) tuff bed of the Lancy Shale Member of the Green River Formation and in tuffs within the Adobe Town Member of the Washakie Formation, both of Eocene age. The REB bed consists of light-blue to greenish-blue zeolitized tuff altered to 50-70 percent clinoptilolite. This bed averages between 7 and 10 ft in thickness, reaches a maximum thickness of 15 ft, and varies in sand content throughout the broad Washakie synclinal basin. The sand content is generally inversely proportional to the overall clinoptilolite quality. Extensive drilling and testing have established that the REB bed is locally very high-quality clinoptilolite, suitable for a wide range of both low-quality and high-tech applications, including nuclear waste cleanup.

Figure 20 is an SEM image showing highly etched clinoptilolite crystals typical of REB occurrence on the southwest rim of the Washakie Basin. Figure 21 is an SEM image of nonetched euhedral clinoptilolite crystals from the Fort Clede prospect on the northern flanks of the basin.

Rocky Mountain Energy Corporation, the mining and minerals subsidiary of the Union Pacific Corporation, attempted to develop occurrences of REB clinoptilolite on its checkerboard lands on the north rim of the Washakie Basin during 1978-1983. Exploration work included mostly bulk and channel sampling, as the REB bed is slightly dipping, is well exposed, and has a low stripping ratio near its outcrop. The company also staked mining claims



Figure 20. SEM image of "Robin's Egg Blue" clinoptilolite, northern Washakie Basin, Wyoming. Note that clinoptilolite crystals are highly etched.

in two intervening federal sections, expanding its potential clinoptilolite reserves to several million tons. IMC joined Rocky Mountain Energy in joint venture development of the REB deposit about 1980, assisting primarily with agricultural testing of the clinoptilolite products. Consumer product testing followed, and the joint venture produced limited tonnages of blue-green clinoptilolite for cat litter and other deodorant use. IMC subsequently dropped out of the joint venture, and Rocky Mountain Energy discontinued its development and market research efforts when the subsidiary wound down operations and closed most of its active mining efforts.

U.S. Zeolites, operated principally by Tom Van Fleet, former vice president of Rocky Mountain Energy Corporation, gained control of the Rocky Mountain Energy fee lands and claims through leasing from Rocky Mountain Energy as well as additional state mining leases on several additional sections covering other promising local REB occurrences along the rim. U.S. Zeolites is now conducting testing and marketing studies and has produced small tonnages of clinoptilolite for cat litter additive and industrial uses.

Another state lease is held on REB tuffs by Tom Sharps, former industrial minerals geologist with Rocky Mountain Energy Corporation.

Beaver Rim zeolites: Beds of chabazite, mixed chabazite-clinoptilolite, and clinoptilolite-erionite occur within Tertiary volcanic rocks in the Beaver Rim district, Fremont County. U.S. Energy Corporation produced and sold small but significant tonnages of clinoptilolite during the 1980's into western aquacultural markets. Individual zeolite beds are fairly thin, and much of the zeolite resource may require underground mining. Apparently no effort has been made to develop chabazite and erionite resources in this district.

MARKETING PACIFIC NORTHWEST ZEOLITES

Natural zeolites produced in the Pacific Northwest will sell by three principal marketing approaches:

1. As low-spec ground clinoptilolite into regional markets for agricultural and low-quality industrial uses.
2. As better quality ground and fine-ground clinoptilolite products into North American and Pacific Rim markets for higher specification industrial fillers, waste stream filters, etc.
3. As high-quality specialty zeolite products into the domestic and export value-added markets, e.g., for paper filler and nuclear waste treatment media, principally as highly-processed clinoptilolite, chabazite, and mordenite products.

Current production and sales of natural zeolites in the Pacific Northwest are limited at this time to clinoptilolite for low-value agricultural, pet deodorant products, and very limited aquacultural applications. A small but growing tonnage of export sales of clinoptilolite is reaching consumer and specialty industrial markets in Europe and the Far East. North American demand for other natural zeolite minerals, principally chabazite, mordenite, erionite,



Figure 21. SEM image of "Robin's Egg Blue" clinoptilolite. Letters "CL" indicate large, euhedral, unetched clinoptilolite crystal.

and phillipsite, is too limited to justify their development in the Pacific Northwest at present.

Very large reserves of high-quality clinoptilolite in the Owyhee region of Idaho and Oregon will dominate regional and high-quality North American and export sales of clinoptilolite in Pacific Northwest production. Large resources of chabazite occurring in the Durkee and Harney Basin districts of Oregon are not well defined in tonnage or quality and should be investigated as alternative sources to production from the Bowie chabazite deposit, Arizona, and very large chabazite occurrences near Naples, Italy. Large reserves of very fine-grained mordenite and of mixed mordenite-clinoptilolite in the upper Rome Beds in the Rome district, Oregon, may prove a major future mordenite source for domestic and export sales. Huge tonnages of erionite are available in the Rome and Harney districts, Oregon, but considering its fibrous nature and questionable carcinogenic status, it is unlikely to reach significant production. Mined phillipsite resources appear limited to marginal areas in the Harney Basin district, but their quality and quantity have not been clearly established.

Teague Mineral Products is currently working to develop newspaper filler products and nuclear waste cleanup materials to supply both national and export markets. If these efforts are successful, Oregon-Idaho clinoptilolite sources, in particular, will prove a major source.

Continued research and new product development may develop commercial applications for the other natural zeolite minerals, some of which may be present in small occurrences throughout the region. Certainly, the trend of rapid new materials uses, particularly for specialized fillers, will ultimately increase the number of economic natural zeolite minerals from the current five discussed in this paper.

New product testing and market development efforts by Anaconda Minerals and Occidental Minerals during 1974-1982 defined many potential product uses and agricultural and industrial markets for the natural zeolites of the Pacific Northwest. Particular emphasis by both corporations on agricultural markets established that the materials could be used in many soil conditioning, animal feeding, and agricultural product filler applications. Demise of these corporate efforts in 1983 ended these market research programs, which are being followed on a more limited scale by several smaller entrepreneurial producers.

Teague Mineral Products conducted a wide range of product testing, principally agricultural, with its very limited resources and has established itself as the principal clinoptilolite producer with reliable processing facilities. Teague is currently selling crushed and ground clinoptilolites as soil conditioning additive, animal feed supplement, filler carrier for herbicides and pesticides, and other uses. Steelhead Resources is also conducting marketing and product development studies from its facilities in Spokane and is moving to produce clinoptilolite products from its properties in the Sheaville and Harney Basin districts. Steelhead's current production of clinoptilolite is principally from sources in southern California.

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Problems in mineral products testing

by Edwin H. Bentzen III, Ore Sorters (North America), Inc., 777 S. Wadsworth Blvd., Building 4, Suite 210, Lakewood, Colorado 80226

INTRODUCTION

The basic problems in mineral products testing can be divided into two groups: (1) not knowing what you are doing, and (2) not doing what is wanted. Part 1 is easy to understand, but part 2 is more difficult to explain. Take, for example, the following statement:

"I know you believe you understand what you think I said, but I am not sure you realize that what you heard is not what I meant"—otherwise known as "That's what I said, but that's not what I meant!"

Also, as there are differences in testing equipment, there are differences in standards, water, personnel, techniques, procedures, and specifications employed. The results of any set of tests on the same material can vary from laboratory to laboratory. However, the variations should be within standard deviation for the number of times the tests are conducted. You will also discover that who conducts the test may be just as important as how the tests are conducted.

This paper describes several actual instances in which (1) the answers generated were correct—but the data were not what was wanted, (2) the data were incorrect—but nobody realized there was a problem, and (3) specified procedures for one industry were applied to material that was used in another type of industry. Examples of problems in sampling, sizing, brightness, chemical analysis, abrasion, and calculations are described.

This paper should serve as a guide on what to look out for when evaluating the results from any laboratory.

PROBLEMS IN MINERAL PRODUCTS TESTING

At one time or another, most of you will experience problems with the results of tests, studies, or evaluations of mineral products. Naturally, the source of the problems will always be someone else's fault. Or will it be? Generally, the sources of problems can be classified as (1) communication, (2) standards or the lack thereof, and/or (3) sample preparation before a standard test procedure.

COMMUNICATION

What do I mean by communication? For example, "I know you believe you understand what you think I said, but I am not sure you realize that what you heard is not what I meant." Or, "That is what I said, but that is not what I meant!" And, even worse, "Oh, no! You did it exactly the way I told you!"

In this context, communication consists of describing in detail exactly how you want a test conducted or exactly how the results will be used to market a mineral product. For example, when you instruct a laboratory to conduct a "standard brightness determination," you have told them nothing except where to send the invoice. You are responsible for either providing a copy of the procedure required by the consumer or insisting that the laboratory conduct research into the methods generally employed and informing you if they can do the same test at their facility.

It follows that before you can communicate the procedures you want, you need to know what these procedures are. When you ask for a test or for the determination of a physical or chemical characteristic, you as the asker must know exactly what you as the evaluator want. You had better be familiar with these procedures before you ask someone else to do the testing.

For your own industrial mineral products or potential products, you should know what markets you will be targeting and what the raw material specifications are for those markets. Familiarize yourself with the test procedures specific to the producing industry

and the consuming industry. You have to know if there are special tests that are unique to a specific market. A standard test or a test procedure for the same mineral sold to one consumer may not always provide the information required to sell to a different customer.

Do you even want a standard test, or perhaps a unique test? Generally, you will get what the laboratory refers to as a "standard test," even though it may be unique to a market or mineral. You may use these results to evaluate the minerals for sales to potential markets, and you may even get lucky.

After spending the time necessary to research the right procedure, the results will come back from the laboratory, and you can confidently evaluate a deposit or product based on the properly selected standard test procedure.

But what happens when you guessed wrong—or picked the wrong standard test procedure? What happens is that the deposit or product will be rejected because the results were not within the range of the required specification? Or worse, you could have the plant built to make the product, and when your customer uses the product, it does not react as expected. End of contract, end of plant, end of business!

STANDARDS

How can you know when you have selected the right test, the correct test procedure, or even the best laboratory to conduct the test?

To keep from getting burned, you must do your homework. Before you send samples out for testing, you as the client, should know all the standard test procedures and all the market specifications for the material tested.

Do your research to determine (1) what the material is, (2) what industries it may be suitable for, and (3) who are recognized authorities on beneficiation or altering raw material to meet the quality requirements for those industries.

How does one get this type of information? Research available literature. Visit libraries, read books on the raw materials from other deposits, and find out in which end products the material is currently being used. Then determine which physical and chemical characteristics are desirable and which are undesirable in the minerals.

Check with other mineral-producer testing laboratories. Visit other producers' operations, and talk with the laboratory personnel. Ask questions not only on how to conduct a test but why the test should be conducted in a certain way.

Obtain copies of product specification sheets. Virtually all companies that will be serious competitors for your material will have product specification sheets on their material that will not only provide a value with which to compare but will often provide details of the method used to obtain the value.

From this type of research, you get information about standards—producing company standards, consuming company standards, standards in methods, standards in equipment, and standards in reporting.

Organizations such as TAPPI, ASTM, APPI, AWWA, AFS, and others publish standard test procedures and acceptable deviations in the values obtained from test to test. They tell you how well the test should be reproducible, but they do not tell you whether the results make the raw material suitable for your potential customer. Generally, these national societies have been established to provide members with reproducible test procedures—one in which the same test conducted by any number of people on the same

sample will generate the same result. In terms of raw materials, they generally do not specify pass/fail guides for the material undergoing testing, because they cannot cover all the possible uses for any single mineral by all the various consumers.

If all mineral deposits were the same, there would be no need for so many different product specification sheets. In reality, each mineral deposit is unique. It is unique in terms of mineralogy, particle-size distribution, age, geological source, chemistry, and method of treatment. By collecting as many product specification sheets as possible, you will be able to determine the range in values acceptable to the marketplace for each mineral commodity. You may also be able to determine the range of materials that can be produced from one deposit. You can compare the same mineral commodity from different parts of the country and the world. All this information is useful in determining how your mineral product should be tested and how the results can be compared with existing materials.

By collecting as many product specification sheets as possible from the many different producers, you should be able to compile a comprehensive list of the tests conducted and the methods used to determine the values. However, do not place exacting levels on the results quoted. The product specification sheets generally provide "typical specifications." This means that the values, while quoted to the third decimal, may or may not be exactly the values of what is shipped from the producer in each bag or boxcar. Therefore, if your material does not meet exactly all the specifications, do not be discouraged. Chances are that material from your competitors does not either.

Where did the existing producers get their standard test procedures? Often they got them because they were the first to conduct a test in a particular way. Or they may have been the first to use a particular piece of equipment to test their raw material. Or they may be just following the methods used by others to test similar minerals.

Where did the existing consumers get their standard test procedures? They got them from the same places—either from producers, from other consumers, or from in-house, by determining specific qualities necessary to meet a specific usage for the mineral.

Well, if other producers can make up their own standard procedures and the consumers can make up their own standard procedures, why can't you? Actually, you can—but only if you know (1) what the consumers require in performance of the mineral product, and (2) how to relate the results you obtain with the way the mineral will react in the consumer's process. But if you do not know that much about the consumer and the consumer's process and products, do not attempt to make up a new "standard test procedure."

Are you confused? Do you really understand what you should expect to get by using standard test procedures? From a test laboratory, be it either an independent laboratory, a mineral producer's laboratory, or mineral consumer's laboratory, you should expect to get the following:

1. On different samples from the same deposit tested at the same laboratory, it is likely you will get slightly different results—because the samples are different.

2. On the same sample tested at different labs, you may get different results, because the sample testing people and procedures are different, even when using so-called standard procedures.

3. On different samples at different laboratories, you will get different results. No explanation necessary.

4. On the same sample tested at the same laboratory, you had better get the same results. Moral to the story: "Always submit blind duplicates to determine if the laboratory knows what it is doing."

Why may the results differ? Since there is no one set of standards for all minerals or mineral products, the laboratory will use either the test procedure with which it is most familiar or, more likely,

the procedure most suitable for the equipment it has. Standards are standards—are standards—but not necessarily the same standards.

Once you have decided upon the test methods and all the samples are collected, what is the next step? You test the samples or get another laboratory to conduct the tests for you on the samples you have collected.

SAMPLE PREPARATION

What will you find lacking in all, or almost all, mineral sample testing procedures? They lack specifics on how the mineral samples should be prepared before testing.

A classic example is size reduction. To what maximum particle size should you reduce a sample before conducting physical tests? What is the ideal particle size distribution that should be tested? How should the size reduction of the material be conducted, and in what type of equipment?

Why are there no specifications? As outlined above, most standard test procedures were, and are still, based on tests conducted on finished products from existing plants or on products used as-received from the producers. The sample preparation has already been taken care of by the producers.

But if you are a potential producer without a plant or an exploration geologist looking for a market for your newest discovery, it is unlikely that your material is the same size as material coming from an existing plant. Therefore, you are in trouble. If no single plant will generate exactly the same particle-size distribution as another and if no laboratory is capable of generating the same particle size as a production plant, then how do you make a sample for comparison?

Existing producers have the advantage of experience. They also have the disadvantage of being too familiar with their own deposit. From experience, existing producers have established a correlation between laboratory tests conducted a specific and standard way and the quality of product a raw material will produce after treatment in an existing plant. They also have experience in how samples from a new deposit will react in their existing plant, so they don't try to make the product exactly the same as produced in the full-scale plant.

Very few in-house testing laboratories are capable of producing a product in the laboratory that is exactly like the product that will be made in a production plant. The laboratory equipment is different, the scale is different, the operators will be different, and the sample will be different from the production material. Generally speaking, in-house testing laboratories also have trouble dedicating the time and resources necessary to study how new deposits can be treated to produce existing products using newly developed beneficiation methods.

Remember, when you get a value from a test, that value is a reflection of the test procedure and the sample tested. These values are good to use when comparing samples from the same deposit or from other deposits when tested the same way. But they are not a good reflection of how one mineral end product compares with a similar mineral end product produced in a full-scale production plant with different raw material feed.

Finally, what do you do if the standard test procedure involves the use of a trained part of the body? There are still some evaluations of mineral products based on the opinion of experts who can tell by experience whether a mineral product will be suitable for use based on looks, feel, taste, or smell—or if it sticks to the wall when thrown. Examples include the following:

1. The human eye can detect a difference in hue or cast of two mineral powders that have the same G.E.B. value.

2. A person with a trained nose can detect the alteration of a fragrance by the carrier, even where there is no difference in chemistry, mineralogy, or particle size in the two mineral products.

3. A standard method to determine the grit in mica products is to place a sample between the teeth and "bite." Hence, the

bite test. How would you quantify this method and be able to reproduce the test from person to person, let alone from laboratory to laboratory?

4. In certain foundry and casting shops, one method to determine the proper mix of sand, clay, binder, and catalyst is to mix the materials by hand and throw a sample of the mix against the wall. If this sample sticks, the shipment will be accepted; if not, the entire shipment of sand or clay may be rejected. While the materials in the mix may meet all the specifications provided by the purchasing agent, since it does not meet the "stick test" in production, then the materials go right back to the supplier.

What do you do? Since no one person can know all the various test procedures for all the various mineral products, YOU should undertake to complete the background studies before having the tests conducted. Or at least find a laboratory that knows where to look. But if at the end of the tests you get a result that appears suspicious, don't panic. Remember the results only suggest what can be done in production. They do not provide an exact comparison.

The following true stories are classic examples of Murphy's law and what can go wrong in testing.

1. A large mineral producer had a variation in abrasion characteristics of its final product. The variations were due to changes in feed materials and processing steps. These variations in abrasion could be accommodated by blending the finished products or merely by selling the product to other specific markets. The abrasion characteristics of the finished products were measured using a piece of equipment fitted with "standard" wear screens. The mineral producer purchased all these "standard" screens from one company in an attempt to eliminate variations in the "standard test procedure".

At a later date, during a meeting between the screen manufacturer and the producer, the screen manufacturer proudly informed the mineral producer that the screens were being manufactured using the mineral producer's finished product as the standard to measure the screen resistance to abrasion.

2. A field person collected samples and sent them to a sample preparation facility with instructions to crush and size the sample to a designated top and bottom mesh size before shipping as much as possible of the material to a potential customer for evaluation. The sample preparation facility carefully stage crushed the sample and shipped it off as directed.

The sample failed to meet the specifications required by the customer. By carefully stage crushing and sizing the sample, the laboratory had produced an artificially coarse size distribution. While this maximized the recovery of material, the particle size distribution was unnatural and out of specification. In addition, the sample had been screened at the top size number in U.S. mesh, while the customer specification called for screening the material at a top size number in Tyler mesh—which meant the same size number but a different size opening.

3. An exploration company collected drill core from a limestone deposit, crushed the core, and split the crushed material. From a composite sample, the company wanted to know the brightest reflectance of the material that could be produced. The company authorized the testing laboratory to conduct the studies but with a budget limited to \$50.

Since the technicians worked for an obliging laboratory, they first screened the sample and then from the oversize lumps selected the single cleanest and whitest rock found. After pulverizing this single stone, the technician determined the brightness to be greater than 95 percent. Therefore, the laboratory issued its report stating "that production of a brightness of 95 percent G.E.B. was obtained by screening and sorting the sample." For a \$50 fee, the laboratory did not test the dark material nor a blend of the dark and white material that was present in the sample provided.

Correct answer, correct method, correct report—but it's really not what the client wanted. But as you know, you get what you pay for.

4. A client wanted to know the composition of a rock to determine its value and potential markets. Quotation from an analytical laboratory was \$115 for X-ray diffraction analysis and \$45 for X-ray fluorescence analysis. The client opted for the cheaper analysis method, because he considered that he "could calculate the mineralogy from the chemistry."

The chemistry suggested the sample was a very impure limestone, or at least that is what the client thought. High-calcium and high-silica contents but no loss-on-ignition determinations suggested the material was not high-quality limestone.

True, but what the client had was a high-quality wollastonite deposit. Again, the right answers, but based upon incomplete data, the wrong conclusions.

5. A deposit of diatomite was being evaluated for marketing as a filtration media. A laboratory having a good reputation for price and speed in completion of studies was selected to conduct the tests. This laboratory had conducted filtration tests on diatomite from other deposits in the past (over five years ago) and still had the homemade equipment it had used then. A new engineer was assigned to the new study. After reading the reports on the earlier tests, he was able to get the samples tested and even provide comparative results on a commercial standard diatomite. Unknown to them, however, the filtration industry, led by another diatomite producer, had developed a new test procedure for evaluating filter media. The results using the new methods were quoted in current sales literature without reference to any new testing method. The current mineral producer had determined that this new method was more reproducible in the laboratory and easier to equate to real live filtration media applications. A comparison of the results obtained using the old procedure on the standard sample and the new sample led to the conclusion that the new sample would produce filtration rates better than the existing standard material.

So the decision came, "Let's get into production!" Unfortunately, they were comparing apples and oranges. Were the answers right? Yes. Were the answers what the company asked for? Yes. Was the answer what the company needed? No.

6. A new deposit that was capable of producing a high-grade glass sand suitable for the production of flint and tableware glass was located. With a little additional processing, the material could also make a product suitable for some optical glass markets. However, the client was interested only in the production of ultra high-purity quartz. The specifications for ultra high-purity quartz required a total impurity level of less than 10 ppm. After four years of research, costs of several thousand dollars, input from three engineering and design companies, several core drilling studies, and many geological studies, the deposit is still under study, with production years away.

In the meantime, the markets for the lower quality products in the area are attracting interest from others with similar deposits. Sometimes, if you shoot too high, you hit nothing.

7. A clay sample was collected from a region of the country that had no kaolin clay production and was sent to a major kaolin producer for evaluation in the "as-collected" condition. The established kaolin producer sent the sample to its own laboratory for evaluation. The production laboratory tested the sample using its "standard test procedure" (as used for its own deposit) and determined the clay would not meet any product specifications if processed through the existing plant.

The major kaolin producing company rejected the deposit. However, the property owner had samples from the deposit subjected to more studies by others. The new studies included additional stages of trials, tests, and research programs. The deposit now appears capable of producing suitable kaolin for the nearby markets and may be suitable for other markets such as a ball clay and as a ceramic clay.

So, as shown by these examples, you win some, you lose some. But, you hope to win more than you lose.

1990 Forum on the Geology of Industrial Minerals: Virginia

by Palmer Sweet, Virginia Department of Mines, Minerals, and Energy, Division of Mineral Resources, P.O. Box 3667, Charlottesville, Virginia 22903

ABSTRACT

The 26th Forum on the Geology of Industrial Minerals will be held in Charlottesville, Virginia, on May 14-18, 1990. The meeting will focus on the industrial minerals in the middle Atlantic states and the history of and the unique industrial minerals that are presently exploited in Virginia, namely kyanite, dimension slate, and soapstone. The meeting will consist of three days of technical sessions, including an afternoon excursion and two days of field trips.

The proposed field trips will be to Kyanite Mining Corporation and LeSueur-Richmond Slate Corporation in Buckingham County; The New Alberene Stone Company, Inc., in Nelson County; and the Powhatan Mining Company (Morefield pegmatite) in Amelia County (Figure 1). Other field trip possibilities include The Feldspar Corporation in Hanover County and Virginia Vermiculite Ltd. in Louisa County.

Kyanite Mining Corporation mines kyanite on Willis Mountain from quartzite in the Arvonian Formation of Ordovician age. Mullite, calcined kyanite, is mainly marketed for the ceramic industry, where it aids in resisting cracking, warping, slagging, and deformation at high temperatures.

The LeSueur-Richmond Slate Corporation quarries blue-black slate of Ordovician age in northern Buckingham County south of Bremono Bluff near Arvonian. Sixty percent of the slate is marketed for shingles; other markets include architectural slate for facing stone, plaques, signs, walks, and patios.

The New Alberene Stone Company began quarrying soapstone from the Lynchburg Formation in Schuyler, Nelson County, in March 1987. Soapstone stoves and various architectural products such as facing stone, walkways, and stair treads are being produced.

The Morefield pegmatite in Amelia County was acquired in 1985 and is presently being operated by Powhatan Mining Company on a fee basis for mineral collecting.

INTRODUCTION

A variety of nonfuel minerals are produced from all five physiographic provinces in Virginia and represented more than \$460 million production in 1987; preliminary figures for 1988 indicate production is up to about \$473 million (U.S. Bureau of Mines, 1989). The Coastal Plain Province in the eastern part of the state is underlain by mainly clays, sands, and gravels. The Piedmont Province lies to the west of the fall line, which runs north-south through Richmond to the Blue Ridge Mountains. The Piedmont Province consists of metamorphic and igneous rocks such as slates, schists, quartzites, marbles, granites, and granite gneisses. Some sandstone and shale are found in scattered Mesozoic basins in the province.

The Blue Ridge Province consists mainly of greenstones, amphibolites, and granite gneisses and extends along the Blue Ridge Mountains from the West Virginia line to Roanoke and then southwest through Floyd, Carroll, and Grayson Counties to the North Carolina state line. The Valley and Ridge Province is underlain by limestones and dolomites, with valleys of shale and ridges supported by sandstone. The extreme southwestern part of the state, which represents the Cumberland Plateau Province, is underlain by coal-bearing rocks and is the site of more than three-

1. THE NEW ALBERENE STONE CO., INC.
2. LESUEUR-RICHMOND SLATE CORP.
3. KYANITE MINING CORP.
4. POWHATAN MINING CO.



Figure 1. Location of field trip stops. Star denotes meeting location in Charlottesville, Virginia.

fourths of the total mineral production in Virginia, mainly coal, petroleum, and natural gas.

STONE PRODUCTION INCREASE

Total mineral production in Virginia in 1987 was \$2.005 billion current dollars (Sweet, 1989a), which was equal to the value of gross farm income in the state. The total value, which was more than 25 times greater than the value of the fishing industry, was equal to \$49.126 per square mile and represented \$340 per Virginian.

Increased demand for crushed stone in Virginia is a result of the road and transportation program approved by the General Assembly in 1987 and the five-year \$70-billion federal road program. Substantial state funds resulting from increases in Virginia titling, gasoline, sales, and aviation taxes are now being utilized in road construction (85 percent), mass transit (8.4 percent), ports (4.2 percent), and airports (2.4 percent). Crushed stone use is projected to increase substantially over the next several years. In fact, crushed stone production has increased from 42.3 million tons in 1984 to almost 60.4 million tons in 1987. The majority of the increase in nonfuel mineral production in 1988 is sand and gravel and crushed stone; Virginia ranked fifth nationally in crushed stone production for 1988 (U.S. Bureau of Mines, 1989).

During 1988, W.W. Boxley Company of Roanoke purchased the sand and gravel operation of Eavers Brothers Excavating Company, Inc., located south of Stuarts Draft, Augusta County. Boxley also petitioned the County Board of Zoning Appeals and received unanimous approval to transfer Eavers' special-use permit and for expansion of the operations; this request was approved by the county.

Luck Stone Corporation has opened up a new quarry to produce roadstone from Triassic sandstone in the Piedmont province near Bealeton, Fauquier County, and also applied for a rezoning of land near Ware's Crossroads in northern Louisa County. The company has obtained approval from the Louisa County Board of Supervisors to operate a quarry and related industries.

Other companies have either opened up a new operation, requested a rezoning, or are seeking a conditional use permit in restricted areas in several provinces. These companies propose to produce masonry and concrete sand and crushed stone for construction purposes in Amherst, Fluvanna, Franklin, and Louisa Counties in the Piedmont Province, and Botetourt, Frederick, and Wythe Counties in the Valley and Ridge Province.

FIELD TRIPS

Kyanite Mining Corporation

In central Buckingham County, Kyanite Mining Corporation mines kyanite (Al_2O_3) from two quarries on the recumbent Whispering Creek Anticline. On the west limb of the anticline, the Willis Mountain quarry and plant went into operation in 1957 (Figure 2). The East Ridge operation on the east limb opened in 1978 and doubled capacity at that time. Kyanite Mining is presently the sole domestic producer of the blue to white, non-metallic, high-aluminum silicate mineral kyanite. The mineral is mined from kyanite-bearing quartzite in the Arvonian Formation of Ordovician age.



Figure 2. View looking north along the top of Willis Mountain, Kyanite Mining Corporation, Buckingham County.

Kyanite is a primary source of high-alumina refractory material, and 90 percent of the kyanite-mullite output is used in refractories. Mullite (calcined kyanite) is produced by heating the kyanite at temperatures of 1,100 to 1,480 °C, at which point the kyanite loses its bluish tint and becomes white and opaque. Mullite is stable, has a low coefficient of thermal expansion, and a high disintegration point; it increases the fired strength of ceramic products and improves their thermal resistivity and dielectric properties. Mullite is produced and marketed in 35-, 48-, 100-, 200-, and 325-mesh sizes.

The kyanite-bearing quartzite is quarried from open pits and run through primary crushers. By-product sand is produced from kyanite processing; sales are for golf courses, concrete, and blasting sand (Figure 3). Then the material is passed through a log washer to remove clay and on to classifiers to remove some of the kyanite. A rod mill then reduces the material to minus 35-mesh, and then the ore is passed into froth flotation cells to skim off additional kyanite, which is then dewatered. The ore is then dried, and sulfides (pyrite) are converted to ferrous iron oxide (magnetite). The magnetite is then removed with magnetic separators. Kyanite is ground and bagged at the Willis Mountain operation; raw kyanite that is not bagged is trucked to the East Ridge operation for calcining into mullite. Mullite is pulverized and bagged several miles to the north at a plant in Dillwyn.



Figure 3. By-product sand at plant on East Ridge, Kyanite Mining Corporation, Buckingham County.

LeSueur-Richmond Slate Corporation

In the northeastern part of Buckingham County, blue-black, fine-grained slate of Ordovician age has been quarried for more than 250 years. In the early part of the 20th century, production of roofing slate reached a peak, with as many as eight companies operating quarries (Evans and Marr, 1989). The slate is presently being quarried from two main quarries in Arvonian by LeSueur-Richmond Slate Corporation (Figure 4).



Figure 4. View looking south along cleavage of the Arvonian slate in the north quarry, LeSueur Richmond Slate Corporation, Arvonian, Buckingham County.

There are several dozen old quarries located along the Arvonian Slate Belt, with the slate dipping steeply to the southeast and the cleavage nearly parallel to bedding. The best slate is fine grained and homogeneous, while slate to be avoided is more silty and contains irregular faults and quartz stringers (Sweet, 1989b).

The quality slate is drilled horizontally, and low-velocity explosives are used to blow the stone upward; the slate will shear vertically and break out in large chunks of stone. Stone is loaded into trucks and hauled to the cutting shed, where hammers and chisels are used to cut and split the slate by hand. The slate will split into thin sheets by utilizing the natural slaty cleavage. The slate does not have to be gang-sawed, as it can be split to desired thickness by hand.

Products include 60 percent of the production for roofing shingles, architectural slate for facing stone, plaques, signs, walks, and patios (Figure 5). Some of the waste slate is crushed and marketed for roadstone and stone for drainfields.



Figure 5. Finishing shed for architectural slate products, LeSueur Richmond Slate Corporation, Arvonian, Buckingham County.

The New Alberene Stone Company, Inc.

TuliKivi, a Finnish company, purchased the dimension soapstone operation in Nelson and Albemarle Counties in August 1986 and renamed the operation The New Alberene Stone Company, Inc. The soapstone operations were most recently operated by Alberene Stone Company and the Georgia Marble Company. In March 1987, the company began quarrying blocks of soapstone from the quarry just north of the plant at Schuyler, Nelson County.

The soapstone is present in a 30-mi-wide belt in the Lynchburg Group that has an average width of 200 ft and reaches unknown depths. The soapstone consists of talc and various amounts of chlorite, amphibole, and carbonate. The rock type ranges from hornblende-oligoclase to chlorite-talc and chlorite-tremolite. The grades range from very soft and light gray in color to a very hard serpentine that is greenish-black in color.

Presently, the blocks of soapstone are extracted by drilling corner holes and then cutting the blocks out with a large Korfmann chain saw (Figure 6). The blocks are currently lifted out of the quarry by a derrick, but in the future, quarries will be developed so the blocks can be removed with a forklift. The blocks are transported to the plant, where they are slabbled with Tysaman sand gangsaws (Figure 7). The wet slabs will then be examined for flaws and cracks that may eliminate them from any further processing. Stone is then cut to predetermined sizes, polished, and readied for production of soapstone stoves.

The main product at the company is soapstone fireplaces or



Figure 6. Quarry showing vertical drill holes at the top and smooth surfaces below of stone cut with a Korfmann chain saw, The New Alberene Stone Company, Schuyler, Nelson County.



Figure 7. Soapstone block ready to be slabbled with a Tysaman sand gangsaw, The New Alberene Stone Company, Schuyler, Nelson County.

stoves. Additional products, which benefit from the heat-retaining properties of soapstone, include laboratory counters and architectural materials such as facing stone, walkways, and stair treads. At least 600 years of reserves of soapstone are available in the area.

Powhatan Mining Company

The Morefield pegmatite, operated by Powhatan Mining Company, is located in Amelia County, about 4 mi east-northeast of Amelia Court House, off State Road 628. Silas Morefield first opened the complex pegmatite in 1929, and in the early 1930's, the Seaboard Feldspar Company worked the mine for mica and feldspar. The mine was then intermittently worked by Morefield until about 1940; Seaboard and Southern Minerals, Inc., did some exploratory work in 1941. In late 1942, the Metals Reserve Company took over the mine. At this time, there was an open pit 230 ft long, 8 to 60 ft wide, and about 25 ft deep; a caved shaft was about 45 ft deep. The next year, Morefield reacquired the property, deepened the shaft to below 60 ft, and started a drift to the north at the 45-ft level.

The U.S. Bureau of Mines explored the pegmatite in 1943; they crosscut the pegmatite in five places and put down five diamond drill holes. Placer material in the creek and flood plain south of the mine was washed. In 1948, the Bureau leased the property and carried on experimental development and mining. The pegmatite was proven on the surface for a distance of over 1,000 ft and vertically to a depth greater than 200 ft. Sweet and Penick (1986) note that the body ranges from 5-16 ft wide in the pit to 30 ft wide in bulldozer trench No. 5; drill holes indicate that it tapers downward. The pegmatite has a strike of N. 47° E. and has a northwest dip several degrees from vertical. Wall rock consists of biotite hornblende gneiss.

Brown (1962) states that the eastern part of the pegmatite body for a distance of about 300 ft is mineralogically complex. To the west, at the surface, the body becomes relatively simple and is composed chiefly of partly kaolinized buff-colored perthite (feldspar), small amounts of muscovite and biotite, and stringers and masses of glassy quartz. The complex portion of the pegmatite contains a considerable quantity of phenacite and an abundance of large crystals of topaz and zinnwaldite. Some of the topaz crystals are gem quality.

Brown (1962) also stated that core quartz is not everywhere present; locally, amazonite (blue-green microcline) of the intermediate zone gives way to buff perthitic microcline into which it is gradational. Because they include veinlets, both varieties of potash feldspar are thought to be older than the core quartz. Crystals and masses of topaz, phenacite, and beryl occur with perthite near

or within quartz of the core. Silas Morefield reported one topaz crystal that was 44 in. long and weighed 500 lb; some small crystals showed double terminations. Some beryl crystals reach several feet in length. About 500 lb of placer beryl were also recovered by the Bureau of Mines from the flood plain south of the pit. It is reported that about 7 tons of beryl were sold from the mine prior to 1944.

Clevelandite albite appears to be of late origin in that it fills crevices in or replaces the more common minerals such as quartz and muscovite with which it is associated. Several less-common minerals, including yellow beryl, calcite cassiterite, manganotantalite, microlite, monazite, tantalitecolumbite, and zircon are closely associated with the clevelandite. Tantalite-columbite also occurs in the buff perthite. Lemke, Jahns, and Griffiths (1952) report production between the years 1929 and 1944 of 1,423 lb of tantalite minerals, then valued at \$1,542.75. In the early 1980's, there was some company interest in the tantalite columbite minerals as the value topped \$100/pound. Some sampling and a few trenches were cut south and west of the Morefield shaft.

Book muscovite occurs in the inner part of the albite-quartz-perthitemica wall zones. It is light, amber colored, and clear and occurs in crystals 10 to 12 in. across and 3 to 7 in. thick. During the period 1943-1944, approximately 7 tons of scrap mica valued at \$90 and 630 lb of trimmed punch and sheet mica valued at \$3,775 were sold from the mine.

In 1985, W.D. Baltzley acquired the Morefield pegmatite and is presently operating it as a fee-collecting site for searching in the dumps and using an on-site sluice box. Digging in the vein may be possible in the future.

POSSIBLE FIELD TRIPS

The Feldspar Corporation

The Feldspar Corporation operated an open-pit operation in east-central Virginia, near Montpelier, Hanover County. The company is quarrying medium- to coarse-grained anorthosite feldspar (Montpelier Metanorthosite) at this site. Accessory minerals present in the feldspar include apatite, rutile, ilmenite, sphene, biotite, muscovite, and garnet in minor amounts. Mafic minerals, such as pyroxenite, garnetiferous amphibolite, and biotite gneiss are present in the anorthosite (Marr, 1985).

Feldspar is mined and trucked to the plant for crushing, grinding, classifying, and drying. The material is ground by primary and secondary crushers and pulverized in a rod mill to minus 30-mesh. The resulting slurry is pumped to a storage pile; the material is beneficiated through Humphrey spirals and then through wet magnetic separation. Washing and scrubbing removes unwanted stain on the grains; the material is then dewatered and dried in oil-fired rotary drier. After drying, the feldspar is screened and then passed over high-intensity magnetic separators.

The product is stored in silos until it is shipped by both truck and rail to markets in the southern states, New Jersey, Pennsylvania,

Ohio, and Indiana. Material shipped by rail is trucked 16 mi to the railhead at Beaverdam. The feldspar 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 product makes up about 8 percent of a finished bottle. With more plastic bottles being used, markets are being extended into production of glass-fiber manufacture.

Water in the tailings pile is cycled back in the plant process. Heavy-mineral sand containing mainly apatite, rutile, ilmenite, and sphene continue to be stockpiled on the site. With these minerals having similar electrical and magnetic properties, separation would be difficult.

Virginia Vermiculite, Ltd.

Vermiculite, a hydrated magnesium-iron-aluminum silicate, is mined in west-central Louisa County near Boswells Tavern. The vermiculite is present in a biotite-gneiss that has been intruded with pegmatites and dikes. Virginia is one of three states in the United States producing vermiculite.

The material is mined with a backhoe and front-end loader and trucked to the plant on the site. The vermiculite is sized, washed, run through a rod mill to shear vermiculite to a thin thickness and run over riffle table to remove biotite, feldspar, etc. Material is further concentrated by flotation and is dewatered; drying occurs in a rotary kiln and is separated into four sized products. Vermiculite is not exfoliated at this facility.

Crude vermiculite is shipped by rail to North Carolina, West Virginia, Ohio, and as far west as Texas and Arizona. Uses for the material include packing, insulation, lightweight aggregate, and potting material.

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APPENDIX

List of Registrants at 25th Forum on the Geology of Industrial Minerals
April 30 to May 2, 1989, Portland, Oregon

Ainsworth, Ben Ainsworth-Jenkins, Inc. 525-890 W. Pender St. Vancouver BC V6C 1J9 Canada 604/684-6463	Berkhser, Samuel W. Pennsylvania Geol. Survey 65 Hellam Dr. Mechanicsburg PA 17055 717/787-5897	Dirkes, Carl Marblehead Lime Company 222 North La Salle Street Chicago IL 60601 321/263-4490
Austin, George S. New Mexico Bureau of Mines Campus Station Socorro NM 87801 505/835-5230	Bleeck Joerg Columbia River Carbonates P.O. Box D Woodland WA 98674 206/620-9046	Ferns, Mark Oregon Dept. Geol. & Min. Ind. 1831 First Street Baker City OR 97814 503/523-3133
Barker, James M. New Mexico Bureau of Mines Campus Station Socorro NM 87801 505/835-5114	Boucher, Michel A. Energy-Mines-Resources 6th Floor, 580 Booth Street Ottawa ON K1A 0E4 Canada 613/992-3074	Flechsigg, Jenny Pozzolan North West, Inc. 2448 76th Avenue SE, #222 Mercer Island WA 98040 206/232-9320
Barlow, Jim Oregon Division of State Lands 1600 State Street Salem OR 97310 503/378-3805	Bourne, H. Lyn Consulting Geologist P.O. Box 293 Northville MI 48167 313/462-0005	Fox, Cam Ind. Min. Consultant R.R. #4 Huntsville ON P0A 1K0 Canada 705/635-1538
Bates, Robert L. 180 Canyon Drive Columbus OH 43214 614/268-4989	Brooks, Howard C. Oregon Dept. Geol. & Min. Ind. 1831 First Street Baker City OR 97814 503/523-3133	Ganis, Robert Tethys Consultants, Inc. 2001 N. Front St., Suite 234 Harrisburg PA 17102 717/233-7625
Bearden, Stan D. New Riverside Ochre Company P.O. Box 387 Cartersville GA 30120 404/382-4568	Bryan, Dennis P. Sergeant, Hauskins, & Beckwith 737 E. Glendale Avenue Sparks NV 89431 702/331-2375	Geitgey, Ron Oregon Dept. Geol. & Min. Ind. 1400 SW 5th Avenue Portland OR 97201 503/229-5580
Beaulieu, John D. Oregon Dept. Geol. & Min. Ind. 1400 SW 5th Ave. Portland OR 97201 503/229-5580	Castor, Stephen Nevada Bureau of Mines University of Nevada Reno NV 89557 702/784-6691	Gray, Jerry Oregon Dept. Geol. & Min. Ind. 1400 SW 5th Avenue Portland OR 97201 503/229-5580
Beeby, Dave California Div. Mines & Geol. 650-B Bercut Drive Sacramento CA 95814 916/323-8562	Corcoran, Andy 9551 SW 62nd Dr. Portland OR 97219 503/244-5605	Griggs, George US Borax & Chemical Corp. 3075 Wilshire Blvd. Los Angeles CA 90010 213/251-5555
Bennett, Earl Idaho Geological Survey Univ. of Idaho, Morrill Hall Moscow ID 83843 206/885-7991	Cummings, Michael Portland State Univ., Geology P.O. Box 751 Portland OR 97207 503/725-3022	Grisafe, David Kansas Geological Survey University of Kansas Lawrence KS 66045 913/864-3965
Bentzen, Edwin H. Ore Sorters (N. America), Inc. 777 South Wadsworth Ave. Lakewood CO 80226 303/985-0238	Dalheim, Peggy A. The Mineral Lab 2700 Youngfield, Suite 105 Lakewood CO 80215 303/232-8708	Growney, Larry NERCO Oil & Gas, Inc. 6819 NE 92nd Court Vancouver WA 98662 206/253-3247
Berg, Dick Montana Bur. Mines & Geol. Butte MT 59701 406/496-4172	Dean, Lyndon L. Material Service Corporation 4226 Lawndale Avenue Lyons IL 60534 312/442-4624	Guarnera, Barney Boise Cascade Corporation P.O. Box 50 Boise ID 83728 208/384-7100

Gulick, Charles W. Steelhead Specialty Minerals N. 1212 Washington, Suite 306 Spokane WA 99201 509/328-5685	Hopkins, David A. The J.E. Baker Company 320 N. Baker Road York PA 17404 717/792-3685	Kaczorowski, Ray GCO Minerals P.O. Box 4258 Houston TX 77210 713/651-9261
Gunning, Donald F. Internatl. Marble & Stone Co. Box 1148 Point Roberts WA 98281 604/888-3848	Hora, Z. Dan British Columbia Geol. Survey 3657 Doncaster Dr. Victoria BC V8P 3W8 Canada 604/721-3728	Katsoulis, M.P. State of Minnesota Box 45, 500 Lafayette Rd. St. Paul MN 55155 612/296-4807
Hamilton, Wylie Alberta Res. Council PO Box 8330, Postal Sta. F Edmonton, AB T6H 5X2 Canada 403/438-7634	Horning, Tom ASARCO, Inc. East 920 Wolverton Court Spokane WA 99207 509/489-7870	Kroft, Jeff Oregon Div. of State Lands 1600 State Street Salem OR 97310 503/378-3805
Hartness, Larry ERGON, Inc. P.O. Drawer 1639 Jackson MS 39215 601/944-4660	Hull, Donald A. Oregon Dept. Geol. & Min. Ind. 1400 SW 5th Ave. Portland OR 97201 503/229-5580	Krueger, Allen Dravo Basic Materials Box 2068 Mobile AL 36652 205/432-2651
Hatton, Kay New Mexico EMNRD 525 Camino De Los Marquez Santa Fe NM 87503 505/827-5923	Jackson, Jerry H. Santa Fe Pacific Mining, Inc. PO Box 27019 Albuquerque NM 87125 505/881-3050	Ledger, Ed Hampton Power Products, Inc. P.O. Box 84803 Seattle WA 98124 206/285-8936
Hebb, David H. Hebb Resources International N. 2128 Pines Road, SU-17 Spokane WA 99206 509/926-1036	Jacob, Henri-Louis Min. Energie/Res., Quebec 1620 Boul. de L'Entente Sainte-Foy PQ G1X 1X9 Canada 418/643-1803	Leppert, Dave Teague Mineral Products 1925 Hwy. 201 South Adrian OR 97901 503/339-3940
Herrick, Dean H. Dunn Geoscience Corporation 12 Metro Park Road Albany NY 12205 518/458-1313	Jamieson, Cynthia INDUSMIN, Suite 200 365 Bloor Street E. Toronto ON M4W 3L4 Canada 416/967-1900	Lobdell, David Cassiar Mining Corp. 2000-1055 W. Hastings Vancouver BC V6G 3A5 Canada 604/688-2511
Hoagberg, Rudolph R.K. Hoagberg Assoc., Inc. 430 1st Ave. North, Suite 790 Minneapolis MN 55401 612/338-2322	Jenkins, David Grefco, Inc. P.O. Box 939 Lompoc CA 93436 805/736-4581	Lou, Linda Idaho Dept. of State Lands Statehouse Boise ID 83720 208/334-3610
Hoffman, Eric U.S. Bur. of Land Management P.O. Box 2965 Portland OR 97208 503/231-6812	Joseph, Nancy Washington Div. Geol./E. Res. North 222 Havana St. Spokane WA 99202 509/456-3205	Malhotra, Deepak AMAX Res. & Dev. Center 5950 McIntyre St. Golden CO 80403 303/273-7205
Holmes, David A. Meridian Minerals Company 5613 DTC Parkway—12th Fl. Englewood CO 80111 303/930-9270	Joyce, Carl E. J.M. Huber Corporation Route #4 Macon GA 31298 912/745-4751	Malone, Vic H. Medusa Aggregates Company 880 Corporate Dr., Suite 101 Lexington KY 40503 606/223-2575
Hook, John Consulting Geologist 7315 Battle Creek Rd. Salem OR 97301 503/371-3901		Mason, Ralph 3932 S.W. Idaho Portland OR 97221 503/244-2106

Masters, Jack Illinois Geological Survey 615 East Peabody Drive Champaign IL 61820 217/244-2516	Olson, Richard Ind. Min. Evaluations 1536 Cole Blvd., Suite 320 Golden CO 80401 303/239-9250	Santini, Ken Dunn Geoscience Corporation 12 Metro Park Road Albany NY 12205 518/458-1313
Maybin, Arthur H. South Carolina Geol. Survey 5 Geology Road Columbia SC 29210 803/737-9440	Papke, Keith G. Consultant 2180 Schroeder Way Sparks NV 89321 702/358-3095	Schrader, Ed L. Millsaps College 1701 N. State Street Jackson MS 39215 601/944-4660
McBride, Mary W. Texas Bur. of Econ. Geology University Station, Box X Austin TX 78713 512/471-7721	Petterson, Frank C. Supreme Perlite Company 4600 North Suttle Road Portland OR 97217 503/286-4333	Scott, Dale W. Ontario Min. of Nat. Resources Whitney Bl., Queens Pk. #3636 Toronto ON M7A 1W3 Canada 416/965-3172
McClave, Michael A. ASARCO Incorporated E. 920 Wolverson Court Spokane WA 99207 509/489-7870	Power, W. Robert Georgia Marble Company 1201 Roberts Blvd., Bldg.100 Kennesaw GA 30144 404/421-6534	Seymour, Denny U.S. Bur. of Land Management P.O. Box 2965 Portland OR 97208 503/231-6812
McGee, John Georgia Marble Aggregates Gp. P.O. Box 28 Lithonia GA 30058 404/482-8776	Prentice, John E. Eastwood, Great Comberton, Pershire Worcester WR10 3DT Great Britain 038/674/244	Sharpe, Roger D. US Gypsum Company 700 N. Hwy 45 Libertyville IL 60048 312-362-9797
McNary, Sam U.S. Bur. of Land Management East 360 Third Avenue Spokane WA 99202 509/456-7938	Radasch, Charles Oregon Dept. Geol. & Min. Ind. 1400 SW 5th Ave. Portland OR 97201 503/229-5580	Shelden, Jim USDA Forest Service, Region 1 Box 7669 Missoula MT 59807 406/329-3577
Montgomery, Bill Jerico Dredging, Inc. 100 E. D Street Petaluma CA 94952 707/374-2642	Rice, William L. U.S. Bureau of Mines E. 360 Third Avenue Spokane WA 99202 509/456-7914	Shore, Irv F&S Alloys & Minerals Corp. 1 Penn Center West Pittsburgh PA 15276 412/787-9680
Newman, Thomas E. J.M. Huber Corporation Box 4005 Quincy IL 62305 217/224-1100	Rimal, Durga U.S. Bur. of Land Management P.O. Box 2965 Portland OR 97208 503/231-6812	Simon, Craig Boise Cascade P.O. Box 50 Boise ID 83728 208/384-6195
Oak, Leo C. Martin Marietta Aggregates R.R. #2, Box 33 Fortville IN 46040 317/573-4460	Riordan, Richard F. Geomapping Association 2674 Robidoux Road Sandy UT 84093 801/943-3062	Steuart, Charles T. Malvern Minerals Company P.O. Box 1238 Hot Springs AR 71902 501/623-8893
Odom, I. Edgar American Colloid Co. 1500 W. Shore Drive Arlington Heights IL 60004 312/392-4600	Robertson, Dan Steelhead Specialty Minerals N. 1212 Washington, Suite 306 Spokane WA 99201 509/328-5685	Stewart, Maxine Hazen Research 4601 Indiana Street Golden CO 80403 303/279-4501
O'Driscoll, Michael Industrial Minerals Journal 220 Fifth Avenue New York NY 10001 212/213-6202	Rueff, Art W. Missouri Geological Survey Box 250 Rolla MO 65401 314/364-7603	Sweet, Palmer C. Virginia Dept. Mines/Mins./ En. P.O. Box 3667 Charlottesville VA 22903 804/293-5121

Timmons, Bobby J.
Timmons Associates
P.O. Box 50606
Jacksonville Beach FL 32240
904/246-4533

Turner, Dennis
Dunn Geoscience Corp.
12 Metro Park Road
Albany NY 12205
518/458-1313

Valji, Sherm
Meridian Minerals Co.
5613 DTC Parkway, 11th Fl.
Englewood CO 80111
303/796-8586

VanKouteren, Steve
Kline and Company
165 Passaic Avenue
Fairfield NJ 07006
201/808-3463

Visocan, Andrew E.
Eagle-Picher Minerals, Inc.
P.O. Box 640
Valc OR 97918
503/473-3285

Vogt, Beverly
Oregon Dept. Geol. & Min. Ind.
1400 SW Fifth Ave.
Portland OR 97201
503/229-5580

Walker, Robert C.
Dunn Geoscience Corporation
12 Metro Park Road
Albany NY 12205
518/458-1313

Westcott, James F.
A.P. Green Industries
7 Branchwood Road
Mexico MO 65265
314/581-3732

White, Doss
U.S. Bureau of Mines
PO Box L, U. of Ala. Campus
Tuscaloosa AL 35486
205/759-9466

White, Gary
British Columbia Geol. Survey
756 Fort Street, Room 200
Victoria BC V8V 3A3
Canada
604/356-2845

Whitson, David N.
Supreme Perlite Co.
4600 N. Suttle Road
Portland OR 97217
503/286-4333

Williams, Barrett J.
Norfolk Southern Corporation
185 Spring Street SW
Atlanta GA 30303
404/529-1853

Wilson, Ray
Steelhead Specialty Minerals
N. 1212 Washington, Suite 306
Spokane WA 99201
509/328-5685

Witzel, Frank L.
North American Exploration
P.O. Box 348
Kaysville UT 84037
801/544-3421

Younggren, Liz Brenner
2322 Clark Avenue
Billings MT 59102
406/656-8481

Zdunczyk, Mark J.
Dunn Geoscience Corporation
12 Metro Park Road
Albany NY 12205
518/458-1313

Zimmerly, Billie Jean
Zimmerly & Son
8915 NE 130th Ave.
Vancouver WA 98682
206/892-7620

Zimmerly, Roy
Zimmerly & Son
8915 NE 130th Ave.
Vancouver WA 98682
206/892-7620

Zupan, Alan-Jon
South Carolina Geol. Survey
5 Geology Road
Columbia SC 29210
803/737-9440