ARIZONA INDUSTRIAL MINERALS:
A GROWING INDUSTRY IN TRANSITION

by
Ted H. Eyde
GSA Resources, Incorporated
Box 16509
Cortaro, Arizona 85652

and

Jan C. Wilt
J.C. Wilt & Company
3035 S. Shiela Ave.
Tucson, Arizona 85746

ABSTRACT

Industrial minerals have been mined in Arizona since the dawn of civilization. The applications of these remarkable minerals have become increasingly sophisticated until today industrial minerals are displacing metals from many of their traditional uses. Production of industrial minerals in Arizona has increased steadily because of increasing population and living standards. In 1984, 205 operations produced $245 million of industrial minerals. In fact, the tonnage and value of aggregate production are exceeded only by those of copper. In the past 25 years both the kind and quantity of industrial minerals have increased rapidly. The state is an important producer of aggregate, cement, lime, and gypsum, which are used principally in the construction industry. It also is a major producer of specialty industrial minerals such as bentonite, high-purity salt, perlite, and zeolite. Deposits of hectorite, diopside, and celestite are being developed. Industrial minerals production should continue to increase with an expanding population base unless the resources become unavailable because of increases in the acreage of public lands in wilderness and urban areas. Imposition of a single standard for airborne particulates on all minerals that have fibrous varieties could also restrict development of deposits containing acicular minerals.

INTRODUCTION

The production of industrial minerals and rocks continues to show dynamic growth. According to preliminary production figures from the Mineral Commodities Summaries of 1985 by the U. S. Bureau of Mines, the value of nonmetallic production in the United States in 1984 was nearly $16.7 billion (U.S. Bureau of Mines, 1985). This is nearly three times greater than the $6 billion value of metal production. Thus, it seems incredible that many geological publications still relegate industrial minerals to a list of a few localities accompanied by a brief geological description at the end of a report. In fact, many articles are reminiscent of the elementary description of rocks and minerals found in many beginning geological textbooks. This suggests that even now many geologists do not really understand the reasons why some industrial mineral deposits are exploited and others are not.

In addition, descriptions in the geological literature often lag behind the actual production of marketable products from a deposit of industrial minerals. Perlite, for example, is an industrial mineral that did not appear in publications or on maps showing the location of industrial mineral deposits and occurrences until shortly before commercial production began near Superior, Arizona in 1946 (Wilson and Roseveare, 1945). In fact, the first edition of *Industrial*

Minerals and Rocks by Raymond Ladoo, published in 1925, does not mention perlite. The second edition, published in 1951, includes perlite and notes that the most productive deposits in the United States are near Superior, Arizona (Ladoo and Meyers, 1951).

Even experienced field geologists frequently do not recognize potentially valuable industrial mineral deposits, nor are they familiar with the analytical techniques required to identify and evaluate them. Therefore, industrial minerals are frequently overlooked or unrecognized when mineral resources are being inventoried on lands being considered for inclusion in the wilderness system. This means that important resources of industrial minerals that are needed for products being developed through recent advances in materials science will likely be lost to wilderness areas and to urbanization.

Industrial minerals include all those earth materials used by man except metallic ores, mineral fuels, water, and gems (Harben and Bates, 1984). The term "nonmetallics" is not entirely synonymous with industrial minerals. Many so-called nonmetallics are in fact metallic minerals. For example, the oxidized manganese minerals that have been mined in Arizona are considered to be industrial minerals when used in water treatment systems or dry cell batteries and are considered to be metallics when used in steel and ferroalloys. Thus, the end use of the mineral rather than its

composition often determines whether the specific mineral is considered a metallic or nonmetallic mineral, or sometimes both. In fact, mineralogy rather than concentration is often the principal determinant of the end-use application of industrial minerals. For metallic ores and minerals, grade, which is the recoverable content of the particular metal, determines whether a deposit is exploitable, provided adequate reserves are developed.

Highly sophisticated processing is usually required to convert a crude, mine-run mineral or rock into a marketable product of value-added, specialty industrial minerals. For example, complex processing is required to convert the crude bentonites from the Cheto deposit in northern Arizona into marketable products such as acid-activated bleaching clays, desiccants, catalysts, and organoclad clays used as thixotropic agents and suspension stabilizers. In fact, producing these products requires processing technologies far more advanced than those generally used at most of the metallic milling and smelting complexes in Arizona. The rapid growth of the industrial minerals industry has resulted from recent quantum leaps in materials science, such as the fabrication of such innovative products as fiber optics, composites, molecular sieves, and pillared clays.

Industrial minerals were first utilized at the dawn of civilization as tools, weapons, cooking vessels, and materials used in the construction of shelters for pre-Columbian Indian civilizations in Arizona. Ironically, many of these same industrial minerals are now displacing the metals that were introduced by the Spanish settlers whose metal swords and guns defeated the ancient primitive civilizations. In the past, advances in metallurgy resulted in the replacement of stone tools and implements by those fabricated from bronze, iron, and then steel. Now, materials technology has developed fiber-reinforced resin systems known as composites, which are rapidly displacing metals in many traditional applications such as aircraft wings and fuselages, automobile and truck bodies, and construction materials.

Some of the more recent developments in mineral processing include delamination to disaggregate individual clay crystals into cleavage fragments that are in the micron size range, high-intensity wet magnetic separation to remove magnetic minerals, ultraflotation to separate fine-grained gangue minerals, and attrition milling to enhance the aspect ratio of fibrous minerals used as fillers in high-strength engineering plastics. Other recent advances include the treatment or modification of minerals to alter their surface properties.

Clays can be organoclad by treating them with an organic compound to render them compatible with oil, brine, or fresh water systems. The viscosities of all these systems are greatly improved by organocladding. Mineral fillers used in plastic resins are surface modified with coupling agents such as the silanes to increase surface bonding, a property which is important in the formulation of engineering plastics.

Continuing advances in mineral technology will result in expanding markets for high-purity industrial minerals. This will result in a better understanding of both the mineralogy and ultimately the geologic setting of many deposits of industrial minerals.

The geology and mineralogy of industrial mineral deposits in Arizona that were productive during the past 25 years are described along with their applications as particular end use products. Unique characteristics of the deposits include the mineralogy, chemical composition, geologic setting, or location. These seemingly unrelated factors either together or separately provided the marketability of the mineral products from the deposit.

HISTORICAL PERSPECTIVE

Industrial minerals have been produced and used in Arizona and the Southwest for thousands of years. The use of industrial minerals predated the arrival of the Spanish explorers and may even predate modern man. At the Calico Early Man Site in California, the lowest artifact-bearing deposit at the site consists of an assemblage of stone tools that are at least 200,000 years old (Budinger, 1983).

Montezuma's Castle near Camp Verde, the Casa Grande Ruins, and other Indian ruins that still survive in Arizona demonstrate the prehistoric use of stone and adobe in construction. These ruins also contain artifacts that indicate the inhabitants made flint, chert, and chalcedony into arrow heads, axes, skinning tools, and knives. The Indians developed tools for drilling and shaping turquoise and highly colored stones into beads and jewelry. They also shaped and colored clays and fired them into nonporous, durable, colored ceramic pots.

In addition, the Indians were aware of the need for salt in human and animal nutrition and in food preservation. Evidence of pre-Columbian salt mining was discovered at the Camp Verde salt mine in central Arizona. The artifacts and mummified remains of a miner found there prove this to be one of the oldest underground mines in the United States (Thompson, 1983). The early Spanish explorers Antonio Espejo and Marcos Farfan de los Godos saw salt being mined at the Camp Verde deposit as early as 1583 (Bartlett, 1942).

The Spanish settlers brought with them skills in building with brick and mortar, including the construction of arches, a skill not possessed by the Indians. The construction of arches required the ability to make dimensionally uniform bricks as well as lime mortar from clean sand and calcined limestone. The Spanish settlers utilized deposits of dimension stone, marble, limestone, sand and gravel, gypsum, and clay as sources of local building materials.

They also brought with them the technology for manufacturing glass and glazes. Certainly, raw materials that are required in the manufacture of glass and glazes, such as silica sand, feldspar, sodium compounds, and limestone, were available in Arizona. Consequently, stained

glass windows, glasses, glazed table ware, and colored ceramic tile soon became commonplace in Spanish settlements in Arizona. At first these products were imported from Spain; later, local artisans manufactured them in Arizona.

American settlers migrating into Arizona during the nineteenth century brought with them a demand for more and better construction materials, sanitary ware, and chemical products. To satisfy these demands, sand and gravel, dimension stone, gypsum, salines, limestone, and clay deposits were developed.

During the twentieth century new markets for specialty industrial minerals began to develop. Deposits of chrysotile, barite, bentonite, perlite, and zeolites were brought into production. Virtually all of the production from these deposits was and still is shipped out of state for processing into high value-added products from industrial minerals. These industrial mineral products are returned to Arizona in electronic equipment, household appliances, automobiles, and many other consumer products.

Future development of the industrial mineral resources of Arizona will continue to be closely linked both to the rapid population growth and to the rising standard of living. As the population of Arizona increases, more value-added processing of industrial minerals will be done within the state to supply mineral products for the rapidly expanding consumer markets.

PRODUCTION

The Annual Report of the Arizona State Mine Inspector for 1984 lists 251 locations, including those operated by the Arizona Department of Transportation, where industrial minerals were mined or processed. The 1984 Directory of Active Mines in Arizona from the Arizona Department of Mines and Mineral Resources listed 205 industrial mineral producers, which includes 168 producers of gravel and crushed stone and 43 producers of other industrial minerals. Six of these operations produced silica flux for copper smelting. Only fourteen companies produced precious or base metals in Arizona in 1984. There are many small mining operations that produce industrial minerals and relatively few large mining operations that produce precious or base metals.

According to The Mineral Industry of Arizona, a 1984 preprint from the U.S. Bureau of Mines, the value of industrial minerals produced in Arizona in 1984 reached $245 million; this is 17.5% of the $1.4 billion value of nonfuel minerals production in the state. Specifically, both the value and tonnage of aggregate produced was exceeded only by that of copper. Historically the value of industrial minerals production has kept pace with the population growth in the state (fig. 1). If this growth continues, industrial minerals production could surpass metals production both in tonnage and value by the end of the twentieth century.

Though the production of industrial minerals in Arizona can be calculated on a per capita basis, that figure does not indicate the increase in the consumption of industrial minerals outside of the construction industry. According to mineral industry surveys published annually by the U.S. Bureau of Mines and unpublished production data supplied by the producers, more than 98 percent of the tonnage of industrial minerals produced in Arizona is consumed by the construction industry. Most of the remaining 2 percent of industrial minerals production consists of crude or semiprocessed mineral products that are shipped out of state for processing into marketable products.

The data compiled by Austin (1983) and listed in Tables 1 and 2 provide a more accurate appraisal of the increase in both the total production and production per capita of selected industrial minerals in the United States between 1931 and 1981. Overall, the increase in domestic production of construction materials, such as sand and gravel (+396 percent) and cement (+209 percent), lagged far behind industrial minerals used in specialty applications, such as mica (+1,643 percent) and bromine (+4800 percent). These differences are also reflected in the production per capita of these same minerals.

Both Table 1 and 2 present only *production* data. However, if data on the *consumption* of industrial minerals per capita were available, it would include imported industrial minerals. Imports now supply all of the celestite, most of the fluorite and asbestos, and much of the gypsum consumed in the United States; many other industrial minerals are imported. Therefore, the per capita consumption of industrial minerals would be significantly higher than indicated in Table 2. It is reasonable to assume that the per capita consumption of industrial minerals in Arizona is comparable with the rest of the United States. Further, with the introduction of plastic composites, fiber optics, and ceramics, it is probable that the consumption and production of industrial minerals will continue to increase significantly.

CLASSIFICATION

Because of the wide diversity in chemical and physical properties, origin, and end-use applications of industrial minerals, several schemes have been devised to classify industrial minerals. Bates (1960) used both geology and value to establish a twofold subdivision of nonmetallics. Those deposits with a high place value were classified as industrial rocks, whereas those with a high unit value were classified as industrial minerals.

The Bates classification depended on the geological origin of the deposits. However, advances in mineral processing technology moved many commodities that were formerly classified as high place-value industrial rocks to the category of high unit-value industrial minerals. With value-added processing, clay becomes organoclad clays, marble becomes surface modified and micronized grades of
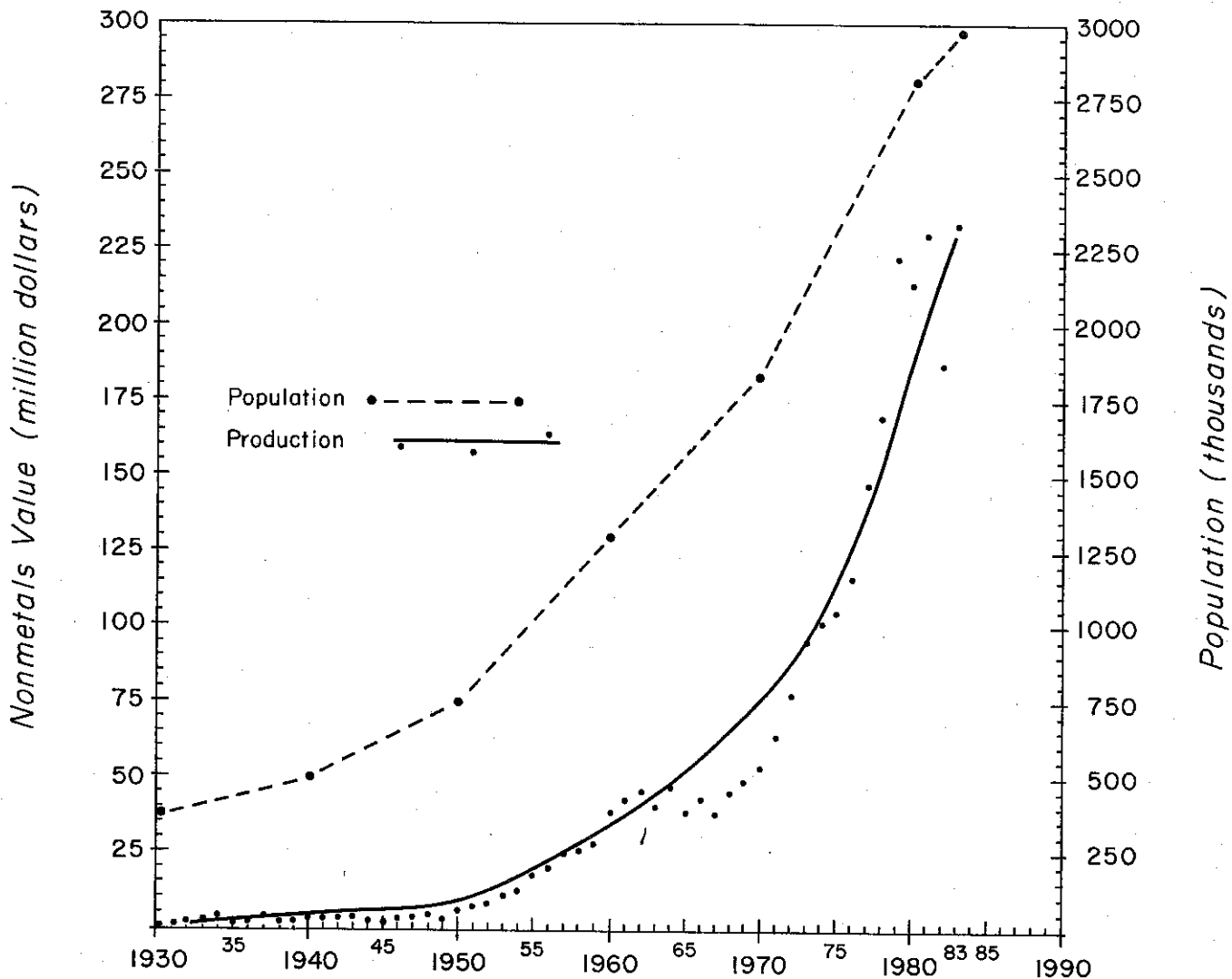
Figure 1. Annual value of nonmetals (exclusive of fuels) produced in Arizona - compared to population, 1930-1983.

calcium carbonate, perlite becomes specialty filler and filtration grades of perlite, and salt becomes high-purity salt. The selling prices of these mineral commodities range from $40 per ton for high-purity salt to over $2,000 per ton for organoclad clays.

Bates (1969) reissued his textbook with an expanded list of references; later Harben and Bates (1984) revised Bate's original classification in a book entitled *The Geology of the Nonmetallics.* Harben and Bates (1984) recognized that recent developments in the industrial minerals industry revealed several main points.

1. More rigid specifications are required by the consuming industries.

2. More elaborate processing techniques are available.

3. More sophisticated applications and new end uses have developed.

Though the revised classification of Harben and Bates (1984) summarized in Table 3 remains geological, it avoids categorizing the low unit-value nonmetallics as industrial rocks and the high unit-value nonmetallics as industrial

minerals, unlike the earlier classification of Bates (1969). Instead, the newer classification recognizes the changing role of industrial minerals in a developing world economy and allows for the continuing shift away from low unit-value nonmetallic commodities to high value-added and processed industrial minerals that could also be categorized as specialty chemical products.

Geological classifications can assist in the discovery of deposits. Grouping industrial minerals according to a geological classification that reflects their genesis is unquestionably useful for mineral exploration. The genesis of specific industrial mineral deposits provides an excellent regional exploration tool when combined with the age of the deposit. For example, the most productive chrysotile asbestos deposits occur in dolomites or ultramafic complexes of Precambrian age. Therefore, in Arizona, an exploration program for chrysotile should focus on mountain belts with exposures of the Mescal Limestone and diabase of the Precambrian Apache Group, which is where all known chrysotile deposits occur in Arizona.

Table 1. Domestic production of 17 commodities in 1931, 1932, and 1981 with percent change in production from 1931 to 1932 and 1931 to 1981.

Commodity	1931	1932	% Change from 1931	1981	% Change from 1931
Industrial					
Asbestos	2.9	3.2	+10 %	81.0	+2693 %
Barite	191	121	−37 %	2,177	+1040 %
Boron	162	165	+2 %	680	+320 %
Bromine	4.0	2.6	−35 %	196	+4800 %
Cement	21.4 Mt	13.0 Mt	−39 %	66.2 Mt	+209 %
Feldspar	149	106	−29 %	626	+320 %
Fluorspar	48.5	22.9	−53 %	104	+114 %
Lime	2.5 Mt	1.7 Mt	−32 %	17.5 Mt	+600 %
Mica	6.4	6.7	+5 %	111	+1634 %
Sodium Carbonate	71.2	50.2	−29 %	7,575	+10,539 %
Sodium Sulfate (nat.)	29.5	29.2	−1 %	540	+1731 %
Sulfur	2.16 Mt	0.90 Mt	−58 %	12.4 Mt	+474 %
Agricultural					
Phosphate Rock	2.62 Mt	1.74 Mt	−34 %	57 Mt	+2076 %
Potash	121	129	+7 %	2,150	+1677 %
Other					
Gypsum	2.3 Mt	1.2 Mt	−48 %	10.9 Mt	+374 %
Salt	6.7 Mt	5.8 Mt	−13 %	35.8 Mt	+434 %
Sand and Gravel	139.0 Mt	80.7 Mt	−42 %	689 Mt	+396 %

Domestic production figures from the U.S. Bureau of Mines (1933a; 1933b) and Lefond (1982).
All tonnages in kilo tonnes unless otherwise indicated.

Table 2. Per capita domestic production of selected industrial minerals in 1931 and 1981.

	1931	1981	% Change
Asbestos	0.05 lbs.	0.8 lbs.	+1500 %
Barite	3.4	21.4	+529 %
Boron	2.9	6.7	+131 %
Bromine	0.07	1.9	2614 %
Cement	378	651	+72 %
Feldspar	2.6	6.16	+137 %
Fluorspar	0.86	1.0	+16 %
Gypsum	41	107	+161 %
Lime	44	172	+291 %
Mica	0.11	1.1	+900 %
Na Carbonate	1.3	74.5	+5631 %
Na Sulfate	0.5	5.3	+960 %
Phosphate	46.2	560	+1112 %
Potash	2.14	21.2	+891 %
Salt	118.5	352	+197 %
Sand and Gravel	2,455	6,779	+176 %
Sulfur	38	122	+121 %

Domestic production figures from the U.S. Bureau of Mines (1933a; 1933b) and Lefond (1982). Population figures for 1932 (124,840,000) and 1980 (224,066,000) were used in the calculations.

Discovering a deposit of industrial minerals does not guarantee a profitable operation. Therefore, it is equally important to recognize the potential end-use applications of industrial minerals. Charles H. Kline published a classification for industrial minerals based on their end-use applications (Kline, 1970). The classification groups industrial minerals into the two categories of chemical minerals and physical minerals.

1. CHEMICAL MINERALS	2. PHYSICAL MINERALS
Chemical raw materials	Structural minerals
Fertilizer raw materials	Filler and extender
Chemical process aids	pigments
Ceramic raw materials	Process aids
Metallurgical fluxes	Absorbents, carriers, and parting agents

Some industrial minerals are both chemical and physical minerals. Barite is a chemical raw material when it is converted to barium carbonate for use in glass radiation shields in television sets. It is a physical mineral when used as a process aid to add weight to drilling fluids or as a pigment extender in paints. Silica is a chemical mineral

Table 3. Classification of nonmetallics.

IGNEOUS	SEDIMENTARY	SURFICIALLY ALTERED	METAMORPHIC
Intrusive	**Clastic**	Vermiculite	Marble
		Manganese minerals	Slate
Olivine	Sand and gravel	Bauxite	Asbestos
Chromine	Sandstone	Iron oxide	Talc
Nepheline syenite	Clays	Tripoli and novaculite	Magnesite and
Granite	Titanium and zir-	Zeolites	magnesia
	conium minerals		Graphite
Pegmatitic and	Rare-earth minerals		Corundum and emery
hydrothermal	Diamonds		Garnet
			Wollastonite
Mica	**Biogenetic**		Sillimanite minerals
Quartz crystal			Pyrophyllite
Lithium minerals	Limestone and dolomite		
Beryllium minerals	Diatomite		
Fluorspar	Phosphate rock		
Feldspar	Sulfur		

Extrusive   **Chemical**

Basalt and related rocks	Barite	Potassium minerals
Pumice and scoria	Salt	Borates
Perlite	Sodium carbonate	Celestite
	Sodium sulfate	Nitrates
	Nahcolite and dawsonite	Bromine
	Gypsum	Iodine

when used as a metallurgical flux and is a physical mineral when used as a pigment extender in reflective paints. This grouping by end-use application is determined by the mineralogy and morphology of the specific industrial mineral.

Grouping industrial minerals by end-use applications may seem superfluous. However, industrial minerals such as perlite and wollastonite, which 30 years ago were only mineral curiosities, are now used as fillers and process aids because the shape, size, and nonreactivity of the mineral particles make them suitable for filler and filtration applications that were recognized and then enhanced by sophisticated processing techniques. Some industrial minerals are site specific because of unique physical or chemical characteristics that occur only at a specific deposit.

The zeolite mineral chabazite from the Bowie deposit, for example, is used as a specialty adsorbent. This application developed because it has a higher silica content that increases its acid resistance and also because its microcrystallinity results in a large surface area which promotes rapid adsorption and desorption of liquids and gases (fig. 2). These special properties led to the use of chabazite from the Bowie deposit as a physical and chemical process aid marketed by the Linde Division of Union Carbide Corporation as its specialty adsorbent AW-500 molecular sieve. It is used in pressure-swing-adsorption installations that treat sour natural gas to remove water, carbon dioxide, and hydrogen sulfide from methane.

PRODUCTIVE INDUSTRIAL MINERALS DEPOSITS IN ARIZONA

During the 25-year period between 1960 and 1985 at least 14 industrial minerals were produced from deposits in Arizona (fig. 3). Production of two industrial minerals ceased during this period. The discontinued operations include the feldspar mine and grinding plant at Kingman and the chrysotile asbestos mines and processing plants near Globe. However, during the same 25-year period, production began at the high-alumina clay deposits at Pantano and near Clay Springs, a hydrafrac sand deposit near Houck, a zeolite deposit near Bowie, marble deposits near Tucson, and a salt deposit near Litchfield Park.

The feldspar mine and plant at Kingman closed because the reserves of feldspar and coproduct quartz that were exploitable by surface mining were approaching depletion. The grinding plant in Kingman, which operated on stockpiled quartz for several years after the mine closure, was closed partly because the plant would require substantial modification to meet standards for free silica in airborne particulates. Closure of the chrysotile asbestos operations in Globe was forced because of an alleged risk to persons not employed by the industry who resided at the nearby Mountain View Mobile Home Park (Peirce and Garcia, 1983).

Mining and processing operations for industrial minerals face two threats to their continued operation. The first threat is that urbanization, recreational uses, and scenic

Figure 2. Chabazite (long chains of individual crystals) approximately 0.2 microns in size and clinoptilolite (larger coffin-shaped crystals) from the Bowie chabazite deposit.

values are usually accorded a higher priority than the development and production of industrial mineral resources. Thus, industrial mineral deposits become locked up in wilderness areas or are designated as public nuisances and forced to close when their surroundings are urbanized.

The second, and even more serious, threat is the policy initiated by the Occupational Safety and Health Administration (OSHA) to place all of the estimated 152 minerals that have fibrous varieties under a single standard for fibrous minerals based only on the size and shape of the fiber. Mineralogy, chemical composition, and surface reactivity of the minerals are not considered. Thus, minerals such as tremolite, wollastonite, and chrysotile would all be classified as asbestiform and the airborne particulates from

these minerals would be subject to stringent regulations. Imposition of a single standard for fibrous minerals would be tantamount to legislating against the crust of the earth and would result in the permanent closure of many mines, quarries, and gravel pits (Thompson, 1984). This situation underscores the importance of quantitative mineralogy in monitoring not only processing plant feed and product quality but also liquid and solid waste products and particulate emissions.

Aggregate

Aggregate is the most important industrial mineral produced in Arizona, and is exceeded in tonnage and value only by copper. Most of the aggregate produced in Arizona
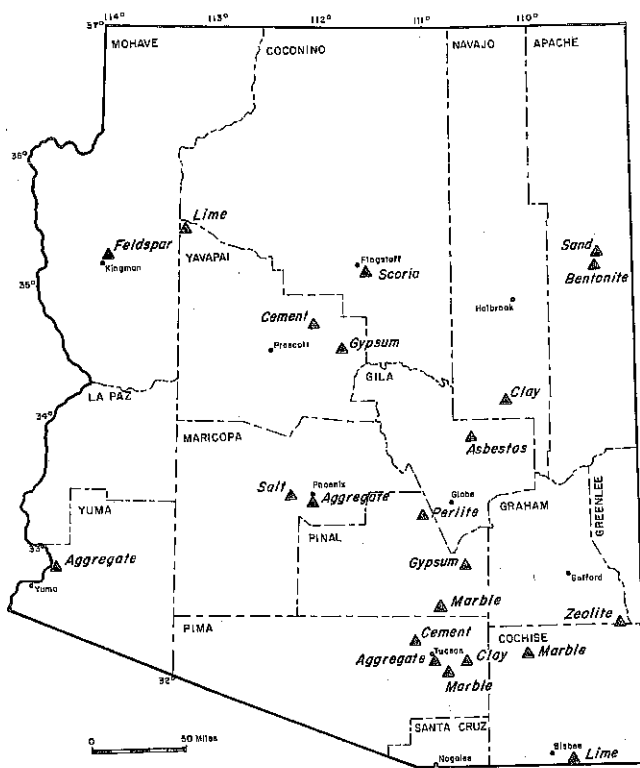
Figure 3. Major Arizona industrial minerals deposits productive between 1960 and 1985.

is sand and gravel. It is classified by origin as a clastic sedimentary rock and by end use as a physical mineral, whether it is sand, gravel, or crushed stone. When used in concrete or asphalt, aggregate is a structural mineral that increases the strength of the final product. Without the addition of sand and gravel, asphalt roads would flow during hot weather and crack during cold weather.

The addition of sand and gravel to asphalt and concrete reduces their cost while improving their structural properties. Therefore, aggregate used in either application must possess a high compressive strength and must contain the proper mix of size fractions. In addition, to promote bonding with the concrete or asphalt, the aggregate must be crushed and washed to produce fresh, clean fracture surfaces. And finally, the aggregate should not be reactive. Large amounts of silicic volcanic rocks in concrete aggregate can cause serious complications associated with moisture retention in the massive sections of concrete needed in large structures (Migues, 1985).

In Arizona most construction aggregate consists of sand and gravel mined from stream deposits or from terrace gravels near urban areas. Most production comes from gravel pits along the Salt and Agua Fria Rivers in the Phoenix metropolitan area and along the Santa Cruz River or its tributaries in the Tucson metropolitan area. In the Phoenix area sand and gravel deposits are characterized by an excessive quantity of coarse fraction, whereas in the Tucson area the deposits contain an excessive amount of the fine sand fraction (Eyde and Dresher, 1977).

Most other aggregate operations in smaller communities exploit deposits of sand and gravel in dry stream channels or alluvial deposits along the mountain ranges. Frequently, the quality of concrete or asphalt products containing aggregate from these deposits is poor. Although sand and gravel are the most abundant industrial mineral commodities in Arizona, few deposits are suitable sources of nonreactive aggregate for large concrete structures (Migues, 1985).

The sand and gravel deposits in both Tucson and Phoenix contain fragments of siliceous volcanic rocks and are therefore reactive. Consequently, sand and gravel initially used in the concrete for the Palo Verde Nuclear Generating Station had to be shipped from deposits along the San Gabriel River in California when local deposits of aggregate were discovered to be reactive. The additional shipping costs increased the cost of the concrete by $178 million above the initial estimate (Lopez, 1985). As soon as the local aggregate sources were found to be reactive, an investigation was started to locate nonreactive aggregate resources closer to the generating station. The investigation revealed a deposit of nonreactive aggregate about 150 miles west of the generating station on the western slope of the Gila Mountains north of Yuma, Arizona. This deposit supplied the bulk of the aggregate used in the construction.

Most of the large sand and gravel operations in the Phoenix and Tucson metropolitan areas produce several sizes of rock products ranging from coarse architectural gravel to fine reject sands used for back-filling foundations. Aggregate producers add value to their product by making asphalt road mix and ready mix concrete. Thus the value of the aggregate in these products is substantially higher than the $2.95 per ton indicated by the production statistics in the the U.S. Bureau of Mines mineral commodity summaries for 1985.

Aggregate producers in Arizona are facing several serious problems. First, sand and gravel resources are being urbanized. Second, the degradation of stream channels caused by the removal of sand and gravel has prompted legislation banning sand and gravel mining in stream channels. Third, the promulgation by the Occupational Safety and Health Administration (OSHA) of a single standard for airborne particulates that includes all fibrous minerals regardless of mineralogy could place severe regulatory constraints on all operations, particularly those in which the aggregate contains a high percentage of amphibole minerals. In the future more aggregate operations will probably exploit terrace gravels and some may begin mining and producing crushed stone products.

Asbestos

Asbestos was the first of the high value-added industrial minerals to be produced in Arizona. Commercial exploitation of the deposits in central Gila County began in 1913 and continued at a rate of 1,000 to 2,000 tons per year until the Jacquays Mining Corporation closed their mines and mill in 1982. The closure was the result of litigation resulting

from the presence of chrysotile in the soil of a mobile-home park near the Metate Asbestos Company mill in Globe. The asbestos controversy is described in an excellent paper by Peirce and Garcia (1983).

Chrysotile asbestos is classified geologically as a metamorphic mineral and by end use as a physical mineral. It is used as a structural mineral in specialty asphalt roofing compounds, asbestos cement pipes, high-temperature insulation and fire-resistant textiles. As an extender-filler, asbestos is used in friction products such as brake linings and other plastic resin systems. Also, asbestos is a process aid when used as a filtration media.

Processed chrysotile asbestos products from Arizona are low in iron. Consequently, the products were sold to specialty markets for high value-added products, such as high-temperature electrical insulation, plastic resin systems, and filtration media. Arizona asbestos products sold in 1981 (Asbestos, January, 1981) for the following prices in dollars per ton F.O.B. Globe, Arizona:

No. 1 crude (soft)	$3,000
AAA	2,000
Grade 32 nonferrous filtering-plastic	1,350-1,400
Grade 4 T nonferrous filtering-plastic	700-1,350
Group 7 white shorts	50-200

Product prices depend on fiber length, harshness, and iron content. Long, soft fibers command the highest prices.

The chrysotile asbestos deposits occur in the Apache Group of Precambrian age where certain beds in the Mescal Limestone are intruded by sills of diabase. Chrysotile occurs as cross-fiber veins within thin beds of serpentine. Veinlets as thin as 1 1/2 inches thick have been mined. Subtle, hard-to-recognize structures such as monoclines, domes, and folds may localize the veinlets of chrysotile (Keith, 1969a). Virtually all production came from underground workings. The chrysotile veins were carefully cobbed and sorted at the mine.

Until the regulatory climate improves it is doubtful that asbestos production in Arizona will resume. Unfortunately, the hazard of asbestos exposure has been greatly exaggerated by regulatory agencies that do not differentiate between the fibrous variety of serpentine, chrysotile, which is not a health hazard from non-occupational exposure (Ross, 1982), versus the fibrous variety of the amphibole mineral, crocidolite, which is a known carcinogen even from non-occupational exposure (Ross, 1981). It may take years before the Occupational and Safety Health Administration (OSHA) can adopt reasonable standards, because of highly politicized and emotional responses to the issue. The Occupational and Safety Health Administration (OSHA) may eventually adopt multiple standards for exposure to airborne mineral fibers based on the disease-producing potential of specific mineral dusts. These multiple exposure standards are in effect in Great Britain and other European countries.

Even if these multiple standards are adopted, reactivating the asbestos operations would require covered stockpiles, wet processing equipment, installation of dust collectors, and a negative-pressure system to prevent airborne particulates from escaping to the outside air. The cost of installing this equipment at an operation with gross sales of only $1 to $2 million a year would make reactivating the asbestos industry in Arizona unlikely.

Bentonite

Bentonite was the second of the high value-added industrial minerals to be produced in Arizona. Commercial production began at the Allentown mine in 1924. The Chambers underground mine began producing bentonite in 1926, and the surface mines at the Cheto deposit southeast of Sanders (fig. 4) began producing in 1933 (Kiersch and Keller, 1955). Most of the bentonite was used in the production of carriers for acid-activated petroleum catalysts. This end-use application increased each year until 1957, when 270,000 tons of bentonite were produced. This application of bentonite was replaced by synthetic zeolites that were introduced into petroleum refining during the mid-1950's. Consequently, bentonite production declined to the present range of 25,000 to 40,000 tons per year. The crude clays are processed in New Mexico, California, and Mississippi into high value-added desiccants, which sell for $700 per ton, and into acid-activated bentonites, thickeners, and gellants, which sell for $2,000 to $3,000 per ton.

Figure 4. The bentonite bed being mined at the Cheto deposit.

Most bentonites result from alteration of volcanic ash in lacustrine environments. Therefore, although Harben and Bates (1984) did not classify bentonite, it could be geologically classified as a surficially altered volcanic ash, as are sedimentary zeolites with a similar origin. In the end-use classification bentonite is a physical mineral used as an extender-filler where the bentonite is a thickener or gelling agent in such products as paints, printing inks, greases, and liquid soaps. Cheto bentonite is a physical mineral used as a process aid when used as acid-activated bentonite for decolorizing edible oils and as a moisture absorbent when used as a desiccant.

The Cheto bentonite deposits, which occur in the Bidahochi Formation, formed during Pliocene time in a series of interconnected lakes on the west side of the Defiance uplift. The bentonite is the alteration product of vitric ash deposited in the lakes in at least two horizons with a thickness range from less than a foot to over 10 feet. The bentonite is a remarkably pure dioctahedral montmorillonite, a member of the smectite group of clay minerals. It is a combination of the nearly monomineralic composition and unusually high surface area of the montmorillonite that produces its extraordinary sorptive properties (Eyde and Eyde, 1985a).

The most serious problem facing all of the operators in the district is the increasing depth of overburden, which now averages nearly 100 feet. Fortunately, in certain areas of the district a thick bed of hydrafrac sand occurs in the overburden. By selectively mining the sand during the stripping operations this resource can be processed into a salable product, thus reducing stripping costs.

Cement

In 1984 the two cement plants in Arizona produced 1.5 million tons of cement. The older and larger plant is operated by Arizona Portland Cement at Rillito, 18 miles northwest of Tucson. The newer plant is operated by Gifford Hill and Company, Inc. at Clarkdale, 109 miles north of Phoenix. Cement is a synthetic stone product composed of about 45 percent tricalcium silicate, 27 percent dicalcium silicate, 11 percent tricalcium aluminate, and 8 percent tetracalcium-aluminoferrite (Ames and Cutcliff, 1983).

At the Rillito plant, the primary sources of limestone are the Martin, Escabrosa, and Naco formations. The Martin Formation is also a source of silica and shale. These limestones are blended with aluminous clays from Pantano, iron ore, and gypsum from near Winkelman to manufacture cement (Rains, 1985). At the Clarkdale plant, limestone from the Redwall Limestone and limestone, dolomite, and clay from the Verde Formation are blended with slag or iron ore and with gypsum from a deposit near Camp Verde to manufacture cement.

In Arizona the U.S. Bureau of Mines (1984) ranks cement a close second to aggregate in value of production. When compared with the mined value of the limestone and other raw materials that are blended to manufacture cement, this synthetic mineral product is a good example of value that is added through processing.

Because cement is a synthetic product, Harben and Bates (1984) do not include it in their classification. Kline (1970) included cement with the physical minerals and classified it as a structural mineral. When cement is mixed with aggregate, which is another physical mineral that acts as a structural filler and adds strength to cement, the resultant product is concrete.

Most cement plants have been faced with the problem of cleaning up airborne particulate emissions. This has been done by covering stockpiles and using dust collection equipment. Even so, many cement rock quarries and plants would be faced with a serious problem in meeting more stringent, airborne particulate standards if a single standard for all fibrous minerals is promulgated by the Occupational and Safety Health Administration (OSHA), because many raw materials in cement contain acicular minerals which would be classified as fibers.

Clay

Clay used in structural applications is produced from two widely separated localities in Arizona. The high-alumina clays from the Pantano deposit southeast of Tucson are used for making bricks and also as a source of alumina in cement production at the Rillito cement plant. The kaolinitic clay mined at a deposit near Pinedale is blended with aluminous shales and other mineral additives in the fabrication of vitrified pipe. Geologically, these clays are classified as clastic sedimentary rocks. Although structural clays do not appear in the end-use classification, kaolinitic clays used in refractory and ceramic applications are categorized as ball clays, which are chemical minerals. Certainly, these clays are raw materials for ceramics and should be classified as chemical minerals.

The clays being mined near Pantano occur near the base of the Pantano Formation of late Oligocene to early Miocene age. The clay beds range in color from a light to dark reddish brown and contain veinlets of satin spar, a fibrous variety of gypsum (Pennebaker, 1959). Experience has shown that blending the Pantano clays produces bricks exhibiting a wide range of colors after firing. The Pantano clays are blended with clays from Tolleson for brick manufacturing at the Phoenix Brick Yard. The clays near Pinedale are kaolinitic underclays at the stratigraphic position of coal beds in the Cretaceous rocks (Morris, 1985). These clays do not contain calcite and therefore can be used to manufacture vitrified pipe.

Vitrified pipe and bricks are examples of value that is added by processing crude clays into fired or ceramic clay products. These ceramic products require high-purity raw materials. Thus, ceramic clays mined at Pinedale and Pantano should not be classified as common clays.

Feldspar

Feldspar production began in 1923 from a pegmatite deposit in Precambrian granitic rock on the east side of the Cerbat Mountains north of Kingman. After over 50 years of production, the Taylor mine suspended operations in the late 1970s when reserves available for surface mining were depleted. The milling facility operated until 1984 by grinding quartz that had been stockpiled as a byproduct of the feldspar mining operation. The geological classification lists feldspar as an igneous intrusive mineral and the end-use classification lists it as a chemical mineral used as a ceramic raw material.

Most of the feldspar produced from the Kingman operation was sold as a ceramic raw material. However,

during the final years of operation some of the feldspar and all of the quartz were sold for use as abrasives in scouring powders. In this application both feldspar and quartz were physical minerals used as process aids.

It is doubtful that the feldspar mining and processing operation will resume unless the grinding plant is modernized and 'dust-collection equipment is added. Further, the mine would require a major exploration program to evaluate the remaining feldspar resources. Even if sufficient reserves are discovered, a major stripping program would be required before feldspar production could resume.

Gypsum

Gypsum is produced from two widely separated deposits located in central and southern Arizona. Most of the gypsum production in Arizona comes from a deposit on the east side of the San Pedro Valley about 6 miles south of Winkelman, Arizona. In 1984 the district produced about 200,000 tons of gypsum used in wall board, Portland cement, and soil conditioners. A gypsiferous zone occurs within a fine-grained facies of the Gila Conglomerate of Pliocene age (Krieger, 1968; Keith, 1969b). Based on information from outcrops and drill holes, the basin is known to occupy at least 18 square miles, principally along the east side of the San Pedro River. The lacustrine section strikes N. 50° W. and dips 3 to 7° NE. (Hardas, 1966). An exploration hole drilled to evaluate one of the deposits intersected a continuous 300-foot thickness of interbedded clay and gypsum. Stratigraphic correlations between drill holes indicate that the section of interbedded clay and gypsum may be over 595 feet thick (Shearer and Wilt, 1985).

Aravaipa Creek bisects the deposit. North of the creek a zone that is 30 to 50 feet thick consisting of massive gray gypsum with clay partings is being mined by National Gypsum Company and the Superior Companies. South of Aravaipa Creek the Pinal Mammoth Gypsum Company mines a surficial deposit of gypsite, which has an average thickness of 5 feet.

The gypsum must be drilled and blasted at both the National Gypsum Company mine and the Superior Companies operation. The broken gypsum is loaded and hauled to crushing plants where the minus 3/8-inch fraction is screened off. At both operations the final product contains 90-92 percent gypsum and less than 4 percent insolubles.

The Superior Companies ship gypsum to the Arizona Portland Cement Company at Rillito where it is used as a cement retardant. National Gypsum Company ships gypsum to their wallboard plant in Phoenix. Crude gypsum used as a cement retardant sells for $8 per ton F.O.B. the mine, whereas in 1985 wallboard sold for the equivalent of $50-$80 per ton of gypsum.

The Pinal Mammoth Gypsum Company is the major producer of agricultural gypsum in Arizona. Gypsite containing 70 to 80 percent gypsum is scraped from the surface and pushed into stockpiles with a dozer. The crude gypsite is hauled to a screening and bagging facility at Coolidge, Arizona. The screened gypsite is spread on croplands, golf courses, and parks to reduce soil alkalinity.

The gypsum deposit being mined in central Arizona is located southeast of Camp Verde and occurs in the Verde Formation of late Miocene age. The thick gypsum-bearing zone exposed at the mine may be over 100 feet thick. The gypsum is crushed and screened to remove the clay fraction before it is shipped to the cement plant at Clarkdale.

Geologically, gypsum is classified as a chemical precipitate. Gypsum can be classified according to end use as both a physical and a chemical mineral. As a physical mineral gypsum is used in wallboard and joint cements. Both natural and synthetic gypsum are used as a filler with high-aspect ratios in resin systems as a substitute for asbestos (Kusakawa, 1982). As a chemical mineral, gypsum is used as a soil conditioner in alkaline soils and as a chemical process aid when used as a cement retardant. Gypsum production will continue to increase in Arizona as more homes and offices are built to accommodate a growing population. Most gypsum is consumed in construction applications in wallboard, joint compounds, and cement.

Limestone and Marble

Limestone and marble are grouped together because both are utilized in many of the same end-use applications. Crushed limestone and marble are used for road gravel, railroad ballast, concrete, asphalt and architectural aggregate, and dimension stone. Both limestone and marble are used as flux stone and are calcined into lime products.

Lime, which is produced by calcining limestone, is one of the major industrial minerals produced in Arizona. It is exceeded in tonnage and value only by aggregate and cement. At the Nelson quarry east of Kingman, the Redwall Limestone is the source of limestone for their horizontal kilns (Henderson and Collins, 1978). At the Paul Spur operation west of Douglas, the Mural Limestone of Cretaceous age is the source of limestone for their vertical and horizontal kilns. Several of the copper mining and milling complexes have produced limestone for both flux rock and calcined lime from deposits on their properties. However, none of these were operating in 1985.

At both Nelson and Paul Spur the limestone is carefully explored by drilling to avoid zones of chert and dolomite. Chemical-grade lime products must be 93.25 to 98.00 percent calcium oxide, which demands stringent quality control during mining operations (Boynton and others, 1983).

Geologically, limestone is classified as a biogenetic sedimentary nonmetallic mineral. Based on end use, lime is a widely used chemical mineral. It is used as a chemical raw material in the production of glass, soda ash, sodium bicarbonate, calcium carbide, and bleaches. Lime is a fertilizer raw material when used to treat acid soils. It is a

chemical process aid in sugar refining, in the flotation of sulfide minerals at metal mining and milling operations, in paper mills, and in other manufacturing processes. Limestone is both a ceramic raw material and a metallurgical flux. When used in lime-cement mortars and plaster, lime can also be classified as a structural mineral.

Much of the lime produced in Arizona is used as a chemical process aid to adjust the pH of the feed in the flotation cells used to concentrate sulfide copper minerals in milling operations. The other major and growing use is in lime scrubbing units, which remove sulfur dioxide from the stack gases at coal-fired power plants. Limestone is used as flux rock at copper smelters.

Marble used as an architectural aggregate is now being produced from deposits in the southeastern part of the state. These operations exploit marmarized Paleozoic limestones in contact with Cretaceous or Tertiary intrusions. In 1985 the three producers were the Dragoon Marble Company operating the Ligier deposit south of Dragoon, the Andrada Marble Company operating the Andrada deposit in the Santa Rita Mountains southeast of Tucson, and the Catalina Marble Company operating a deposit in the Tortolita Mountains west of Catalina. The marble at the Ligier deposit is marmarized Missippian Escabrosa Limestone (Cooper and Silver, 1964), as is the Andrada deposit (Townsend, 1962). The Catalina deposit is developed in marmarized roof pendants of Permian Concha Limestone.

The marble from these deposits is used for architectural aggregates in applications such as roofing granules, terrazzo, ground cover, and concrete facing panels. At the quarries the marble is sorted by color and then crushed to the size required for the specific end-use application. Marble used in applications where it is exposed to weathering cannot contain pyrite, which alters to limonite and stains the marble.

Sales of crushed marble are closely related to building activity. In an area growing as rapidly as southern Arizona, the consumption of crushed marble will continue to grow. Nevertheless, improvements in roofing materials such as foam and reflective coatings, which are both lighter and more energy efficient than marble decorative stone, have reduced the consumption of marble for this application. The consumption of marble for ground cover in residential areas will continue to increase as the cost of watering lawns increases.

Contact metamorphic deposits of marble such as those in Arizona should be carefully evaluated for the presence of tremolite. Often tremolite is difficult to identify in high-purity white marble, particularly in the fine-grained varieties. Because of its high aspect ratio and fibrous habit, the Occupational Safety and Health Administration (OSHA) has classified tremolite as asbestiform (C.S. Thompson, 1984). Clearly, the presence of excessive amounts of tremolite in marble could increase the

producer's potential exposure to lawsuits because of product liability.

Perlite

The first commercial production of perlite in the United States came from deposits on the east side of Picket Post Mountain southwest of Superior, Arizona. In 1984 the district produced an estimated 50,000 tons of sized perlite in unexpanded and crude form.

Perlite is mined from the perlite facies of the Arnett rhyolite of Tertiary age (Crosswhite, 1984). The perlite horizon that is mined ranges from 5 feet to more than 100 feet thick. Guzman Construction Company produces crude crushed perlite for processing in Arizona. The Harborlite and Silflo companies crush, screen, and dry the perlite in processing facilities west of Superior. The sized perlite products are shipped out of state for expansion, or "popping," into a light-weight cellular aggregate (Kadey, 1983).

Geologically, perlite is classified as an extrusive igneous rock. According to end use, perlite is classified as a physical mineral. It is a structural mineral when used as a light-weight aggregate in concrete and in prefabricated, light-weight roofing panels and board that are used in commercial building construction.

The expanded products, depending on the particle size and density, are used in formed construction products such as ceiling tile, roof insulation board and pipe insulation, in horticultural aggregate, in loose fill-insulation, and in light-weight aggregate. Several high value-added products are prepared by grinding and sizing the expanded perlite. These include filter aids and fillers. Attrition milling of the expanded product comminutes the perlite particles into a cellular filler with a high aspect ratio and a low bulk density. Surface-modified perlite is now used as a filler in engineering plastics.

Sized, unexpanded perlite sold for $39 per ton F.O.B. the plant in 1985. The expanded products sold for $165 per ton. The attrition-milled products with high aspect ratios sold for over $250 per ton. Perlite is an excellent example of how value can be added by additional processing.

Salt

The Luke salt body, which underlies Litchfield Park near Phoenix, is exploited by solution mining. The salt deposit is of late Miocene age and was deposited between 15 Ma and 10 Ma as the salt is overlain by a volcanic flow dated at 10 Ma (Shafiqullah and others, 1980). The Luke salt body is more than 3,500 feet thick, and, although its complete lateral extent is not known, it may contain as much as 30 cubic miles of salt (Pay Dirt, 1984). The halite was deposited as an evaporite facies in a local structural basin (Peirce, 1976, 1981), although there appears to be evidence of some upward salt movement (Peirce, 1974). The Luke salt body is composed of nearly pure halite, which contains only traces of the blocking ions magnesium and calcium.

Geologically, salt is classified as a chemical nonmetallic. Classified by end use it is a chemical mineral when used as a chemical raw material or chemical process aid.

In 1985 the operation at the Luke salt deposit was the only producer in Arizona. Morton Salt Company, which purchased Southwest Salt Company in 1985, uses solution mining to produce brine from the deposit. Solar ponds concentrate the brine to a saturated solution. In this environment the salt precipitates to form a layer of salt on the bottom of the ponds; this layer is then removed by a salt-harvesting machine. The crude salt is brine-washed to remove the insolubles and traces of magnesium and calcium and then is allowed to dry (Grott, 1985a). It is shipped in bulk or bags to the users.

The salt, because of its low magnesium and calcium content, is a specialty product which sold for $40 per ton in 1985. It is a chemical raw material when used to produce chlorine for swimming pool chemicals and is a chemical process aid when used in fluids for tertiary oil well recovery and in additives for domestic and industrial water softeners.

Chemical raw materials with higher purity are being demanded by the consuming industries. Today the cost of disposing of the waste brines from chlorine production often exceeds the cost of the raw materials. The amount of waste products generated can be reduced significantly by using chemical raw materials with higher purities. This in turn reduces manufacturing and processing costs. At the Luke salt deposit three solution cavities are now leased to Cal Gas for storage of propane and butane. All the waste brine and solids from the brine washing operation are reinjected into the salt through an injection well.

Sand

Sand production from deposits in the Houck area in northern Arizona began in 1961. Although sand is a mineral resource believed to occur almost everywhere, deposits of sand suitable for use as a proppant in hydraulically fractured strata in oil and gas wells are uncommon. The deposits of proppant sands near Houck were derived from eolian sandstones of Permian age that were reworked in a deltaic environment where streams draining the Defiance Plateau entered a series of lakes along its west side. The sands are confined to the Bidahochi Formation of Pliocene age (Eyde and Eyde, 1985a).

These sand deposits would be classified geologically as clastic sedimentary nonmetallics. Kline (1970) did not have a category listed for hydrafrac sands. However, proppant sand is a physical mineral that could be classified as a structural mineral because it props the fractures open to allow oil and gas to flow into the well bore.

Most of the hydrafrac sand produced near Houck is in the minus 20—plus 40 mesh size fraction. It contains about 97 percent silica, has a roundness of 0.6 to 0.7 on the Krumbein scale and has a low acid solubility. Oil well service companies use about 40,000 tons of sand from Houck per year completing oil and gas wells in the

Farmington, New Mexico area (Norman, 1979). This is a high-value-added, specialty sand product, which in 1984 sold for over $25 per ton.

Production from the deposit at Houck is restricted because homes have been constructed on the westward extension of the deposit. Similar sand deposits overlie the bentonite deposits at the nearby Cheto bentonite deposit. These deposits may ultimately provide sand for the plant at Houck.

Scoria

Scoria is the mafic counterpart of pumice and forms many volcanic cinder cones. This pyroclastic material is rusty red to black in color and has an andesitic to basaltic composition (Harben and Bates, 1984). Scoria, referred to as pumicite (Keith, 1969c), has been mined in the Flagstaff area for many years. Scoria is geologically classified as an igneous extrusive and is classified by usage as a physical mineral used in structural applications. Because of its high porosity and light weight, scoria is used extensively in manufacturing lightweight concrete cinder blocks.

Blocks made from scoria must have an acceptable compressive strength. One major advantage of using basaltic and andesitic scorias in concrete blocks is that basic volcanics are less likely to be reactive aggregates that could cause deterioration of the blocks. Therefore only a few deposits contain scoria that can be used for the aggregate in lightweight blocks. The principal problem encountered in scoria production has been the perception by the public that all scorias are identical. This has resulted in attempts to stop the mining of scoria of good quality in highly visible areas.

Zeolites

Zeolites have been mined since 1961 from a deposit of chabazite north of Bowie, Arizona (Eyde, 1978, 1982). This is the largest known deposit of high-purity chabazite in the United States, if not the world.

Geologically, sedimentary zeolites would be classified as surficially altered minerals. Zeolites are physical minerals when used as process aids in adsorption, catalysis or cation exchange applications. The chabazite from Bowie is used mainly as a specialty adsorbent for treating sour natural gases. It has also been used to remove by cation exchange the radioactive isotopes cesium-137 and strontium-90 from nuclear reactor waste streams (Sheppard and others, 1978).

The principal producer of chabazite from the Bowie deposit is the Linde Division of Union Carbide Corporation. Their molecular sieve product AW 500 is a specialty adsorbent used to remove carbon dioxide, water, and hydrogen sulfide from methane. Their ion exchange products are IE 95, a sodium-modified natural chabazite ion exchange product, and IE 96, a natural high-sodium ion exchange product. A combination of Linde Ionsiv A-51, a synthetic zeolite, and IE 96 were used to remove radioactive cations from the water in the basement of the reactor building at Three Mile Island, Pennsylvania (Collins and

others, 1982). In 1985 AW 500 sold for $2.50 a pound and the IE 95 and IE 96 for the somewhat higher price of $7.50 per pound (Eyde and Eyde, 1985b).

The zeolite horizon is a vitric tuff that altered to the minerals chabazite, erionite, and clinoptilolite in a saline-alkaline lake. It is enclosed in the Green Lake Beds, which are believed to be of Pliocene-Pleistocene age. The deposit is exploited by surface mining techniques that recover the lower massive or "high grade bed," which is about half a foot thick. All production is shipped out of state for grinding prior to extrusion and activation. The deposit supplies a growing market for specialty adsorbent and ion exchange products.

FUTURE DEVELOPMENTS

Increases in both the standard of living and the population in the southwestern United States will certainly stimulate the demand for industrial minerals. Both the quantity and type of industrial minerals produced will increase. Exploration for deposits of specialty clays, such as the bentonites used as viscosifiers and stabilizers, in acid-activated products for edible oil clarification, and as desiccants, will increase. So too, will exploration for extender-filler minerals such as wollastonite and mica. The demand for high-purity salt and sodium sulfate will also increase as the cost of disposing of waste brines increases.

Research into utilizing the storehouse of previously ground mine tailings will increase. For example, one of the

largest resources of rutile, which is used in the manufacture of titanium dioxide pigments, is the tailings pile at San Manuel (Force, E.R., 1981). These tailings also contain extensive resources of quartz, mica, and feldspar, all of which may be convertible into marketable products as high value-added industrial minerals.

The only cloud on the horizon is the effect of public land and environmental policy on the exploration, development, and production of industrial minerals. Valuable deposits of industrial minerals are often not recognized and as a result are included in wilderness areas or are urbanized and therefore become unavailable as resources. Equally serious is the attempt to establish a single standard for airborne particulates that includes all minerals that have fibrous varieties. Strict imposition of this standard would be a disasterous attempt to legislate against using most of the Earth's crust. The 152 minerals that have acicular varieties would all be considered asbestiform based entirely on particle shape (Harben, 1980). Imposition of this standard would close many mines, quarries, and gravel pits and result in significant increases in the prices of mineral products marketed by the remaining producers.

With reasonable land use and environmental regulation, the production of industrial minerals in Arizona will continue to increase. Assuming this occurs, the value of industrial minerals production could exceed that of copper by the end of the century.

Figure 5. Major Arizona industrial minerals deposits which may be productive in the future.

DEPOSITS OF INDUSTRIAL MINERALS IN ARIZONA THAT MAY BE PRODUCTIVE IN THE FUTURE

Bentonite

A major deposit of high-magnesium bentonite occurs along both sides of Burro Creek about 8 miles west of Bagdad (fig. 5). Several bentonite horizons occur within a tilted section of Miocene lacustrine beds. The bentonite horizons contain both saponite and trioctahedral smectite clay. The highest purity smectite and saponite occur near the contact of linear masses of travertine that appear to be localized along faults. The bentonites apparently result from alteration of lacustrine beds by thermal spring waters. Chalcedony and dolomite concretions occur within the saponite and smectite horizons.

This bentonite would be classified as a surficially altered industrial mineral. The parent bentonite apparently results from alteration of a volcanic ash that was subsequently altered by hydrothermal solutions. The bentonite would be classified as a process aid on the basis of its end use as a thickener and stabilizer.

Because of its high brightness, color, and purity, the near white-colored bentonite clay along Burro Creek has potential applications as a high-unit-value thickener and stabilizer for use in paints, greases, pharmaceuticals, and
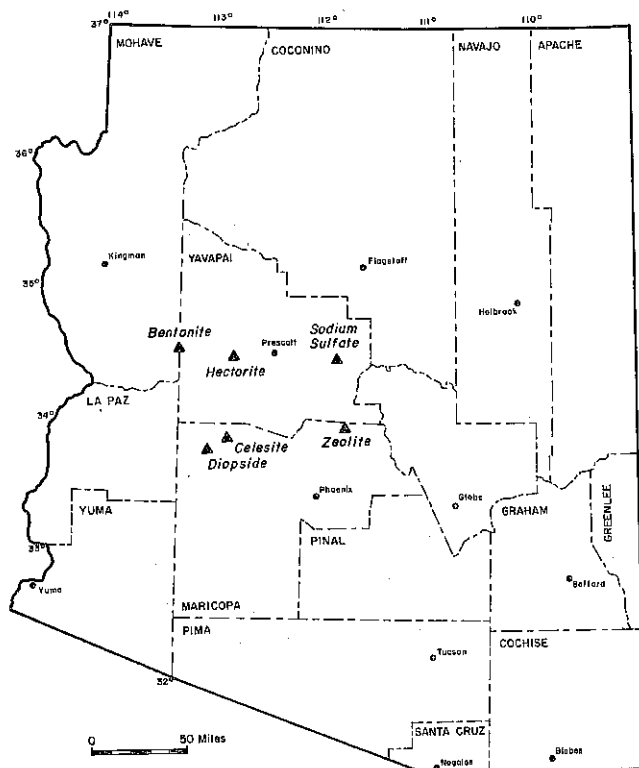
cosmetics. The bentonite is reported to have commercial potential as a raw material for producing stabilizers and thickeners with relatively unsophisticated treatment (Schreiner, 1985).

The deposit is adjacent to and within the Lower Burro Creek Wilderness Study Area. The final location of the permanent boundary of the area will determine whether that portion of the deposit on the west side of Burro Creek will be brought into production.

Diopside

A unique deposit of diopside occurs about 18 miles south of Aguila near Sunset Canyon in the Harquahala Mountains (fig. 5). The diopside occurs in a contact-metamorphosed section of Paleozoic limestone. An exposure of the diopside bed in a pit indicates that the bed consists of a 12 foot-thickness of coarsely crystalline white diopside. The bed strikes east and dips about 20° N. and can be traced several hundred feet along strike (Matson, 1985).

According to Funnel and Wolfe (1964, p. 98) the diopside deposit was known as the Yellow Flower mine. Diopside from the deposit was shipped to California for use in ceramics (Davis, 1967, p. 148). The deposit has not been productive for many years.

Diopside is a metamorphic mineral whose end-use application is as a chemical mineral in ceramics. Because of its chemical composition, calcium and magnesium silicate, and its fibrous habit, diopside apparently improves the thermal shock resistance of ceramics. R. T. Vanderbilt Company, Inc. has considered producing diopside from a small deposit at their Gouverneur talc deposit in New York for specialty ceramic applications (Thompson, 1985). The Yellow Flower diopside deposit could also be developed as a source of a specialty ceramic raw material.

Celestite

An important deposit of celesite occurs in the Vulture Mountains about 15 miles south of Aguila near Black Butte (fig. 5). The celestite-bearing beds, which are at least 156 feet thick, occur in a west-dipping section of Miocene lacustrine beds. Both the massive and shaly horizons contain celestite. Two samples collected at the deposit contained 85.3 and 73.1 percent celestite (Moore, 1936). Three samples of individual beds, ranging from 3 to 10 feet thick, were analyzed by Chemical Products Corporation and found to contain 61.4, 73.1, and 69.9 percent celestite (Bearden, 1983). The celestite appears to be fine-grained and would require fine grinding prior to flotation.

The celestite deposit appears to be an evaporite, which Harben and Bates (1984) classified as a chemical nonmetallic. The end-use applications of the celesite after conversion to strontium carbonate are in glass radiation shields on color television sets and in permanent magnets, greases, soaps, lubricants, and paints. In these applications celestite is classified as a chemical mineral.

The Black Butte celesite is one of the major celestite resources in the United States. Nevertheless, its purity is much lower than the productive deposits in Mexico, Turkey, and Spain. Development of this deposit is being considered to provide an alternative source of celestite in the event foreign supplies are cut off.

Hectorite

The Lyles hectorite deposit (fig. 5) is one of only three deposits producing hectorite in the United States. Other hectorite deposits include the N.L. Chemicals operation at Hector, California, and the Industrial Minerals Ventures (IMV) operation at Imvite, Nevada, which is a subsidiary of Gulf Resources and Chemical Corporation. Sometime during the mid 1950s Joseph Lyles of Yarnell discovered that clay from the Arizona deposit contained detectable amounts of lithium. He brought the property to the attention of E. T. Turley of Phoenix, Arizona, who explored the deposit with pits and auger holes. Later Turley mined hectorite for use as a sealant for irrigation ditches and stock ponds (Norton, 1965).

The James Stewart Company of Phoenix was interested in the deposit as a source of lithium and acquired the deposit during the early 1960s. In 1982 GSA Resources acquired the deposit and began a drilling program to evaluate the hectorite deposit. Bulk sampling and pilot-plant testing were completed in 1985. The first shipment was made from the deposit to a specialty clay producer in 1986.

The deposit would be classified by Harben and Bates (1984) as a surficially altered deposit. The hectorite horizon is interbedded within a section of lacustrine clays that are at least 70 feet thick; this clay section is overlain by a 1 to 2 foot-thick bed of vitric tuff that is zeolitically altered to phillipsite. Another bed of vitric tuff that is zeolitically altered to clinoptilolite occurs below the hectorite bed. The zeolite beds are excellent marker horizons.

The hectorite bed is 8 to 35 feet thick. It is both overlain and underlain by high-alumina smectites. The color of freshly mined hectorite ranges from a translucent waxy white to light yellowish white. In fact, much of the hectorite actually resembles white candle wax (fig. 6).

Figure 6. Loading supersacks at the Lyles hectorite deposit.

The hectorite horizon contains large concretions of chalcedony and dolomite. A travertine mass crops out in the valley along the east side of the deposit. The relationship between travertine masses and high-magnesium smectite has been noted at both the Imvite and Hector deposits as well as at other deposits of saponite and high-magnesium smectite.

The hectorite appears to be a hydrothermal clay deposit that formed when thermal spring waters rich in magnesium were introduced into the normally high-alumina smectite clays in the lacustrine beds. The existence of the thermal springs is strongly suggested by the travertine deposits, which are usually linear, veinlike structures. The hectorite bed may be the result of magnesium metasomatism of a high-alumina smectite clay horizon. The silica and dolomite concretions may indicate the migration of thermal waters through the hectorite bed.

Hectorite is a physical mineral when used as a thickener and viscosifier in many products such as paints, saltwater drilling muds, and liquid shampoos. Some hectorite products are organoclad with quaternary compounds to make the hectorite organophyllic. Organoclad hectorite is used in thickeners and viscosifiers in oil-based paints, greases, oils, and oil-based drilling muds. In 1985 organoclad clay products, such as the Bentones and Benagels produced by N. L. Chemicals, sold for over $1.00 per lb.

Sodium Sulfate

The Camp Verde sodium sulfate deposit has been known for at least 2,000 years. In fact, it may be the oldest mine in the State of Arizona. Evidence of pre-Columbian activity, which included artifacts and the mummified remains of a miner, were discovered when the mine was operated during the 1920s. The Spanish explorers Antonio de Espejo in 1583 and Marcos Farfan de los Godos in 1598 are both believed to have visited the mine (Bartlett, 1942).

The evaporite sequence, which consists of halite, mirabilite and glauberite, is as much as 46 feet thick at the Camp Verde salt mine. The evaporites grade into gypsum and halite in the deeper part of the basin southeast of Camp Verde (Thompson, 1983). The Superior Companies mine gypsum from a deposit in the gypsiferous facies and ship it to the Gifford Hill and Company Inc. cement plant at Clarkdale, Arizona. Aragonite crystals and needlelike pseudomorphs of glauberite can be found on the high wall along the west side of the old pit. Acicular crystals of mirabilite can be found in the drainage ditches. Sodium sulfate is classified as a chemical nonmetallic.

The Verde Formation, which hosts the evaporites, consists of at least 3,000 feet of sediments (Nations and others, 1981). It is believed the basin formed during Miocene time possibly as a result of movement along the Verde fault zone. Drainage through the south end of the valley was blocked by volcanics resulting in a closed basin in which a saline-alkaline lake formed during the Miocene.

Pliocene limestones are predominantly nonevaporitic indicating freshwater lacustrine conditions (Nations and others, 1981). When the Verde River breached the volcanics during Pleistocene time, the resultant erosion exposed the evaporites.

Western Chemical Company began surface mining operations during the 1920s to exploit what was believed to be the largest deposit of sodium sulfate in the world. In the early 1930s Arizona Chemical Corporation, a joint venture between American Cyanamid and International Paper Company, acquired Western Chemical Company. Underground mining was started using room and pillar mining methods.

The crude sodium sulfate and halite mined underground was transported to processing facilities on a conveyor belt. About 100 tons of salt cake, anhydrous sodium sulfate, was produced per day to make it the largest producer in the United States (McDermid, 1934). The mine closed in 1933 when low-priced, high-purity sodium sulfate from Germany began entering the United States. Some exploration drilling was done on the sodium sulfate deposits in the Camp Verde area by Stauffer Chemical Company in the 1960s, but the mining operation was not reopened (Grott, 1985b).

Sodium sulfate, which is classified as a chemical mineral, is used as a process aid in the manufacture of kraft paper pulp, also known as sulfate pulp. About 88 pounds of sodium sulfate is used to produce a ton of kraft paper pulp.

Another major and fast-growing use of sodium sulfate is in washing detergents where it is a noncorrosive, neutral, and cheap filler with mild detergent properties. The other principal use is in flat glass production. The major markets for sodium sulfate in the United States include kraft paper pulp (55 percent), detergents (35 percent), glass (5 percent), and other uses (5 percent). In 1984 sodium sulfate sold for $90 to $96 per ton in carload lots F.O.B. the processing plant.

The Camp Verde sodium sulfate deposit could be reactivated as the use of sodium sulfates increases in detergents, particularily in liquid soaps. There are many sources of sodium sulfate available as byproducts from the manufacture of hydrochloric acid, rayon, and other chemicals that compete directly with natural sodium carbonate. However, as a result of the decline of rayon manufacturing, natural sodium sulfate has captured over half the market in the United States (Weisman and McIlveen, 1983).

Zeolites

The largest known deposit in Arizona of high-purity clinoptilolite, a zeolite mineral, occurs near Horseshoe Dam on the Verde River about 55 miles northeast of Phoenix (fig. 5). At least 6 beds of clinoptilolite, which range from 2 to 18 feet thick, are interbedded in a section of Miocene lacustrine beds striking N. 50° W. and dipping 50° SW. The main zeolite bed is 9 to 18 feet thick, crops out

continuously for 5000 feet, and contains over 80 percent clinoptilolite (Eyde, 1963).

The clinoptilolite is geologically classified as a surficially altered mineral. It is unique because the clinoptilolite contains 1.5 percent strontium, which has replaced some of the calcium in the crystal lattice. This substitution appears to have made the pore size of the clinoptilolite large enough to allow oxygen adsorption. The clinoptilolite from the Horseshoe Dam deposit is the only deposit of this mineral in the United States that is known to adsorb oxygen (Donald W. Breck, written communication, 1963).

Bulk samples of clinoptilolite from the deposit have been used successfully as deodorizers and cation-exchange media for ammonia nitrogen removal. Because of its high brightness and uniform particle size the clinoptilolite has been found suitable for paper filling. This clinoptilolite could also be used as a filler-catalyst in the production of reinforced plastic resins from mixed plastic scrap (Choparinov and others, 1985). In all of these applications the clinoptilolite would be classified as a physical mineral when used as a process aid or as a structural mineral in filler applications.

Much of the Horseshoe Dam clinoptilolite deposit is within a withdrawal area for a reservoir site and irrigation works on the Verde River. This temporary withdrawal occurred in 1903, which was long before the economic potential of zeolites and other industrial minerals was recognized. This is an excellent example of how withdrawals that are made before the discovery of applications such as pollution abatement can prevent the mining of an economic deposit (Eyde, 1978, p. 5). Development of this deposit could be impeded or prevented by this withdrawal.

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Geologic Evolution
of Arizona

J. P. Jenney and S. J. Reynolds, *Editors*

Arizona Geological Society Digest 17

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