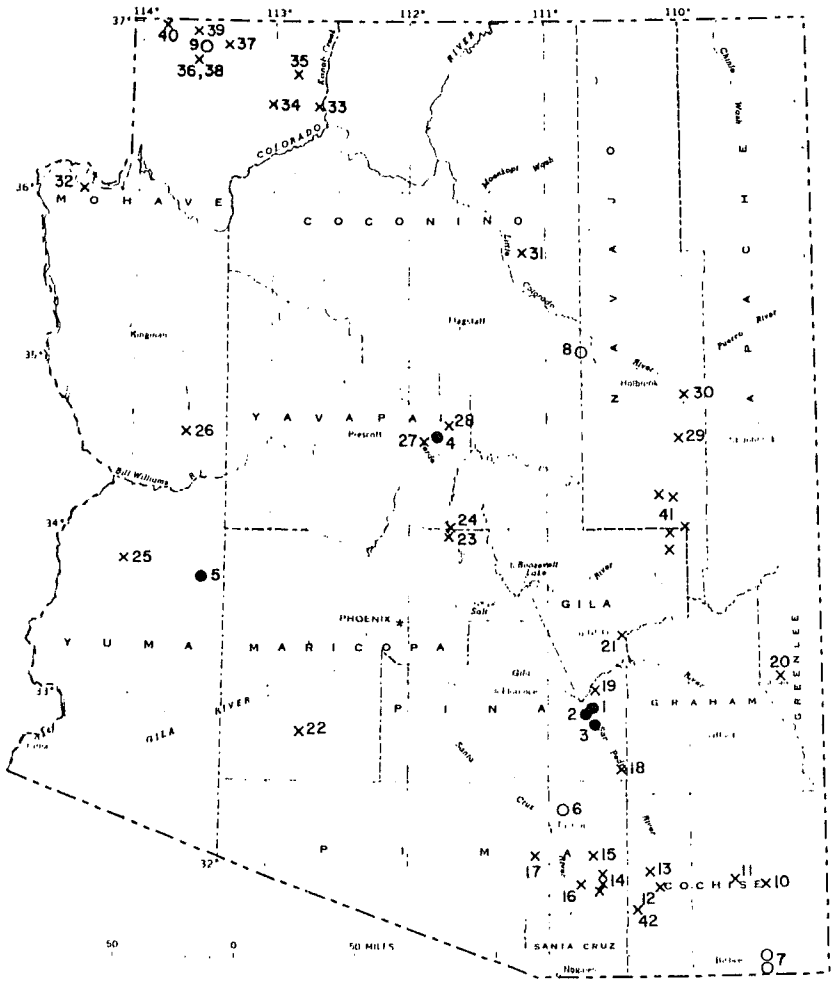

EXPLANATION

●3
Active mine in 1966

○7
Inactive mine in 1966

×40
Notable occurrence

(Numbers refer to localities listed in table 31 and mentioned in text)

FIGURE 57.—Gypsum in Arizona.

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KYANITE AND RELATED MINERALS

(By G. H. Espenshade, U.S. Geological Survey, Washington, D.C.)

INTRODUCTION

A group of aluminous silicate minerals (kyanite, sillimanite, andalusite, dumortierite, and topaz) that contain about 60 percent alumina have been used since the 1920's to manufacture various types of ceramic materials (Foster, 1960; Klinefelter and Cooper, 1961; Cooper, 1965).

These minerals (known as the kyanite or sillimanite group) are all converted at high temperatures to the compound mullite ($3Al_2O_3.2SiO_2$), a material that will withstand high temperatures and abrupt temperature changes. Mullite can also be made from other high-alumina materials, such as diaspore clay, bauxite, and alumina, if the impurity content is low; this product is known as synthetic mullite. Spark-plug insulators were one of the major products made from minerals of the kyanite group in the early days. The principal products now are high-temperature refractories for use in metallurgical and glass furnaces and certain types of kilns and boilers.

Kyanite has been mined in Arizona, California, Georgia, New Mexico, North Carolina, South Carolina, and Virginia; andalusite in California, Nevada, and North Carolina; dumortierite in Nevada; and topaz in South Carolina. Since about 1950 the entire U. S. production has come from four kyanite mines in Georgia, South Carolina, and Virginia. Before World War II, special needs for high-quality lump kyanite were supplied by imports from India. In recent years these needs have been largely met by domestic synthetic mullite.

Records of production, imports, and exports of kyanite minerals and synthetic mullite, in table 32, show the steady growth and changing pattern of the industry from initial large imports and small exports to small imports and large exports at present. The figures for domestic production of kyanite in recent years have been withheld to avoid disclosing individual data of the few producers.

TABLE 32.—U.S. PRODUCTION, IMPORTS, AND EXPORTS OF KYANITE AND SYNTHETIC MULLITE FOR SELECTED YEARS (SHORT TONS)

	Kyanite production [1]	Synthetic mullite production [2]	Kyanite and mullite imports [2]	Kyanite and mullite exports [2]
Year:				
1950	15,700	(3)	17,417	941
1957 to 1961 (average)	32,300	18,133	5,013	3,014
1962	38,100	19,021	5,281	3,568
1963	44,800	29,588	2,624	5,050
1964	(3)	36,108	2,386	6,080
1965	(3)	40,049	4,047	10,238
1966	(3)	49,551	3,405	17,339

[1] Estimates (Varley, 1965, p. 104).
[2] U.S. Bureau of Mines, 1953, pp. 1347–1348; 1967, pp. 496–497.
[3] Not available.

The kyanite-group minerals occur widely in certain kinds of metamorphic rocks (such as micaceous and quartzose schists and gneisses) and in pegmatites, quartz veins, and placer deposits (Espenshade, 1962). Although these minerals are known at hundreds of places in large areas of the United States, only a relatively small number of deposits have them in sufficient abundance and purity to be minable.

Kyanite-Group Occurrences in Arizona

In Arizona all the kyanite-group minerals occur mostly in areas of Precambrian rocks. According to Galbraith and Brennan (1959), sillimanite and andalusite each occur in five counties, kyanite in two counties, and dumortierite and topaz each in one county and occurrences of these minerals are shown on two recent maps of Arizona

(McCrory and O'Haire, 1961; Stipp and others, 1967), from which the localities shown in figure 49, have been taken. Specific information is available for only a few of these occurrences, which is summarized below.

Sillimanite schist occurs along the Colorado River, about one-half mile below the mouth of Monument Creek, Coconino County (Campbell, 1936) (fig. 49, locality No. 1).

About 38 tons of kyanite was shipped from Squaw Peak, north of Phoenix, Maricopa County by Nels Anderson of Peoria, Arizona (Wilson and Roseveare, 1949, p. 43) (locality No. 5). This deposit is now encompassed by the city limits of Phoenix, so there is little possibility that it will be worked in the future (S. B. Keith, written commun., 1968).

Sillimanite occurs in the Hillside Mica Schist along Copper Creek in the Bagdad area, Yavapai County (Anderson and others, 1955, p. 11) (locality No. 2).

Kyanite, sillimanite, andalusite, dumortierite, and pyrophyllite occur in quartz-mica schist about 3 miles southwest of Quartzsite, Yuma County (Wilson, 1929; Duke, 1960, p. 61–64) (locality No. 3). X-ray analysis of a sample from this deposit by the Arizona Bureau of Mines indicated only kyanite. Additional tests indicated the kyanite was fine grained and that it was necessary to grind the material to minus 35 mesh in order to liberate the kyanite, thus suggesting that the deposit has little if any commercial value (S. B. Keith, written commun., 1968). Perhaps a few miles west of this locality, a kyanite deposit said to be about 1,000 feet long has been reported 12.1 miles [east] from Blythe, Calif. (Funnell and Wolfe, 1964, p. 22).

Dumortierite and kyanite also occur in boulders of quartzose schist along the Colorado River near the former settlement of Clip, Yuma County (Schaller, 1905; Wilson, 1933) (locality No. 4).

The information available is insufficient to show whether any deposits in Arizona are of the size and quality required to have economic value. Apparently only two deposits have been explored—the one near Quartzsite, Yuma County (Duke, 1957, p. 61–64), and the kyanite deposit on Squaw Peak, Maricopa County (Wilson and Roseveare, 1949, p. 43). Promising deposits must be explored thoroughly to determine if quality and size of reserves are adequate to meet the competition of currently productive deposits in the Southeastern States.

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LIMESTONE, DOLOMITE, AND MARBLE

(By S. B. Keith, Arizona Bureau of Mines, Tucson, Ariz.)

Introduction

Limestone, dolomite, and marble are calcium and calcium-magnesium carbonate rocks that are very important and useful to man in the construction industry and for chemical and industrial use. These rocks are plentiful and economical to use.

Pure limestone is 100 percent calcite ($CaCO_3$) and pure dolomite rock is 100 percent dolomite $CaMg(CO_3)_2$ but in nature these rocks rarely are pure, as dolomite substitutes for calcite in limestone and calcite substitutes for the mineral dolomite in dolomite rock. As used here, the names "limestone" and "dolomite" include rocks consisting of at least 80 percent carbonate. Calcite greatly predominates in limestone and dolomite predominates in dolomite rock. When calcite and dolomite are present in more equal proportions, the rock is termed a magnesian limestone.

Trace to small quantities of other metals such as iron and manganese may replace calcium and magnesium and various amounts of sand, silt, clay, and organic matter are generally present as impurities. Due to the various compositions, limestone and dolomite are classed as high lime or low lime and high magnesia or low magnesia, respectively; and as argillaceous or siliceous.

Marble, which is limestone or dolomite that has been recrystallized, may have the same chemical and mineralogical composition as the original carbonate rock or it may contain new minerals formed by the chemical reaction between the carbonates and impurities originally present or introduced during the recrystallization. Marble is almost always more coarsely crystalline than the original carbonate rock. The mineral crystals may be oriented in a parallel direction to make the rock semitranslucent or at random to give it a dense, opaque appearance. An important physical quality of some marble is its ability to take a smooth polish.

Other types of carbonate rocks closely related to limestone and dolomite are marl, a poorly consolidated mixture of carbonates and clay; chalk, a fine-grained, powdery, carbonate rock; and travertine or tufa, a hot- or cold-water calcareous spring deposit. Calcium carbonate deposits formed by the precipitation of successive layers of carbonate in varying colors are called onyx marble or Mexican onyx. Some marl that occurs in lake bed deposits in central Arizona was tried unsuccessfully as a cement additive. In general it is not considered as an economic mineral resource in the State. No chalk deposits are known in Arizona. Travertine and onyx marble or Mexican onyx are closely related in origin and occurrence. They are found in numerous localities in the State, and have been exploited. Their more important occurrences are described in "Gem materials" (see p. 357).

Limestones accumulate mainly in relatively shallow seas but a few originate in fresh-water lakes. Many forms of plant and animal life absorb lime and form calcium carbonate shell or skeletal structures whereas others precipitate calcium carbonate from the sea water during their life. Extensive limestone beds result from the accumulation of fragmented skeletal structures or by direct precipitation of calcium carbonate derived from either lime secreting organisms or from terrestial rocks. Subsequent burial under additional sediments causes compaction and induration into solid rock. Most dolomite probably forms by the replacement of some calcium in limestone by magnesium at some stage in the development of rock.

The carbonate rocks have been used by man since prehistoric time. They are relatively easy to break, crush, and cut but also are strong and durable. Calcined limestone, that is, heat treated to liberate carbon dioxide (CO_2) and form lime (CaO), makes an excellent mortar and binder; when carefully calcined with small, correctly proportioned amounts of alumina, silica and iron, it forms a dry portland cement. Furthermore, carbonate rocks have many chemical applications in various chemical and industrial manufacturing processes.

Limestone and marble dimension stone are used for rough construction, rough architectural, dressed architectural, and ornamental purposes and for curbing and flagging. Magnesium limestone and dolomite dimension stone are used mainly for rough construction. Moderate to large, sound, clean blocks of uniform and attractive texture and color are required. Kessler (1919, 1927) and the American Society for Testing and Materials (1967) have developed test methods and specifications for dimension limestone and marble and many government agencies and nongoverment construction architects and builders set their own specifications.

Crushed and broken limestone, magnesian limestone, dolomite, and marble are used by many industries. All are used for concrete and roadstone, riprap, railroad ballast, cast stone, and concrete products, roofing granules, drilling muds, asphalt filler and filter beds. High-calcium limestone is required for cement rock, lime, alkali manufacture, limestone sand, some glass and paper manufacture, sugar refining, whiting, mineral food, coal dusting, and calcium carbide. It also is used in some chemicals and is used for acid neutralization, electrical insulation, disinfectant and animal sanitation, in patching plaster, for water treat-

ment, and as metallurgical flux in copper and lead smelting. High-magnesian limestone or dolomite is required for dead-burned dolomite, for agricultural use, in some glass and paper manufacture, refractories, some chemicals, magnesia and magnesium production, and as metallurgical flux in iron and steel production.

There are many other miscellaneous uses of the carbonate rocks. The physical and chemical specifications for most uses are quite rigid; some are detailed in the publications of the American Society of Testing and Materials, in publications of trade organizations, and as specified by individual users of carbonate rock.

Although the carbonate rocks in Arizona are limited to a relatively few of these uses, the list suggests other possible markets. In general, only limestone and marble have been used in sizable amounts and dolomite has been used locally as construction stone, either in dimension or crushed and broken form. Investigations as to the use of dolomite beds for industrial purposes, such as a refractory material or a source of magnesia or magnesium metal, have not lead to commercial production because more accessible and economic sources of magnesium were available elsewhere (Wilson and Roseveare, 1949). Thus, the following discussion concerns mainly limestone and marble.

Most of the carbonate rocks are quarried from the surface by various cutting or breaking methods dictated by the size, type, and quality of stone required. High quality or special dimension stone may be shipped long distances in finished or unfinished blocks or slabs because it has high value. Crushed and broken stone, however, is normally prepared for market or use close to the quarry site because it has low value and cannot bear much transportation expense.

Production and Use

The following statistics on the production and use of limestone, dolomite, and marble in the United States and Arizona in 1966 is from the U.S. Bureau of Mines (1967, p. 578, 579, 586–588) and supplemented by additional information on Arizona production and use from Arizona Bureau of Mines file data. The amount of dimension limestone sold or used for dressed and rough building stone, and stone veneer in the United States was 728,000 short tons, valued at $18,270,000; none was produced in Arizona. The amount of dimension marble sold or used in the United States, more than half as dressed building stone and the balance as rough architectural and monumental stone, was 83,000 short tons with a value of more than $14 million. Two Arizona producers sold or used 364 short tons, valued at $6,700. Almost all of it was rough building stone valued at $6 to $27 per ton, depending on size and quality, and a small amount was dressed, sawed, or cut for exterior and interior facing, valued at more than $80 per ton.

Crushed and broken limestone and dolomite are the most important carbonate rock products. The amount sold or used in the United States in 1966 was more than 568 million short tons, valued at $776 million. About 60 percent was used for concrete and roadstone, 17 percent for portland cement, 6 percent for metallurgical flux, 5 percent for agriculture, 3 percent for lime, and 9 percent for miscellaneous uses. In

Arizona the amount sold or used was 1,590,000 short tons, valued at $2,262,000. More than 50 percent was used for portland cement, at about $1 per ton, and more than 25 percent for lime, at about $2 per ton. Approximately 13 percent was used for metallurgical flux, at about $1.70 per ton, 1 percent for concrete and roadstone, at about $3 per ton, and the balance for agriculture, mineral food, paper manufacture, and miscellaneous uses, at $3 to $8 per ton.

Crushed and broken marble is used in the United States for concrete and roadstone, acid neutralization, asphalt filler, cast stone, poultry grit, roofing chips, stucco, whiting, and terrazzo. The amount sold or used in the United States in 1966 was 2 million short tons valued at $22 million. Arizona producers sold or used 22,000 short tons valued at $272,000. The uses and price per ton for each use were as follows: roofing granules ($6–$9), stucco ($9), mineral food ($6), terrazzo ($18.50), precasting ($18.75), polyester filler ($6), and general landscaping ($8).

Arizona production of these carbonate rocks rates low compared with other states (13th of 15 for dimension marble, 9th of 17 for crushed and broken marble, and 40th of 45 for crushed and broken limestone and dolomite). Nearly 100 percent of the State's production of crushed and broken limestone came from captive quarries and was used for commercial cement, lime, and copper plants.

Marble was quarried in Arizona prior to 1900. Burchard (1914) noted that a variety of marbles used for monuments occurred in the Santa Rita Mountains, Pima County; that a white statutary marble was found on the northeast side of the Santa Catalina Mountains, Pima County; that various colored marbles were known and quarried on the east side of the Chiricahua Mountains, Cochise County; and undeveloped marble occurred at the north end of the Dragoon Mountains, Cochise County, and in northwestern Yuma County. Quarrying of dimension marble in Arizona has been intermittent, never exceeding more than one or two thousand tons per year, mainly between 1924 and 1934, and the total output for the 1900–66 period is estimated at 14,000 tons. Dimension limestone production for the same period is even more erratic and totals only about 20,000 tons.

Crushed and broken marble production in Arizona for the 1900–66 period was 109,000 tons valued at $1.7 million. About 80 percent of the tonnage was produced since 1961 when the output increased to as much as 22,000 tons per year. The bulk of the carbonate rock production was crushed and broken limestone. Figure 58 shows graphically the apparent annual consumption and value of this rock product from 1900 to 1954 and actual consumption from 1954 to 1966. The consumption was equivalent, approximately, to production. The total production for the period is estimated at 22.9 million tons with a value of more than $28 million. Until 1954 the annual amount of limestone consumed in the cement and lime industries was not reported and actual production before that date can only be estimated from the average amount of limestone used to produce the estimated and known cement and lime turned out for that period. While lime production has been continuous since 1900, cement production, except for a brief time in the early 1900's, did not start until 1949.

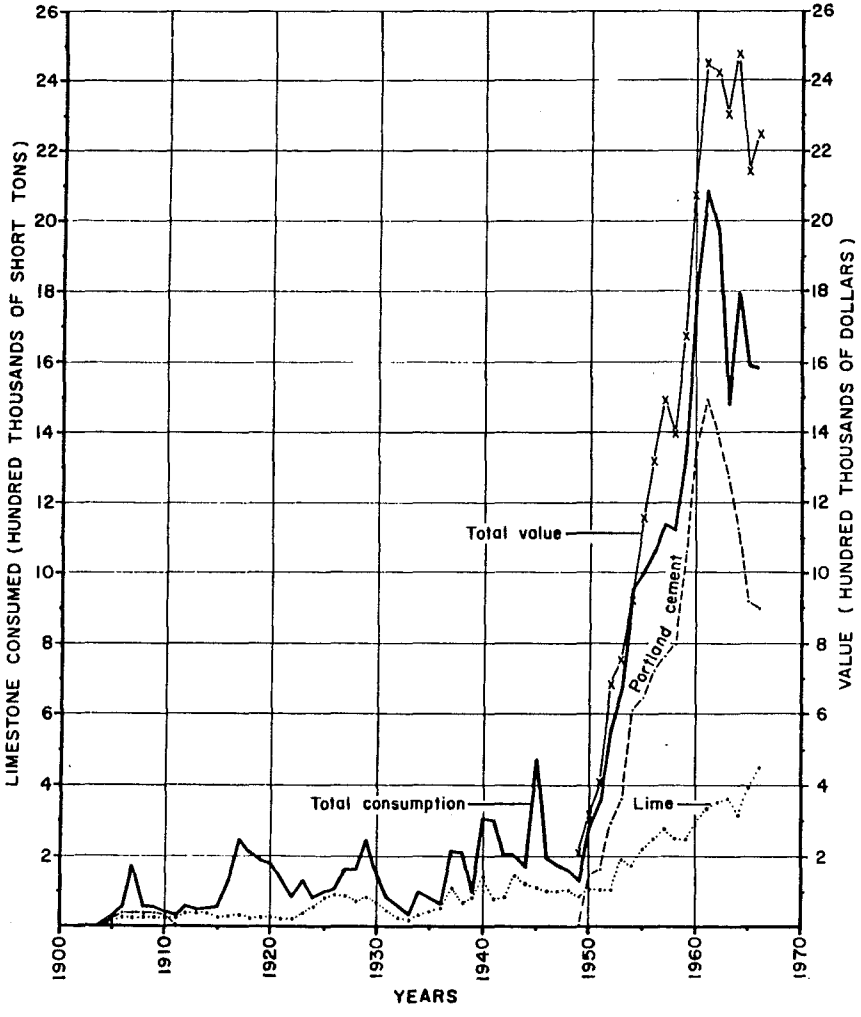


FIGURE 58.—Annual tonnage and value of limestone consumed and annual tonnage of amounts used in portland cement and lime in Arizona, 1900–66.

Commercial production of crushed and broken limestone rock dates back to at least the 1880's when lime plants were operating in northern Yavapai County. By the early 1900's limestone also was being quarried for copper smelter flux in various localities in the State and for a short period was used in producing portland cement at a government-owned plant for the construction of Roosevelt Dam. Limestone production fluctuated with the local demands for lime and crushed limestone for construction and copper metallurgy until 1949 when the sharp rise in use signaled the start of commercial cement production in Arizona at Rillito, Pima County, and in 1959, at Clarkdale, Yavapai County. The peak production in 1961 is related to the Glen Canyon Dam construction. Table 33 lists the limestone and marble producers in Arizona in 1966, the products produced, and the formational sources.

TABLE 33.—*Limestone and marble producers in Arizona in 1966*

County and location (No. shown in fig. 59)	Producer	Formational source and products
Apache		
Unknown	Contractors for U. S. Bur. Indian Affairs.	Source unknown; road material.
Cochise County		
1. Paul Spur	Paul Lime Plant, Inc.	Mural Limestone; lime, metallurgical flux, road material, and mineral food.
Gila		
2. 4 mi. N. of Miami	Hoopes & Co.	Escabrosa Limestone; lime.
3. Near Hayden	Ray mines Div., Kennecott Copper Corp.	Escabrosa Limestone; metallurgical flux, lime, and road material.
Greenlee		
4. Morenci	Phelps Dodge Corp.	Modoc Limestone; lime, metallurgical flux.
Maricopa		
5. Harquahala Mts.	Agnes D. Mick.	Marmorized Paleozoic limestone; building stone.
Pima		
6. Picacho de Calera (Rillito)	Arizona Portland Cement Co. Div., California Portland Cement Co.	Escabrosa and Naco Group limestones; cement.
7. N. end Santa Rita Mts.	Andrada Marble Co.	Marmorized Escabrosa Limestone; roofing granules, feed additive, landscaping.
Pinal		
8. Camp Grant	San Manuel Div., Magma Copper Co.	Escabrosa Limestone; lime, metallurgical flux.
9. Hewitt Canyon, NE. of Florence Jct.	McNeice Stone Works.	Marmorized and serpentinized Mescal Limestone; dressed, cut and sawed, and rough building stone.
Yavapai		
10. Clarkdale	Phoenix Cement Co., Div., American Cement Corp.	Redwall Limestone; cement.
11. Nelson	U. S. Lime Div., The Flintkote Co.	Redwall Limestone; lime, paper manufacture, agriculture, and other miscellaneous uses.
Unknown	Hidden Valley Stoneyard.	Redwall Limestone; road material.
Yuma		
5. Harquahala Mts.	U. S. Marble.	Marmorized Paleozoic limestone; terrazo, precasting, roofing granules, stucco, mineral food, and polyester filler.

SOURCES OF SUPPLY

There are many sources of limestone, magnesian limestone, dolomite, and marble in Arizona but only a few have been or can be quarried for commercial and industrial purposes because of difficult access and other economic reasons. Table 34 lists the principal limestones and dolomites in the State with brief notes on their location, thickness, and character.

The best Arizona limestones for chemical and industrial use are Mississippian, Pennsylvanian-Permian, and Cretaceous in age. The two best limestones for overall purity, thickness, and availability over wide areas are the Escabrosa and Redwall Limestones of Mississippian age. The former crops out mainly in the folded and faulted mountain ranges of southeastern Arizona and the latter, generally considered

TABLE 34.—*Principal limestone and dolomite in Arizona*

General age and stratigraphic unit	Distribution by county and area	Thickness (feet)	Characteristics and remarks
Cenozoic			
Verde Formation	Yavapai; Verde River valley.	As much as 2,000.	Limestone occurs with varying amounts of chert and marl in central part of basin area and fingers outward into more clastic and sandy facies towards the sides. Locally may be of high-calcium type and has been quarried but generally not suitable for commercial use.
Cretaceous			
Mural Limestone	Cochise; S. Mule Mts. area and in Huachuca Mts.	More than 650.	Lower part consists of interbedded shale, sandstone, and some thin-bedded impure limestone. Middle part is massive, high-calcium limestone with minor clastic constituents. Upper part contains interbedded shale, sandstone, and mudstone with the limestone. Middle part is used for lime and metallurgical flux.
Bisbee Group or Formation	Cochise and eastern Pima; Chiricahua, Pedregosa, Peloncillos, and Whetstone Mts., and Perilla Hills.	Variable, usually relatively thin.	Limestone beds and lenses in shale and sandstone; some may be clean, high-calcium rock suitable for local commercial use.
Jurassic			
Todilto Limestone	Apache; Defiance uplift area.	As much as 14.	Thin-bedded, platy and impure; doubtful commercial value.
Jurassic and Late Triassic(?)			
Navajo Sandstone	Apache and Navajo.	Variable, usually less than 4 in single beds.	Limestone beds generally high-calcium but generally in thin-bedded lenses with silica, chert, and jasper pods. Locally may be suitable for lime and cement.
Triassic			
Chinle Formation	Apache and Navajo.	2 to 4 in single beds.	Limestone beds generally extensive but invariably siliceous and cherty. Suitable only for aggregate.
Permian			
Kaibab Limestone	Coconino, Mohave and Navajo; extensive exposures on Colorado Plateau.	1 to 570.	Mainly massive, magnesian limestone and dolomite interbedded with chert layers, red beds, gypsum and thin sandy or silty limestone. In general carbonate rocks are increasingly sandy and magnesian to the east and south except in Fort Apache Indian Reservation where limestone is relatively clean. Locally suitable for construction stone and in Reservation suitable for chemical and industrial uses.
Toroweap Formation	Coconino, Mohave and Yavapai; best exposures in Grand Canyon area.	As much as 200 in some beds.	Generally massive, dense, crystalline, magnesian limestone and dolomite and alternate red beds. Carbonate rocks become silty and sandy to east and south with variable silica content. May be used locally for rough dimension and aggregate stone.

TABLE 34.—*Principal limestone and dolomite in Arizona*—Continued

General age and stratigraphic unit	Distribution by county and area	Thickness (feet)	Characteristics and remarks
Permian--Continued			
Rainvalley Formation	Cochise, Pima and Santa Cruz; Mustang, Empire, Whetstone Mts. and other localities.	More than 500 in some beds.	Varicolored, medium-bedded limestone and dolomite with interbedded sandstone. Possibly suitable for aggregate.
Concha Limestone	W. Cochise and E. Santa Cruz; various ranges.	130 to more than 1,000.	Dominantly massive, dark, cherty limestone. A possible resource for dimension, aggregate, and industrial stone.
Scherrer Formation	Cochise, Pima, and Santa Cruz; crops out in various ranges.	As much as 165 in some beds.	Sequence of siltstone, fine-grained limestone, and sandstone. Limestone generally thin bedded and highly magnesian. Unlikely resource but may be used locally for aggregate.
Colina Limestone	Cochise and Santa Cruz; in several ranges.	535 to 635.	Dominantly a dark-gray to black, dense limestone with beds up to 25 feet thick. May be suitable for commercial use.
Permian-Pennsylvanian			
Fort Apache Limestone Member of Supai Formation	Coconino, Gila, Navajo, and Yavapai; crops out along Mogollon Rim and on Colorado Plateau in east-central Ariz.	7 to more than 120; thins to north, west, and south.	Highly variable with relatively thin, interbedded, fossiliferous limestone, magnesian limestone, dolomite, and gypsiferous limestone. Some parts in Fort Apache Indian Reservation are high-calcium stone suitable for chemical, industrial, and building purposes.
Earp Formation	Cochise, Pima, and Santa Cruz; local outcrops in some ranges.	As much as 400 in some beds.	Interbedded limestone, magnesian limestone, shale, and sandstone. Suitable only for aggregate.
Naco Formation	Gila, Pima, and Pinal; crops out in many ranges and on Colorado Plateau in east-central Ariz.	As much as 50 in some beds.	Contains generally thin-bedded limestone with interbedded calcareous shale and locally abundant chert nodules. Locally high calcium and nonmagnesian. May include equivalents of Permian-Pennsylvanian age limestone listed in table. Locally suitable for portland cement.
Permian to Mississippian.			
Callville Limestone	Mohave; Virgin Mts. and extreme NW. Ariz.	277 to 675; wedges out southward.	Thick-bedded limestone in lower member and grades upward into silty and cross-bedded, sandy limestone in upper member. May be suitable for commercial use but generally inaccessible for Arizona use.
Pennsylvanian			
Horquilla Limestone	Cochise, Pima, Pinal, and Santa Cruz; crops out in many isolated ranges.	520 to 2,115; thins to north and west.	Very fine- to medium-grained, crystalline, locally cherty to sandy, fossiliferous limestone with interbedded shale increasingly abundant upward. Probably suitable only for aggregate.

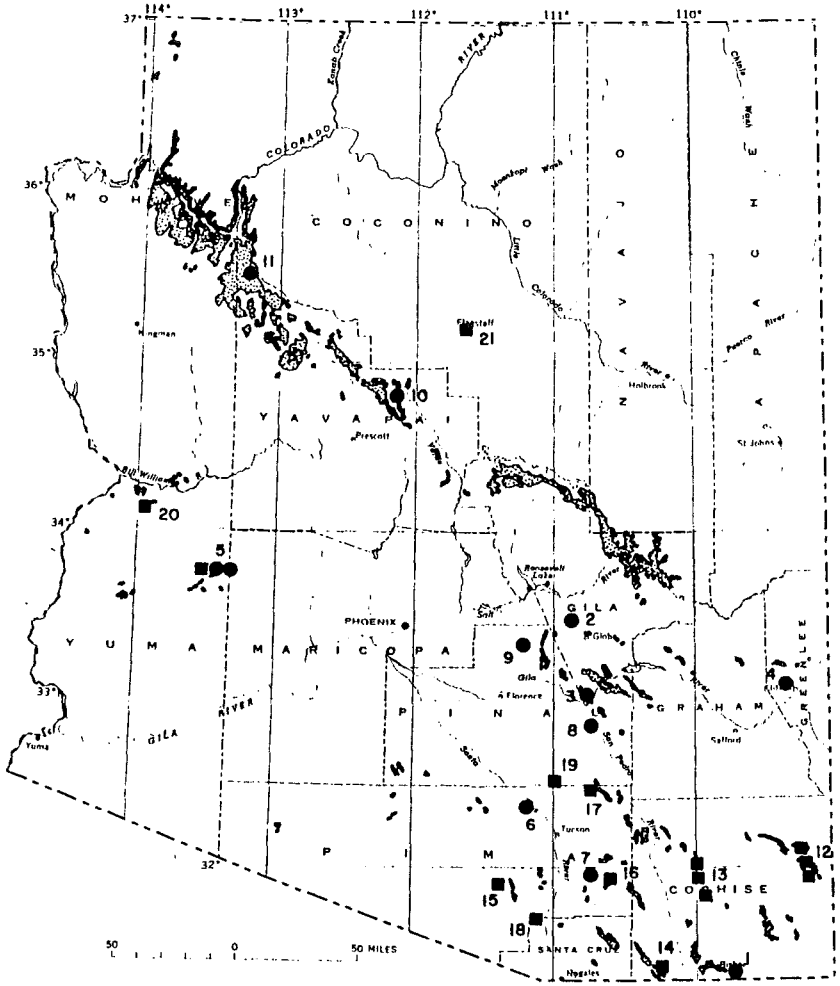
TABLE 34.—*Principal limestone and dolomite in Arizona*—Continued

General age and stratigraphic unit	Distribution by county and area	Thickness (feet)	Characteristics and remarks
Pennsylvanian-Mississippian			
Black Prince Limestone	Cochise; Little Dragoon Mts. and other places in NW. part of county.	140	Medium- to coarse-grained, relatively pure limestone with some chert nodules. Where accessible, this limestone could be of commercial use.
Tule Spring Limestone	Greenlee; N. of Clifton.	As much as 700.	Local occurrence of thick-bedded, cherty limestone. May be used for rough building and aggregate stone.
Mississippian			
Modoc Limestone	Greenlee; Clifton-Morenci area.	As much as 170.	Coarse-grained limestone with some magnesian limestone and calcareous quartzite beds. Generally irregular in quality but locally moderately high-calcium beds are used for lime and metallurgical flux. Some also used as road aggregate.
Escabrosa Limestone	Cochise, S. Gila, Pima, Pinal, and Santa Cruz; crops out in many ranges in SE Ariz.	365 to 800; thins to north.	Escabrosa and Redwall Limestones are similar and probably equivalent stratigraphic units. Both are mostly thick bedded, cliff forming, white or reddish, granular, high calcium nonmagnesian, and fossiliferous with irregular continuous bands or nodules of chert in some parts. Locally the lower part is magnesian and siliceous and the upper part contains interbedded shale. Middle and upper parts generally are suitable for chemical and industrial use and more massive beds yield good dimension and crushed and broken stone. Locally the limestone is marmorized.
Redwall Limestone	Coconino, Gila, Mohave, Yavapai, W. Maricopa, and N. Yuma (?); crops out along Mogollon Rim and in many places in central and NW. Ariz.	28 to 800; thickens northward.	Do.
Devonian			
Martin Formation	In SE. and central Ariz. where lower Paleozoic rocks are exposed and traced NW. into Mohave, Virgin Mts. area.	As much as 600.	Contains limestone beds that generally are highly variable within short distances. Generally is thin bedded, often strongly magnesian or dolomitic and shaly with local chert zones. NW. extension formerly called Muddy Peak Limestone. Locally the limestone units may be suitable for aggregate.
Temple Butte Limestone	Coconino; Grand Canyon area.	0-100.	A local, magnesian, and sandy limestone suitable only for aggregate.
Ordovician			
Pogonip Group	N. Mohave; Virgin Mts.	As much as 215; thins markedly to south and east.	Contains highly magnesian limestone. Of doubtful commercial value but may be suitable as aggregate.

TABLE 34.—*Principal limestone and dolomite in Arizona*—Continued

General age and stratigraphic unit	Distribution by county and area	Thickness (feet)	Characteristics and remarks
Ordovician--Continued			
Longfellow and El Paso Limestones	S. Greenlee and E. Cochise; local occurrences in Dos Cabezas, Chiricahua, and Swisshelm Mts., and in Clifton-Morenci district.	350 to 715.	Relatively impure limestone. Generally slabby and thin-bedded, with magnesian, shaly, and sandy zones. Locally may be suitable as aggregate.
Cambrian			
Abrigo Limestone	Cochise, Pima, Pinal, and Santa Cruz; crops out in some mountain blocks.	360-800; thins to west and north.	Great variation in physical and chemical character. Generally thin bedded, contains silt in lower part and sand in upper beds. High magnesia content is common and fairly pure limestone is rare. For most part unsuitable for use except locally for aggregate.
Muav Limestone	NW. Coconino, N. Gila, N. Mohave, and Yavapai; crops out along Grand Canyon and intermittently to southeast.	0 to 2,000; thins to southeast.	Highly variable stratigraphically and in extent, both chemically and physically, with many sandy and magnesian beds. No known commercial use but locally may be suitable for rough dimension stone and for aggregate.
Late Precambrian			
Mescal Limestone	Cochise, Gila, Graham, Pima, and Pinal; scattered outcrops in SE. Ariz. and best exposures in Gila and Salt River basins.	225 to 500; thins northward.	In general grades upward from cherty, interbedded limestone and dolomite to massive, cliff-forming, magnesian limestone. Top part generally is thin bedded, silty, and siliceous. Generally is highly variable and mostly impure limestone and locally contact metamorphosed by diabase intrusion. More massive members used for rough dimension and crushed and broken stone, as at Roosevelt Dam. Some marmorized and serpentinized stone exploited as decorative marble.
Bass Limestone	Coconino; Grand Canyon area.	335 or more.	Alternating beds of magnesian limestone and shale. Location and quality limit commercial use but may be suitable for aggregate in some areas.

to be the equivalent of the Escabrosa, occurs in less disturbed form bordering the Colorado Plateaus province from east-central to northwestern Arizona (fig. 59). Both contain thick, massive, strong, and durable beds of high-calcium, low-magnesium stone. Chert nodules and bands are the main impurity. The Escabrosa Limestone has been quarried at Picacho de Calera (No. 6, fig. 59), south of Rillito, Pima County, for cement rock and near Camp Grant (No. 8), Pinal County and Hayden (No. 3), Gila County, for lime and metallurgical limestone. Marble probably derived from the Escabrosa Limestone, is exposed in scattered outcrops throughout southeastern Arizona as shown in figure 59 and listed in table 35. Most of the marble is highly fractured, contains crosscutting igneous dikes, or has color variations which limit the size of blocks or the amounts that have uniform color or color pattern.



EXPLANATION

●7
Limestone and marble operations in Arizona in 1966
(Number is referred to in table 33 and text)

■12
Marble occurrence
(Number is referred to in table 35 and text)

Outcrop of sedimentary formations of Mesozoic and Paleozoic age containing principal limestone and marble deposits.

FIGURE 59.—Limestone and marble in Arizona.

TABLE 35.—*Marble occurrences in Arizona*

Locality No. in fig. 59	County, area, and locality	Formation and remarks	References
	Cochise		
12	Chiricahua Mts., Tps. 15-17 S., Rs. 30-31 E.	Massive and fractured, white and colored marmorized Escabrosa Limestone. Variable, chemically and physically. No recent production.	Burchard, 1914, p. 1342-1343; Wilson and Roseveare, 1949, p. 48; Townsend, 1962, p. 19-20.
13	Dragoon Mts., Tps. 16-18 S., Rs. 23-24 E.	Massive and fractured, white and colored marmorized Escabrosa Limestone. Quality variable. Ligier quarries. No recent production.	Do.
14	Huachuca Mts., T. 23 S., Rs. 20-21 E.	Marmorized Escabrosa Limestone.	Ariz. Dept. Mineral Resources, 1962.
	Pima		
7	Santa Rita Mts., Tps. 17-18 S., Rs. 15-16 E.	White and colored, massive and fractured Escabrosa Limestone. Andrada Marble quarry.	Burchard, 1914, p. 1342; Townsend, 1962, p. 18-19.
15	Sierrita Mts., Tps. 17-18 S., R. 10 E.	Massive to highly fractured, white to gray, marmorized Paleozoic limestone.	Townsend, 1962, p. 18-19; Ariz. Dept. Mineral Resources, 1962.
16	Empire Mts., T. 17 S., R. 17 E.	Marmorized Escabrosa Limestone.	Ariz. Dept. Mineral Resources, 1962.
17	Santa Catalina Mts., T. 11 S., R. 16 E.	Fine, white, marmorized Escabrosa Limestone.	Burchard, 1914, p. 1342.
	Santa Cruz		
18	3 mi. W. of Amado, T. 20 S., R. 12 E.	White, marmorized Paleozoic limestone.	Townsend, 1962, p. 18-19.
	Pinal		
19	Tortolita Mts., T. 10 S., R. 13 E.	White, dense, highly fractured marmorized Escabrosa Limestone.	Townsend, 1962, p. 18.
9	Hewitt Canyon, T. 1 S., R. 11 E.	Impure, marmorized, and serpentinized Mescal(?) Limestone.	N. E. McNeice, oral commun., 1968.
	Maricopa-Yuma		
5	Harquahala Mts., T. 5 N., Rs. 10-12 W.	White and colored, massive and fractured, marmorized Paleozoic limestone. Blackstone quarry and White Marble quarry.	Townsend, 1962, p. 18; Ariz. Dept. Mineral Resources, 1962.
	Yuma		
20	Buckskin Mts., T. 9 N., R. 16 W.	Coarsely crystalline, marmorized Paleozoic limestone.	Burchard, 1914, p. 1343; Ariz. Dept. Mineral Resources, 1962.
	Coconino		
21	Elden Mtn., T. 21 N., R. 7 E.	Pure, coarse-grained, white marmorized Redwall Limestone.	Robinson, 1913, p. 77.

In general, the localities are not good sources of large blocks of high quality, finished construction stone, but are a source of smaller monument and decorative facing stone. Good opaque dense white crushed and broken stone desirable for roofing granules, terrazzo, stucco, and precast stone can be produced and, for some such uses, the various colors and color patterns may enhance the value. The Redwall Limestone is quarried at Clarkdale (No. 10), Yavapai County, for cement rock and high calcium stone used by the sugar refinery at Chandler, Maricopa County. It is quarried also at Nelson (No. 11) in Yavapai County, mainly for the production of lime. The Redwall Limestone has been marmarized locally by igneous intrusions or flows, as at Elden Mountain, Coconino County. The scattered undifferentiated marmarized Paleozoic limestones of northeastern Santa Cruz County and southern Pima County and the undifferentiated marmarized Paleozoic to Mesozoic limestones of western Maricopa and northern Yuma counties, such as in the Harquahala Mountains (No. 5), may be the equivalent of the Escabrosa and Redwall Limestones. The local Modoc Limestone of Mississippian age near Morenci (No. 4), Greenlee County, is used for metallurgical flux and as a source of lime for copper treatment.

The Naco Group limestones, of Pennsylvanian and Permian ages, lie above the Escabrosa Limestone in southeastern Arizona and the Redwall Limestone in east-central Arizona. At places these limestones are relatively clean high-calcium low-magnesium stone but are relatively thin bedded and have interbedded shale. Naco Group limestones and shales are quarried for cement rock at Picacho de Calera (No. 6), near Rillito in Pima County, and are suitable for such use in other localities. In general these limestones are too thin-bedded to be used for dimension stone and the interbedded shale makes them unsuitable for other chemical and industrial use.

Other limestones of commercial importance or of potential commercial use are the Mural Limestone of Cretaceous age in the Paul Spur-Bisbee area (No. 1), south-central Cochise County, which is quarried mainly for lime production and metallurgical flux; the Mescal Limestone, of late Precambrian age, which is quarried northeast of Florence Junction (No. 9), Pinal County, for varicolored marble building stone, and for rough dimension stone and crushed and broken stone (as used in Roosevelt Dam in east-central Arizona); the Fort Apache Limestone Member of the Supai Formation, of Permian age, in east-central Arizona; and the Kaibab Limestone, of Permian age, that crops out over a large area in north-central Arizona and has been used for building stone and aggregate for various purposes.

Outlook

Limestone and marble are important resources in Arizona. They are plentiful and much of the high quality stone is readily available. In general construction, the carbonate rocks of the State must compete with other stone and concrete and the future use of limestone and marble for dimension purposes is likely to be limited to ornamental paneling and facing stone. Volcanic cinders and scoria are more readily available for most constructional purposes that utilize crushed and

broken stone. Thus, in addition to the present principal uses of limestone and marble (cement, calcium-lime, and metallurgical flux) new industrial markets need to be sought. The character of the deposits and the distance from the current major markets limit their exploitation as dimension stone but their use as crushed and broken stone should increase with the industrial development within Arizona and in southwestern United States.

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MICA

(By Richard T. Moore, Arizona Bureau of Mines, Tucson, Ariz.)

Introduction

Mica is the general name applied to a group of complex hydrous potassium aluminum silicate minerals of which muscovite, phlogopite, biotite, and lepidolite are the most common. Although the members of the group differ in the details of their chemical composition and in some of their physical properties, the group is characterized by a perfect basal cleavage. All can be split into thin sheets having varying degrees of transparency, toughness, flexibility, and elasticity. Of these minerals, muscovite (including the closely related mineral sericite) and phlogopite are the most important sources of commercial mica. Biotite finds only a limited market in the form of ground mica, and lepidolite is most important as an ore mineral of lithium.

Unmanufactured mica is marketed in two broad commercial classes: (1) sheet mica and (2) scrap mica (Skow, 1962, p. 3). These two classes vary widely in their uses, in the forms in which they are marketed, and in the prices they command.

Sheet mica is relatively flat and of sufficient size and freedom of structural defects that it may be punched or otherwise trimmed into specified shapes. The electronic and electrical industries consume more than 90 percent of the sheet mica used in the United States. Several classifications for the grading of sheet mica have been established, based on differences in color, degree of preparation, sheet thickness

and size, visual and electrical quality, and, in the case of phlogopite, the degree of thermal stability. In general, phlogopite is inferior to muscovite for use as sheet mica and exceeds it in quality only in thermal stability, being stable to near 750° C. (1,382° F.), whereas muscovite begins to yield water at 400° to 500° C. (752° to 932° F.).

Scrap mica, because of size, color, or quality is unsuitable for applications in which sheet mica is ordinarily employed. It can be derived either from the trimmings, or otherwise rejected material resulting from the production of sheet mica, or from flake mica, produced from schist or granite specifically for use as scrap mica. Scrap mica, in turn, is primarily the raw material used in producing ground mica. Notable quantities of ground mica are used in the manufacture of roofing materials, wallpaper, paint, rubber, pipeline enamel, and molded electrical insulation.

Prices for mica are generally negotiated between buyer and seller. In the period 1960–67 the price for waste or scrap mica ranged between $25 and $30 per short ton at the mine. Dry-ground mica was quoted at 2¢ to 4¢ per pound and wet-ground mica sold for as much as 9¢ per pound. Sheet mica prices vary widely depending upon quality and grade, and in recent years have ranged from 5¢ per pound for washer grade to over $10 per pound for highest grade and quality of film and block (Skow, 1962, p. 97; U.S. Bur. Mines, 1968).

Production

India, yielding 80 percent of world production in recent years, is followed in order by Brazil, the Malagasy Republic (Madagascar), and the United States (Skow, 1962, table 30). The disparity in the relative amounts produced, however, is great; India's output is about 10 times that of either Brazil or the Malagasy Republic and between 30 and 40 times that of the United States. The bulk of the sheet mica produced in the world is utilized in the highly industrialized countries, principally the United States, the United Kingdom, West Germany, the U.S.S.R., Japan, and Italy (Skow, 1962, p. 110); the countries that produce most of the sheet mica use very little.

In 1965 the United States produced 716,086 pounds of sheet mica (Petkof, 1966, table 2) and imported 11,832,206 pounds, of various types, 81 percent of which came from India (Petkof, 1966, table 11). In contrast, during 1965 our consumption of scrap and flake mica amounted to about 253.2 million pounds, of which about 240.5 million pounds, nearly 95 percent, was produced domestically (Petkof, 1966, tables 2 and 3). In recent years the United States has furnished over 80 percent of the world production of scrap mica.

Domestic production of both sheet and scrap mica comes principally from North Carolina. Other states that recorded production in 1965 included Alabama, Arizona, California, Connecticut, Georgia, New Mexico, Pennsylvania, South Carolina, and South Dakota (Petkof, 1966, table 2).

Arizona has produced mica since at least 1936, and total production is estimated to be approximately 65,500 short tons of crude mica valued at $1 million. At least 12 deposits have been worked for flake and scrap mica at various times since 1936; however, the major part of the production has come from two deposits, one in the Buckeye Hills (No. 3, fig. 60 and table 36), and the other near Quartzsite (No. 17). Both of these properties are owned by the Buckeye Mica Co. The Quartzsite deposit, however, has not been mined since about 1960.

During the period 1942–48 a few hundred pounds of sheet mica was mined from three deposits, the Mica Giant mine (No. 6), M and P Mica claims (No. 7), and the Enid Station deposits (No. 10). Most of this material was purchased by the Colonial Mica Corp., an agency established by the U.S. Government to aid in development of a domestic sheet mica industry to help supply the needs during World War II.

Arizona Deposits and Outlook

Arizona mica deposits fall into three geologic categories: (1) mica schist deposits, including segregations of flake mica in gneissic rocks; (2) pegmatite deposits; and (3) sericite in hydrothermally altered veins and wall rock. By far the most important type, from the standpoint of past production, is the mica schist type, which includes the Buckeye Hills and Quartzite deposits. Some scrap and essentially all of the sheet mica has been obtained from pegmatite deposits. This type is exemplified by the Big Reef (No. 4), Mica Giant (No. 6), M and P Mica (No. 7), and Dixie Queen (No. 13) deposits. The Charleston property (No. 1) is the only deposit of the sericitic vein type known; some ground mica was produced from it during 1958–60 by the Tombstone Mica Co.

During the period 1961–66 an average of about 3,000 tons per year of scrap mica was produced in Arizona. Based on past production, plant capacity exceeds this amount, so the future of the industry in Arizona seems to be more dependent upon market conditions than on reserves.

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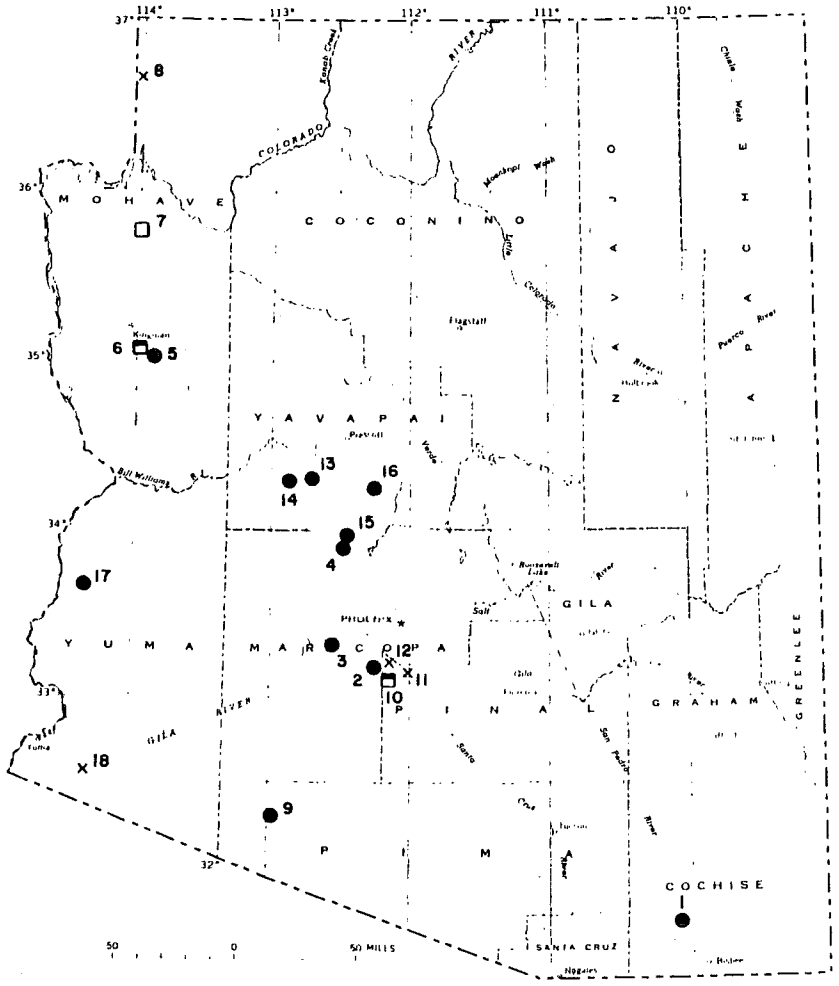

EXPLANATION

□ 7 Sheet mine

● 1 Scrap mine

▣ 6 Sheet and scrap mine

× 8 Occurrence

(Numbers refer to mines or occurrences mentioned in text and listed in table 36)

FIGURE 60.—Mica in Arizona.

TABLE 36.—*Mica deposits in Arizona*

Locality No. in fig. 60	County and property or locality	Manner of occurrence	References
	Cochise		
1	Charleston mine	Veinlike body of finely crystalline sericite in hydrothermally altered rocks. Small quantity processed and shipped as ground mica.	Wilson and Roseveare, 1949, p. 30.
	Maricopa		
2	Estrella Mts., western part	Muscovite books in pegmatite and in coarse flakes in schistose wall rock. Some processed and shipped as ground mica.	Do.
3	Buckeye Hills	Muscovite, in rough, flawed sheets in pegmatite and from schist adjacent to pegmatite and sericite from schist. Requires little milling or grading. Much material processed and shipped as ground mica.	Sterrett, 1923, p. 46; Wilson and Roseveare, 1949, p. 30.
4	Big Reef mine	Muscovite in large, flawed books in the core and intermediate zones of pegmatite dikes, and as small flakes and books in the border and wall zones. Processed for ground mica.	Arizona Bur. Mines, file data.
	Mohave		
5	Mica Hill (Merlo) mine	Nature of deposit not known. Minor amount of scrap and ground mica shipped in 1940's and early 1950's.	Arizona Bur. Mines, file data; Kelly and others, 1957, p. 136; Luff, 1955, p. 119.
6	Mica Giant mine	Muscovite books in pegmatite. Some sheet mica shipped in 1944; scrap mica produced in 1947.	The Mining Jour., 1944; Meeves and others, 1966, p. 20.
7	M and P Mica claims	Flawed muscovite books weighing several hundred pounds each in pegmatite. Small quantity of sheet mica shipped in 1943.	Olson and Hinrichs, 1960, p. 193.
8	Virgin Mts.	Muscovite books in pegmatite dikes and sericite in schistose wall rocks. No production.	Olson and Hinrichs, 1960, p. 189; Sterrett, 1923, p. 47.
	Pima		
9	San Antonio mine (Sunshine deposit)	A very small quantity of scrap mica processed and sold as ground mica.	Wilson and Roseveare, 1949, p. 30.
	Pinal		
10	Enid Station	Flawed muscovite books in pegmatite and sericite in schistose wall rocks. Some trimmed sheet, some scrap and notable quantity of ground mica produced.	Do.
11	Pima Butte	Flaky muscovite in schistose rock adjacent to pegmatite dikes; zones up to 30 ft. in width common.	Wilson, 1963, p. 27.
12	Estrella Mts., eastern part	Muscovite in coarse flakes in schistose wall rock adjacent to pegmatite dikes; zones up to 15 feet in width common.	Wilson, 1963, p. 22, 23.

TABLE 36.—*Mica deposits in Arizona*—Continued

Locality No. in fig. 60	County and property or locality	Manner of occurrence	References
	Yavapai		
13	Dixie Queen	Muscovite in pegmatite dike in granite. Scrap mica produced in 1954.	Meeves and others, 1966, p. 21; Kelly and others, 1957, p. 141.
14	Berrier claims	Muscovite books in pegmatite dikes in granite, and as segregations of flake mica in Yavapai Schist. Small production of scrap mica.	Galbraith and Brennan, 1959, p. 104; Wilson and Roseveare, 1949, p. 30.
15	Long Dike mine	Fine- to medium-grained book muscovite in massive quartz in inner parts of pegmatite dikes.	Jahns, 1952, p. 103.
16	Black Magic mine area	Medium-grained book muscovite in pegmatite dikes and as flakes in schistose wall rocks bordering pegmatites.	Galbraith and Brennan, 1959, p. 104; Meeves and others, 1966, p. 21; Wilson and Roseveare, 1949, p. 30.
	Yuma		
17	Quartzsite	Coarse to fine flaky muscovite and sericite in schistose rocks derived from silty shale. Considerable production of scrap in 1955-60.	Bancroft, 1911, p. 25.
18	Fortuna mine area	Flaky muscovite in pegmatite dikes and coarse-grained sericite in schist adjacent to dikes.	Wilson, 1933, p. 201.

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PERLITE

(By H. W. Peirce, Arizona Bureau of Mines, Tucson, Ariz.)

History and Production

Petrologically, perlite is the name given to a glassy volcanic rock of rhyolitic composition that has a perlitic (onionskin or pearl-like) structure. Typical perlite contains 2 to 5 percent combined water and, when heated to a specific temperature, "pops" or suddenly expands like popcorn to produce a lightweight cellular product that has many commercial applications. Commercially, the term "perlite" has been extended to include any glassy volcanic rock that has this ability to expand.

The perlite industry in the United States began in 1946 with the production of 4,206 short tons of crude perlite reported by five companies, four of which operated near Superior, Ariz. (U. S. Bur. Mines, 1948, p. 1294). Twenty years later, in 1966, U.S. production of crude perlite was about 548,000 short tons (U. S. Bur. Mines, 1967, p. 525).

Of the 9.5 million short tons of crude perlite produced in the country since 1946, the Arizona Bureau of Mines estimates that less than 2 percent came from Arizona. Since inception of the perlite industry, New Mexico has become the principal source of crude perlite in the United States, having supplied about 84 percent of the total in 1965 (Burleson and Henkes, 1967, p. 558). In 1965 Arizona was second to New Mexico in crude perlite production, followed in decreasing order by California, Nevada, Colorado, Idaho, Utah, Texas, and Oregon. In these nine states, 17 companies operated 18 mines.

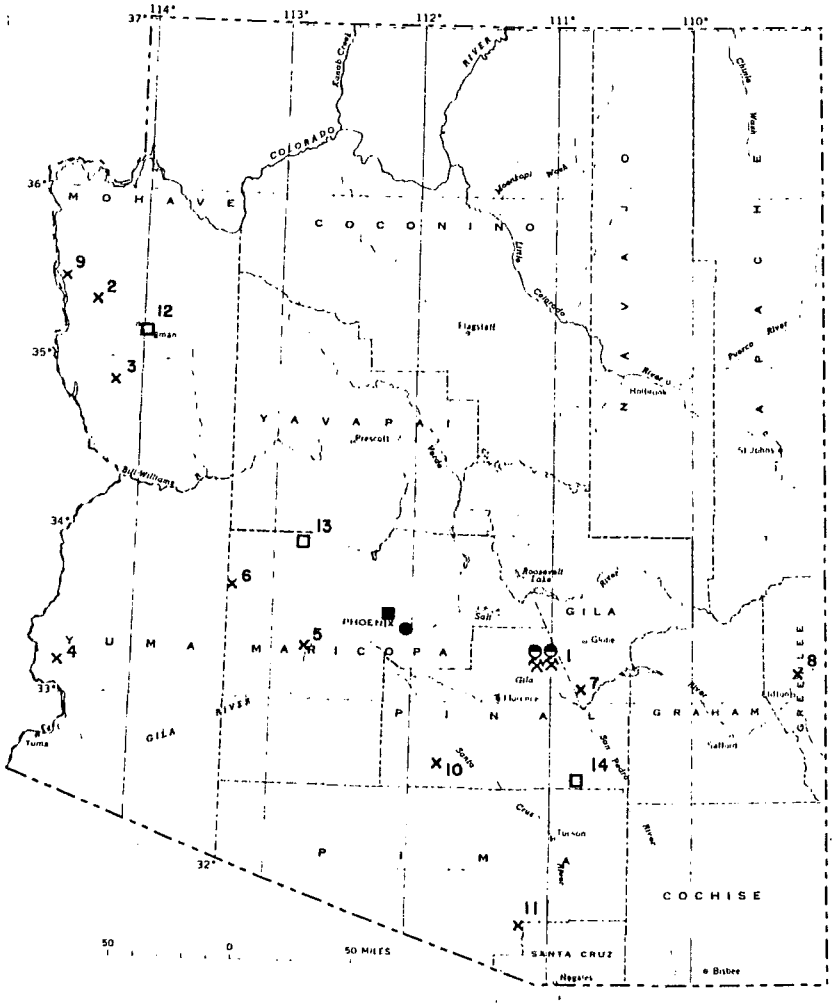
The United States, in 1966, produced 394,300 short tons of expanded perlite valued at $16,403,000 for an average of $41.60 per ton (U. S. Bur. Mines, 1967, p. 525). Illinois was the largest producer of expanded perlite in 1965 (May, 1966, p. 709), the last year the leading producer was announced. In 1966 in the United States crude perlite was expanded by 83 companies at 97 plants (U. S. Bur. Mines, 1967, p. 106) and was used in plasters, insulation, filter aids, fire-resistant materials, soil additives, lightweight aggregates, and in cementing material for oil-well drilling (Burleson and Henkes, 1967, p. 558).

In 1966 Arizona supplied over 30,000 short tons of crude perlite valued in excess of $250,000. Over 98 percent of this material was shipped to plants outside of Arizona and less than 2 percent was "popped" within the State. All of the crude material came from quarries operating in the vicinity of Picketpost Mountain west of Superior, Pinal County. Arizona Perlite Roofs, Inc., operated two mines and crude perlite was shipped to an expanding plant in Maricopa County operated by Supreme Perlite, Inc. The expanded perlite was used as concrete aggregate, as an aggregate replacing sand in plaster, as loose-fill insulation, and as a soil conditioner. Harborlite Corp. operated the Harborlite mine and shipped crude perlite to company-owned and other expanding plants outside the State (Larson and Henkes, 1967, p. 100). In 1967 two sizing plants were operating in the Superior field and preliminary estimates by Arizona Bureau of Mines personnel indicate that production increased at least 25 percent with some shipments being made as far as New York State.

In the Basin and Range province of Arizona volcanic rocks of Cenozoic age commonly contain volcanic glass but their popping or swelling characteristics must be determined in the laboratory. At least preliminary tests have been made on glasses from all localities shown except one.

Arizona Deposits

Figure 61 shows the locations of the principal perlite occurrences in Arizona. Of primary importance, because of large potential reserves and commercial development, is the Picketpost Mountain area about 4 miles southwest of Superior in northeastern Pinal County (fig. 61, locality No. 1). A general discussion of the occurrence of the perlite is provided by Wilson and Roseveare (1945, p. 5), a petrologic description by Anderson, Selvig, Bauer, Colbassani, and Bank (1956, p. 11), and the general volcanic geology is described by Lamb (1962, p. 149), and Peterson (1966, p. 159). According to Wilson and Roseveare (1945), a 5- to 100-foot thickness of perlite is associated with a rhyolitic volcanic phase which is only a part of a larger volcanic complex,



EXPLANATION

Perlite		Vermiculite
Mine	Expanding plant	Occurrence
Occurrence	Sizing plant	Expanding plant

(Numbers refer to localities mentioned in text)

Figure 61.—Perlite and vermiculite in Arizona.

presumably of Tertiary age, that attains a maximum thickness of 1,970 feet in Picketpost Mountain. Lamb (1962) says that locally, glassy siliceous flows reach a thickness of 600 feet and that much of the glass is perlitic. The perlite deposits are extensive and crop out at many places within a northwestward-trending area that is about 10 miles long and 2½ miles wide. The region is served by U.S. Highway 60 and by the Magma Arizona Railway which connects with the Southern Pacific Railroad.

Large deposits of perlite also are known in the southern and middle parts of the Black Mountains of western Mohave County. Apparently some effort has been made to work the deposits although there is no known record of production. According to Wilson and Roseveare (1945, p. 6) perlite from 25 to more than 100 feet thick occurs in the upper part of a volcanic series, totaling 8,000 to 10,000 feet in thickness, consisting of trachyte, andesite, latite, tuff, and basalt. Specifically, they indicate that in the middle area perlite is well exposed in Tps. 22–23 N., Rs. 19–20 W. (locality No. 2), and that in the southern area perlite crops out in secs. 22, 26–28, 34, and 35, T. 17 N., R. 18 W. (locality No. 3). These southernmost exposures are within a mile or so of the Santa Fe Railway.

In addition to the above-mentioned areas, McCrory and O'Haire (1961) show perlite occurrences in T. 3 S., R. 22 W., Yuma County (No. 4); T. 1 S., R. 5 W. near Hassayampa (No. 5) and T. 4 N., R. 10 W. (No. 6) Maricopa County; T. 4 S., R. 15 E. north of Winkelman, Gila County (No. 7); north of Morenci, Greenlee County (No. 8); in T. 24 N., Rs. 21 and 22 W., Mohave County (No. 9); and south of Casa Grande, Pinal County (No. 10). Smith (1966, p. 137), in discussing the geology of the Cerro Colorado Mountains, indicates that dark-gray to pinkish-gray perlitic glass 100 to 200 feet thick occurs in the upper part of a rhyolite vitrophyre (No. 11). This occurrence has not been laboratory tested.

Outlook

Although widespread occurrences of expandable volcanic glass in the Basin and Range province of Arizona offer opportunities for further exploration and development, it is probable that the Superior perlite field is best situated with respect to size and quality of reserves and transportation facilities. Because of these factors the development of a larger perlite industry in Arizona is likely to be centered around the development of the Superior field.

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PUMICE AND PUMICITE

(By S. B. Keith, Arizona Bureau of Mines, Tucson, Ariz.)

Properties and Uses

Pumice and pumicite are acidic glassy volcanic materials having chemical composition similar to that of rhyolite, quartz latite or dacite. They are often referred to as volcanic ash, dust, tuff, rhyolitic sand or pumiceous material. They differ from each other, however, in mode of formation, occurrence, and textural characteristics. Both are normally white to light gray and are composed mainly of silica with lesser amounts of alumina, potash, soda, lime, magnesia, and iron oxide. In general they are chemically inert but can be reactive when in a finely granular condition. The glassy particles or fragments are nearly as hard as quartz and are brittle, breaking with conchoidal and sharp angular fracture. In their natural occurrence, the particles and fragments may be either loosely or well consolidated. Glass usually devitrifies with age so that it is most common to find pumice and pumicite associated with Cenozoic volcanics.

In commercial usage and as reported in the production and use statistics by the U.S. Bureau of Mines, basaltic volcanic cinders and scoria are grouped with pumice and pumicite. There is some textural and genetic similarity between these two types of materials but the differences in chemical composition and the more specialized uses of pumice and pumicite suggest separate treatment in this report. Volcanic cinders and scoria are reviewed under "Basalt and related rocks" (see p. 315).

Pumice is a highly cellular, dull, glassy material consisting of fragments and blocks ranging from about one-eighth inch to several feet in size. The open cavities or cells may be spherical, tubular, or irregular in shape and are separated by thin glassy walls. Due to its sponge-like character, dry pumice is light in weight and many fragments and blocks of pumice will float on water and may absorb as much as 3 percent or more of its weight in water. Pumice originates from molten, silica-rich lava that is highly impregnated with water vapor and other gases. The release of pressure upon extrusion of the lava allows the gases to expand and the rapid cooling and vitrification of the melt preserves the mass of gas bubbles. Silica-rich lavas solidify at high temperatures and thus are found close to centers of volcanic activity.

Deposits of pumice are found as irregular, lenslike bodies closely associated with other volcanic flows and tuffs near major volcanic vents. Such deposits may originate as a part of a volcanic flow, as an ash or pumice fall or flow, or from deposition of pyroclastic material.

Pumicite consists of finely divided, closely packed, angular, glassy fragments ranging downward in size from about an eighth of an inch to extremely fine powder. Despite the fineness, pumicite will sink in water. It originates as volcanic ejecta, blown into the air by volcanic eruptions. The airborne particles are sorted in weight and size by gravity and wind and, after falling to the earth's surface, may be further classified by wind and water action. Thus, pumicite may occur thinly spread over wide areas or in thick accumulations in local basins. In either case, the deposition is often distant from the original source.

Pumice and pumicite have long been used as abrasive materials, either in lump form or as a powder for dressing wood or metal surfaces, preparing metal surfaces for plating, cleaning lithographic stone or metal cooking surfaces, and in industrial and domestic cleaning and scouring compounds and soaps. For these purposes, the particles must be fine, sharp edged and strongly striated to be most effective, and they should not be thin or platy. Pumice and pumicite have been used also as carriers of insecticide, for brick manufacture, filtration, absorption media, soil conditioners and for roughening slippery and icy surfaces. Some water-rich pumice has been heat expanded to produce lightweight aggregate and insulation.

Block pumice is seldom used as a building stone but it is sometimes cut into bricks and panels for lining fireplaces or for decorative purposes. Coarse pumice can be used as a lightweight aggregate for building block but it should be thoroughly dried and all finely divided pumiceous material eliminated since included moisture and fines can result in cracking and spalling of the concrete product. Excessive water in the pumice weakens the bond between the cement and aggregate and the amorphous glass in pumice reacts with any alkalies in the cement to produce soluble silicates that can dissolve under moist conditions or set up stresses in the concrete. Raw pumice is not used as lightweight aggregate in more massive concrete structures due to the risk of this reaction.

The use of pumice and pumicite as a cement material or admixture (pozzolan) in construction dates back more than 2,000 years, to the Romans. This use apparently died out for over a thousand years and was not revived in Europe until the late 1880's. It was not until the 1930's that substantial amounts of pumice and, or, pumicite started to be used by the construction industry in the United States as a pozzolanic material. Pozzolan is a siliceous material which, when in a finely divided form and in the presence of moisture, reacts with calcium hydroxide and possibly other ingredients, at ordinary temperature, to form a cement. The various pozzolanic materials have been investigated by several researchers (Mielenz and others, 1951; Davis, 1949; and Faick, 1959). Thoroughly dried pumicite and pulverized pumice rate as the best potential pozzolans. Other possible pozzolanic materials are artificial fly ash, diatomite, opaline chert, and some types of clay and shale. Other volcanic glasses such as obsidian and perlite

can be pozzolanic but high grinding costs discourage their use for this purpose. However, any suspected pozzolanic material must be thoroughly tested to be sure that it will react in the manner desired for the specific use. Williams (1966) investigated potential pozzolan resources in Arizona and discussed the technology, development, advantages, and disadvantages of these materials. He also listed analyses of some Arizona pumice made by the U.S. Bureau of Reclamation in Denver.

Production

Pumice and pumicite production statistics are reported annually in the U.S. Bureau of Mines Minerals Yearbook but until 1953 the figures were combined with volcanic cinders and scoria. Since 1953, the reported U.S. pumice and pumicite production has averaged over 800,000 short tons per year with values from $3 to $5 per short ton. The unit price was lowest in 1957, 1963, and 1964 when the annual domestic production was more than 1 million tons. In 1965 and 1966, domestic production dropped to 483,000 short tons with an average per ton value of $5.06 and 549,000 short tons valued at $4.79 per ton, respectively. There is no available breakdown of the production of pumice and pumicite by individual states. In recent years, the use of domestic pumice for abrasive use has decreased since foreign sources, mainly West Germany and Italy, can supply the United States market with higher-grade abrasive pumice at competitive prices. In 1966, 270,000 short tons were imported (U.S. Bur. Mines, 1967, p. 545).

In Arizona, the amounts of pumice and pumicite that have been produced can only be roughly estimated. Wilson and Roseveare (1949, p. 51) reported that more than 1,000 carloads of pumice were shipped from a deposit south of Williams in 1947–48 for use mainly in making lightweight concrete block at a plant in Phoenix. In late 1948, 24 carloads of crushed and screened pumice were shipped from northeast of Flagstaff and probably also used mainly as lightweight aggregate. Reportedly, the high moisture content weakened the finished products and the use of this pumice for this purpose was discontinued. The only other notable and definite production of pumice or pumicite in Arizona occurred during 1961–63 when more than 200,000 short tons were mined, crushed, screened, classified, and heat treated for use as a concrete admixture (pozzolan) in the construction of Glen Canyon Dam in northern Coconino County. The source of this material was deposits on the eastern side of Sugarloaf Peak, north of Flagstaff (Williams and Zinkl, 1965). Apparently only minor amounts of pumice or pumicite have been produced in the State since 1963.

Arizona Deposits

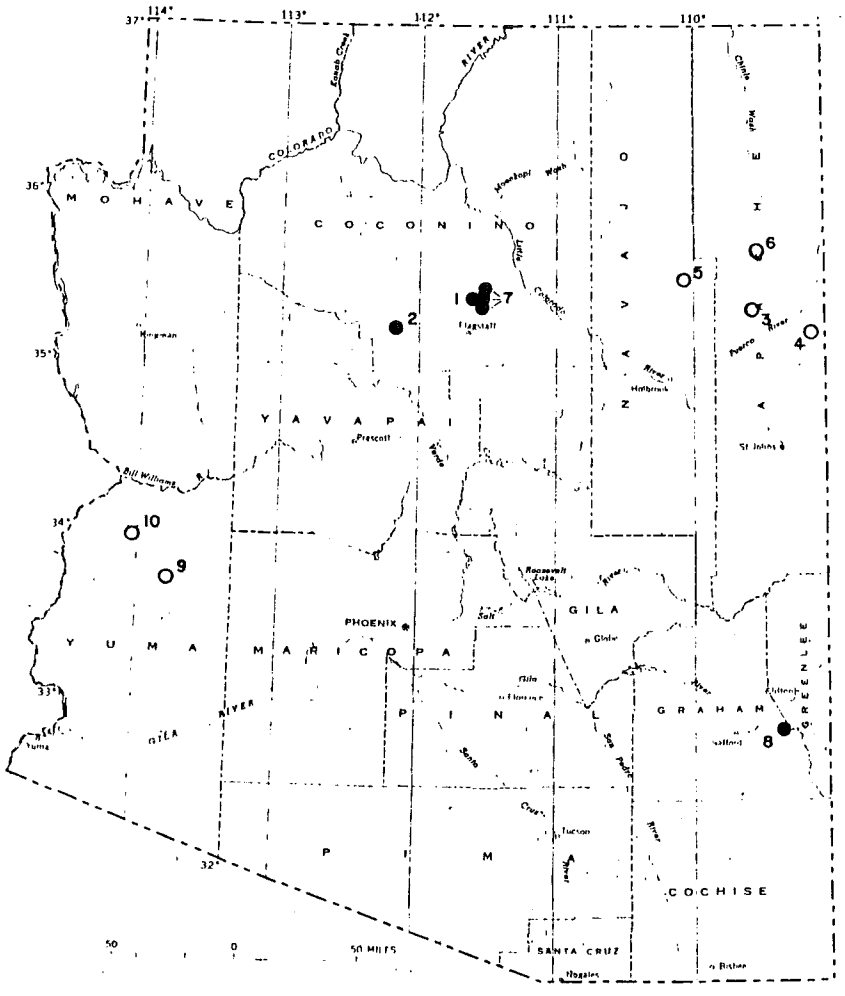
Pumice occurs throughout much of Arizona, particularly in areas near major volcanic vents in some of the large areas underlain by Cenozoic basaltic flows, as indicated on the geologic map of the State (fig. 5). The large central-type vents, now showing as extinct cones, craters, necks and plugs, are most prominent in the San Francisco and surrounding volcanic fields in southern Coconino and northeastern

Yavapai Counties as exemplified by San Francisco Mountain, O'Leary Peak, Kendrick Peak, Sitgreaves Mountain, Bill Williams Mountain, and Mount Floyd. Around such vents, vast quantities of basalt, andesite, latite, dacite, and rhyolite flows and pyroclastics were deposited (Robinson, 1913; Sabels, 1960, 1962). Sabels' studies suggest that much of the rhyolite pyroclastics originated in late Miocene to early Pliocene time, prior to the major period of basaltic flows, but that some rhyolitic to dacitic pyroclastics appear throughout the entire sequence of basaltic flows. Other areas in the State where pumice occurs, such as in southern Graham and Greenlee Counties, appear to have a similar setting but detailed geologic studies of the pumice deposits have not been made.

Pumicite occurs mainly in northeastern Arizona within the Navajo-Hopi Indian Reservations where it occurs as thin beds in the Bidahochi Formation (Cenozoic). Sabels (1960, 1962) believes the material came from the Thirteen Mile Rock volcano, the remnants of which can be seen in the Hackberry Mountain area at the south end of the Verde Valley, northeastern Yavapai County. Repenning, Lance, and Irwin (1958) and Howell (1959) also discuss the tuff beds in the Bidahochi Formation. In general, these tuff (pumice) beds are too thin or have too much admixed foreign matter to be considered as major sources of pumicite.

The only major exploitation of pumice, that for the Glen Canyon Dam, came from surface pits in T. 23 N., Rs. 7 and 8 E., close to U.S. Highway 89 and just east of Sugarloaf Peak, a part of San Francisco Mountain (fig. 62, No. 1). The pumice fragments are rhyolitic, coarse to fine, angular to rounded, bedded or unsorted and loosely consolidated. The deposits cover a large area to depths up to 200 feet. Apparently other pumice deposits occur in the San Francisco Mountain area but have not been studied in detail. The only other pumice deposit that has been significantly worked is 3½ miles south of Williams on the east side of Bill Williams Mountain. It is a dacite pumice with small scattered fragments and crystals of biotite and hornblende and some altered feldspar grains (fig. 62, No. 2) Kiersch (1955) noted pumicite in the Padres Mesa area and in other parts of the Navajo Indian Reservation, Apache County (Nos. 3–5). Hipkoe (1948) described a clean, white, rhyolitic pumicite bed eight feet thick south of Ganado, Apache County (No. 6). In Coconino County, in addition to the Sugarloaf and Williams deposits cited above, Olson and Long (1957, p. 30–31) reported pumice on the northeast slope of Mount Floyd and they and Cosner (1962) noted the pumice in Wupatki National Monument and around Sunset Crater (No. 7). Other deposits of pumice undoubtedly occur in the volcanic fields of north-central Arizona but have not been described.

Wilson and Roseveare (1949, p. 52) noted deposits of pumice along the old Safford-Clifton highway in southern Graham and Greenlee Counties from which two carloads had been produced (No. 8). Since then a few hundred tons per year from this locality may have been shipped to Safford for lightweight concrete block aggregate. They also reported that pumicite deposits were opened for experimental purposes south of Vicksburg, Yuma County in 1948. Williams (1966, p. 51)



EXPLANATION

●7 Pumice occurrence

○9 Pumicite occurrence

Localities

1 Sugarloaf Peak	6 Ganado
2 Williams	7 Wupatki and Sunset Crater area
3 Padres Mesa	8 Old Safford-Clifton highway
4 Bluebird Well	9 Vicksburg
5 Highway 6	10 Bouse

(Localities are referred to in text)

Figure 62.—Pumice and pumicite in Arizona.

22-299 O—69——27

reported a pumicite bed 1½ miles east of Bouse in Yuma County. Other deposits of pumice and pumicite have been reported in various publications but without adequate descriptions and locations.

Outlook

Although the reserves and resources of pumice and pumicite in Arizona are large, amounting to many millions of tons, it is doubtful if any can be economically exploited as abrasive material. In the construction industry in Arizona, pumice has been used as a pozzolan for the Glen Canyon Dam and to a limited extent as lightweight aggregate in concrete blocks. With further experimenting and testing, additional constructional uses may be found. However, pumice and pumicite as pozzolanic material must compete with fly ash from the Joseph City power plant in Navajo County and as lightweight aggregate with the abundant and readily available volcanic cinders and scoria. Unless new markets for their use can be developed in Arizona, future production is likely to be minimal.

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QUARTZ AND QUARTZITE

(By S. B. Keith, Arizona Bureau of Mines, Tucson, Ariz.)

Properties and Uses

Quartz, silicon dioxide (SiO_2), is the most common mineral in the earth's crust. It is an essential mineral in silicic igneous rocks such as granites and rhyolites and it is the major constituent in most pegmatites and in many large veins. In such rocks the quartz ranges from coarsely crystalline to cryptocrystalline. Quartz makes up a large part of many sedimentary rocks, notably sandstone, siltstone, and conglomerate. Metamorphic rocks, such as quartzite and some gneiss are derived from silicic sedimentary and igneous rocks, respectively, and their quartz content may be massive or granular. Quartz crystals or fibrous and granular varieties of quartz, such as chalcedony, agate, onyx, flint, chert and jasper, occur in a wide variety of rocks, commonly lining vugs, druses, or open fractures. Quartz generally predominates in mineral veins and as a gangue mineral in ore deposits and it is the principal mineral constituent in most sand, gravel, and soil.

Quartz normally is colorless or white but it also occurs in a wide variety of colors due to included impurities. When crystalline, the usual form is a hexagonal prism with pointed terminations. Although quartz crystals weighing as much as a ton have been found, quartz generally occurs in finely crystalline form. Quartz is hard and will readily scratch glass, is extremely durable (strongly resists chemical and physical weathering), has a vitreous luster like glass, and breaks with a conchoidal fracture.

Quartzites are sandstones composed mostly of quartz and in which silica has cemented the sand grains so solidly that the rock breaks across both grains and cement. Such quartzites occur in beds of various thicknesses that generally conform to the attitude of the parent sandstone unit.

Crushed or powdered quartz and quartzite are used in "flint" sandpaper, scouring compounds, and abrasive metal polishes. They are used also for roofing granules, road and sidewalk surfacing, aggregate for concrete, decorative composition stone, and as a substitute for silica sand and gravel for many other constructional, industrial, and chemical purposes. Although often superior in quality to other materials for such uses, the costs of mining and processing quartz and quartzite are normally high relative to the value of the derived products and limit its economic exploitation. Thin-bedded slabs of quartzite may be used as flagging and hard, tough quartz and quartzite are used as grinding pebbles and linings in tube and ball mills. A major use of tough, dense quartz and quartzite, when low in iron and alumina, is as a metallurgical flux; this latter use is the major one in Arizona.

The high chemical resistance, hardness, and limited response to temperature change make quartz, either in crystal or fused form, particularly useful as the main raw material in making laboratory mortars and pestles, optical flats, gage blocks, precision balance weights, quartz tubing, and other specialized equipment. The optical and piezoelectric properties of quartz crystal make it indispensible for high quality lenses, lens components, wedges, plates and prisms; and for accurate

frequency control in communication and other electronic devices. For these purposes, the quartz crystal must be above a minimum size and weight, usually at least 1 inch in cross-section and 2 inches in length along the long crystal axis, and a weight of over 100 grams. It also must be free from such defects as physical, optical, or electronic twinning, cracks, inclusions, and bubbles. Optical quartz crystal must be colorless but if only slightly smoky can meet electronic grade specifications.

Some special types of quartz are considered as semiprecious gem material (see "Gem materials", p. 357).

Sources of Supply

The United States has never been a major producer of natural optical and electronic grade quartz crystal and no domestic production is reported for 1966. In the past, mainly during wartime periods, limited supplies were produced in Arkansas, California, Virginia, and North Carolina. A few suitable crystals have been found elsewhere in other States but investigations of possible sources have not found deposits that could supply substantial amounts of satisfactory, high quality material. In most occurrences, the quartz crystal cannot be extracted without being broken or shattered, thus destroying its optical and electronic value. Brazil is the major world source for natural, high quality quartz crystal. There, large crystals have weathered out of veins and pegmatites and are found in eluvial and alluvial deposits. In 1966, the United States imported 265,000 pounds of quartz crystal valued at $596,000 (U.S. Bur. Mines, 1967), of which Brazil supplied 97 percent (U.S. Bur. Mines, 1968, p. 118).

The lack of domestic reserves of natural quartz crystal during World War II stimulated research and subsequent production of artificially cultured quartz crystal in the United States. In 1966, seven plants with a combined production capacity of 80,000 pounds per year were in operation with 85 percent of the product used for oscillator plates and the balance in filter plates, transducer crystals, and miscellaneous other items. Natural quartz crystal in 1966 sold for $2–$35 per pound, depending on the size and quality. Manufactured crystal sold for $25 per pound (U.S. Bur. Mines, 1968, p. 118). Artificial quartz crystal is equal to natural product for electronic purposes but there is no satisfactory high quality substitute for natural crystal for optical uses.

Although large amounts of quartz, other than crystals, and quartzite are produced for various uses in the United States, the tonnages and values of these materials are combined with those for sandstone in the tabulations published by the U.S. Bureau of Mines. Thus no specific figures on production and use of non-crystal-grade quartz and quartzite are available for the country as a whole or for the producing States. The amount, however, probably totals more than a million short tons annually.

In Arizona some promising quartz crystal material has been submitted to the Arizona Bureau of Mines but investigations of the sources of such material have failed to disclose high quality crystal that could be extracted intact and economically. Relatively small amounts of non-crystal-grade quartz and quartzite have been produced inter-

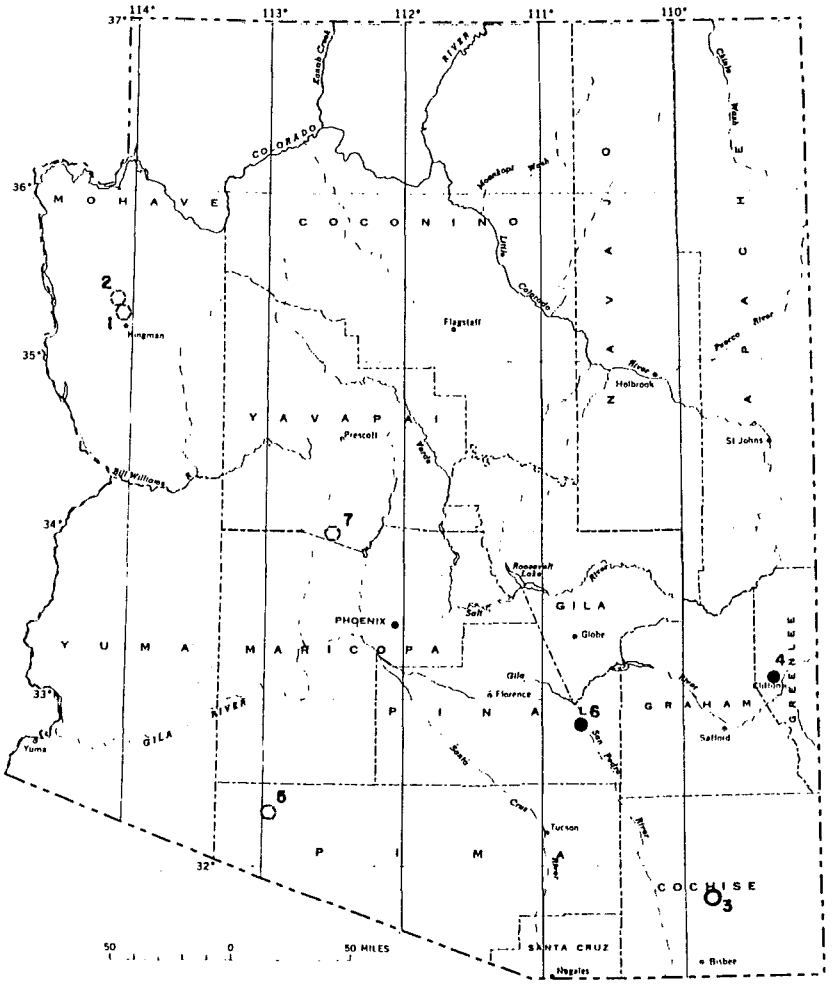
mittently in the State for constructional and decorative purposes. A few carloads of high purity, fused silica were shipped from the periphery of Meteor Crater, Coconino County, during the 1940's and used in California as glass and foundry sand (Wilson and Roseveare, 1949, p. 44). This material was Coconino Sandstone, which had been fused by meteorite impact.

International Minerals and Chemical Corp.'s Taylor Mine and C. F. Week's White Spar mine to the north of Kingman, Mohave County, have been producing quartz for abrasive use from large pegmatite bodies (figure 63, Nos. 1 and 2.) Production figures have not been released but probably totaled more than 15,000 short tons in 1966, with a value between $3 and $4 per ton.

Most quartz and quartzite produced in Arizona has been used for metallurgical flux by the copper smelters. In 1966, over 290,000 short tons were so used and had an average value of about $2.50 per ton. The Andrew J. Gilbert Construction Co. mines quartzite gravel near Courtland, Cochise County, (fig. 63, No. 3), which is used in the Douglas smelter. The gravel is derived from the outcrop of Bolsa Quartzite of Cambrian age, along Turquoise Ridge. Phelps Dodge Corp. and O. Brice Willis mine Coronado Quartzite of Cambrian age, near Morenci, Greenlee County (No. 4) for the Morenci smelter. The San Antonio Mine Co. supplies quartz from a pegmatite body southwest of Ajo (No. 5) which is used to supplement siliceous flux mined in the Ajo open pit for the Ajo smelter. The San Manuel Division of the Magma Copper Co. mines Precambrian or Cambrian quartzite from the Camp Grant deposit along the west side of the San Pedro Valley, Pinal County (No. 6) for use in the San Manuel and Magma smelters.

Arizona cannot be considered a source of more than an occasional specimen of optical or electronic grade quartz crystal but the occurrence of quartzite and non-crystal-grade quartz is so widespread and plentiful in the southwestern half of the State that only a few notable occurrences are cited here. Large masses of coarsely crystalline to massive quartz are found in the pegmatite zone extending from northwestern to southeastern Arizona (Jahns, 1952, p. 6). Only the Taylor and White Spar deposits, north of Kingman, Mohave County, have been extensively worked. The Taylor deposit is described in "Feldspar" (see p. 342) and the White Spar, a short distance further north, is a similar large pegmatite body containing mainly quartz. The product is sold in the California market for abrasive and ceramic uses. Jahns (1952, p. 60) noted that quartz of abrasive, ceramic, and fusing grade would be an expected byproduct of feldspar mining in the White Picacho pegmatite district in southern Yavapai County (No. 7) but noted that the distance from markets would be an unfavorable economic factor. This district also is briefly described in "Feldspar".

The major quartzite deposits of Arizona are of Precambrian or Cambrian age and include the Troy, Dripping Spring, Bolsa, and Coronado Quartzites, of sedimentary origin, in southern Arizona and the Shinumo Quartzite and the metamorphic quartzite beds of the Vishnu Schist in the Grand Canyon area. Only the quartzites of sedimentary origin have been of commercial importance as metallurgical flux but they tend to vary from place to place in quality and thickness.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Kingman
Flagstaff
Prescott
Holbrook
St Johns
PHOENIX
Globe
Gila
Florence
Safford
Tucson
Nogales
Bisbee
Yuma
Bill Williams
Roosevelt Lake
Salt
Little Colorado
Verde
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Muddy
Meadow Valley Wash
Bill Williams
Hassayampa
Agua Fria
Bill Williams
Sonoyta
Sonora
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Rio Grande
Pecos
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Cimarron
Dolores
San Juan
Green
Colorado
Virgin
Muddy
Meadow Valley Wash
Bill Williams
Hassayampa
Agua Fria

The Mazatzal Quartzite (Wilson, 1939), of Precambrian age, occurs in scattered localities in central Arizona but appears to be of little commercial importance. Bryant (1959, p. 40–41) and others have recognized quartzites that might be used locally in the Scherrer Formation, of Permian age, in some mountain blocks of southeastern Arizona. Most of the quartzites or formations containing quartzite units are listed in table 5 (p. 40).

Outlook

The development and production of quartz and quartzite in Arizona depends on available markets within economic shipping distances. The market for abrasive, ceramic, and fused quartz is rather limited and at present is well supplied. The market for quartz and quartzite for construction and decorative purposes is small and less expensive substitutes are abundant. The principal market for quartz and quartzite in Arizona is as metallurgical flux, a low price product, but this market is closely controlled by the needs of the copper smelters and any large increase in such use is not foreseen.

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SALINES

(By H. Wesley Peirce, Arizona Bureau of Mines, Tucson, Ariz.)

Introduction

As used in this report the term "salines" comprises a group of readily soluble substances, or salts, that may occur separately or in combination, and either in solution (sea water or brines) or as solids (evaporite deposits). Of principal economic interest are chlorides of sodium (halite or common salt) and potassium; sulfates and carbonates of sodium; borates; and bromine and iodine. In the United States, products annually derived from naturally occurring salines (exclusive of sea water), are valued in excess of $500 million.

Because a salines industry has not yet been developed in Arizona, all of the essential products in this category are imported from other states. However, because of Arizona's industrial growth, it is only a question of time before some of the State's saline resources are developed.

Of the principal saline resources, only significant quantities of sodium chloride, potassium chloride, sodium sulfate, calcium sulfate (gypsum), and natural brines are known in Arizona. These are described below and shown in figure 64 except for gypsum, which is described in a preceding part of this report (see p. 371, and fig. 57).

Sodium Chloride

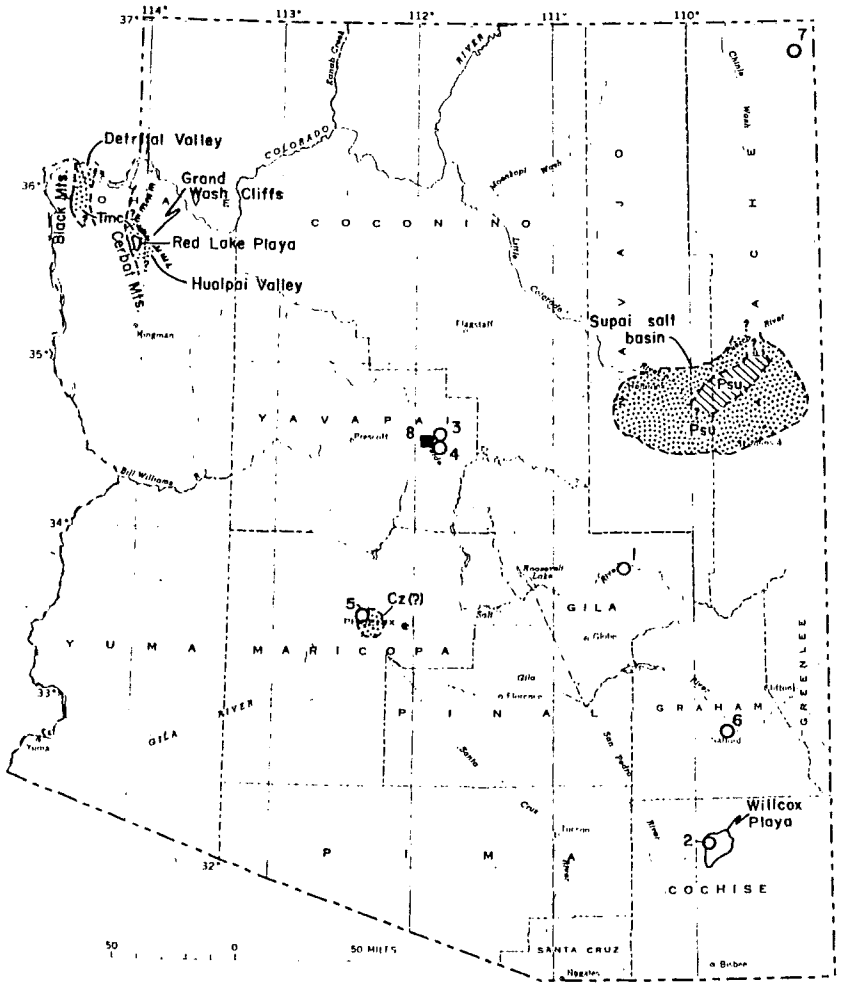
Naturally crystallized sodium chloride is common rock salt, or halite. Solid deposits of halite may either be mined conventionally or subjected to solution extraction and reprecipitation by brining operations. In addition, natural brine lakes, or sea water, may be evaporated to produce sodium chloride. In the United States, in 1965, 36.4 million short tons of sodium chloride were processed to yield products valued at more than $215 million (U.S. Bur. Mines, 1967, p. 547). The chemical industry, producing chlorine, caustic soda, soda ash, and other products, consumed 66 percent of the total production. Salt used for snow and ice removal was second, accounting for 13 percent, and ordinary table salt amounted to only 3 percent of the total. It is estimated that over 50,000 short tons of salt are imported into Arizona from New Mexico and California each year, the major use being as a feed supplement, principally for cattle.

Sodium chloride is widely distributed in Arizona, occurring in many surface and subsurface waters as well as in deposits as crystalline material. Because salt deposits accumulate by evaporation of salty water under a wide range of circumstances, there is a wide range in the nature and size of salt accumulations. However, only the large deposits in the State are of immediate interest. These are discussed below under east-central, northwestern, and central Arizona.

EAST-CENTRAL ARIZONA

The oldest known salt deposits in Arizona are in the Supai Formation (Permian) in the subsurface of southern Navajo and Apache Counties in the southern part of the Colorado Plateaus province (fig. 64) under an area generally referred to as the Supai salt basin, which embraces approximately 2,300 square miles. The principal halite deposits, associated with anhydrite, dolomite, and clastic red beds, occur as discontinuous units or zones within an evaporite-bearing stratigraphic interval between the Fort Apache Limestone Member of the Supai Formation below and the overlying Coconino Sandstone. This interval ranges in thickness from about 450 to 1,300 feet, the halite occurring within the thicker parts (Peirce and Gerrard, 1966). Depths to the top of the evaporite interval, which is marked by an anyhydrite-gypsum zone, range from 600 to 2,500 feet, the deepest parts being in the northeastern part of the basin.

Knowledge about the characteristics, position, and habits of the halite in the Supai has been gained as a byproduct from drilling efforts in search of water, oil and gas, helium, and potassium minerals. Oil and gas tests generally penetrate the entire evaporite interval while other tests normally do not penetrate more than the upper part of the sequence. Drilling designed specifically to determine the nature and



EXPLANATION

Approximate outline of area underlain by halite; questioned where uncertain (Cz(?), salt basin, of Cenozoic(?) age; Tmc, Muddy Creek Formation, of Tertiary age; Psu, upper member of Supai Formation, of Permian age)

Approximate outline of area underlain by potash; questioned where uncertain (Psu, upper member of Supai Formation, of Permian age)

■ 8 Sodium sulfate occurrence at surface

○ 6 Brine occurrence, spring or well

(Numbers refer to localities listed in table 37 and referred to in text)

Figure 64.—Salines in Arizona.

distribution of the halite has not been undertaken. However, indications are that the principal concentration of halite occurs in a zone 400 feet thick within the upper half of the evaporite interval along a northeast-trending belt between Snowflake in Navajo County and Pinta Dome in Apache County, a distance of about 55 miles (fig. 64).

Although the Permian halite deposits in east-central Arizona are not now being utilized, they are potentially useful. Principal potential markets in the Four Corners area are related to the cattle industry and to road deicing. The proximity of the Supai salt basin to the Santa Fe Railway and U.S. Highway 66, both major transcontinental routes, is a favorable factor. In addition, the sparse population and limited agricultural developments in the general area may make these deposits attractive as possible underground storage sites for petroleum products, helium, or radioactive wastes. Storage cavities can be produced by either conventional underground mining or by solution mining.

NORTHWESTERN ARIZONA

Large subsurface deposits of high-grade halite are present below parts of the valley floors of both Detrital and Hualpai valleys in northern Mohave County in the Basin and Range province of extreme northwestern Arizona (fig. 64). In both valleys, salt was first encountered in holes drilled for water wells. Subsequently, in the late 1950's parts of both valleys were drilled to determine the nature of the salt and to search for possible associated "exotic" saline components. In Hualpai valley, Kerr-McGee Oil Industries, Inc., drilled two holes south of Red Lake playa in secs. 28 and 30, T. 26 N., R. 16 W. The deepest hole encountered salt about 1,400 feet below the surface and was still in halite when bottomed at a depth of 2,608 feet. This salt interval, consisting almost wholly of halite, is at least 1,200 feet thick.

In Detrital valley, northwest of Red Lake playa and nearer Lake Mead, several holes were drilled by the Goldfield Consolidated Mines Co. in Tps. 29–30 N., R. 21 W. Halite was encountered at depths ranging between 300 and 800 feet below the surface. The penetrated salt is reported to have ranged between 500 and 700 feet thick (Pierce and Rich, 1962, p. 65).

To the north, in adjacent parts of Nevada, halite crops out along the lower reaches of Virgin valley. The salt under the Hualpai and Detrital valleys probably represents a depositional phase of the Muddy Creek Formation (Pliocene(?)). However, the geologic history bearing on the relations between the origin of the valleys and the accumulation of the seemingly extensive salt deposits has not been worked out satisfactorily, partly because the valleys are separated by the Cerbat Mountains, which obscure any obvious physical connection. Also, the limits of salt distribution along and beneath the elongated valley floors is yet to be determined. It is possible, however, that buried evaporite deposits occur extensively within the valley complex that parallels the Grand Wash Cliffs, both north and south of the Colorado River.

There has been no known attempt recently to utilize the halite deposits of the Hualpai-Detrital valleys, although there have been

reports that preliminary considerations were made to exploit halite in Detrital valley to supply potential needs in the Las Vegas area. As underground storage sites, these deposits might be useful and there could be undiscovered deposits of more highly valued salines in other parts of the valleys.

CENTRAL ARIZONA

In Maricopa County a water well in sec. 19, T. 2N., R. 1 W. (fig. 64, locality No. 5) encountered halite and associated brine at a depth of 2,350 feet in Cenozoic sedimentary rocks (Stulik and Twenter, 1964, p. 10–11. Total depth of the well is not given, so the thickness and nature of the salt deposit is not known. In addition, the notation "solid rock salt" is included in a description of the bottom sedimentary rocks encountered in a water well drilled to a depth of 1,452 feet in sec. 21, T. 2 N., R. 1 W. about a mile from locality No. 5 (Kam and others, 1966, p. 50). These two occurrences suggest the possible existence of a Cenozoic salt basin (fig. 64). Because this area is within 20 miles of Phoenix, plans are currently (1968) being made to determine the nature of this salt deposit. Should there prove to be an adequate reserve, Arizona could have a new industry. Exploitation of such a deposit would involve pumping brine to the surface and recovering the salt by solar evaporation.

Potassium Chloride

Naturally crystallized potassium chloride is the mineral sylvite. Sylvite, when present, is usually intermixed with halite, the resulting rock termed "sylvinite." Although there are other potassium-bearing saline minerals, sylvite is the principal source of potassium for industry. "Potash" is the informal term used to describe potassium-bearing saline deposits. Potassium is an essential plant food element, so its compounds are used primarily as fertilizers. In 1966, the United States produced over 5.7 million tons of marketable potassium salts valued at more than $116 million, New Mexico accounting for about 90 percent of the production; in the same year, the United States imported over 2.5 million tons of potassium compounds mostly from Canada (U.S. Bur. Mines, 1967, p. 535, 536, 540).

In relatively recent times potash deposits consisting principally of sylvite were discovered in the Permian evaporites of east-central Arizona. Initial recognition of potash in the area stemmed from interpretation of mechanical logs run on a hole drilled in 1958 in sec. 23, T. 18 N., R. 25 E., Apache County. Subsequently, in the period 1963–66, about 100 exploration holes were drilled in both Apache and Navajo Counties by six companies who expended several million dollars in an effort to outline commercial deposits of sylvinite. This drilling delineated a northeast-trending potash zone under an area of about 300 square miles (fig. 64), about 50 square miles of which projects under the Petrified Forest National Park and so is closed to exploration. Although the potash zone is irregularly extensive, details of grade and thickness have not been released. Exploration activity has slackened recently, perhaps suggesting that the deposits do not justify major development costs under present conditions.

The potash zone of east-central Arizona is within 150 feet of the top of the evaporite section which, in most places, is marked by an anhydrite bed. Depths to the sylvinite range between 700 and 2,000 feet below the surface, the shallower depths being to the southwest and the deeper depths to the northeast along the zone shown in figure 64. Deposits of sylvinite or other potassium salts are not known to occur elsewhere in the State.

Sodium Sulfate

Sodium sulfate occurs in the natural brines and crystal masses of playa lakes and as beds in sedimentary rocks. The principal sodium sulfate minerals are thenardite (Na_2SO_4), mirabilite or glauber salt ($Na_2SO_4.10H_2O$), and glauberite ($Na_2SO_4.CaSO_4$). In the United States sodium sulfate is produced from brines and as a byproduct of various chemical processes. Its principal use is in the digestion of pulpwood used in the kraft paper and paperboard industry.

In Arizona, the only known sodium sulfate deposit of significant size occurs in the Verde Formation (Cenozoic) 1½ miles southwest of Camp Verde in Yavapai County (fig. 64, locality 8). A flat-lying sedimentary unit, 4½ feet thick, contains a mixture of thenardite, mirabilite, glauberite, halite, gypsum, and clay. The deposit was exploited for a number of years prior to 1933, when, for economic reasons, operations ceased. Current transportation and beneficiation costs handicap the further development of this occurrence.

Natural Brines

Natural brines, as used in this report, are naturally occurring waters that contain a high concentration of dissolved solids. Saline waters containing dissolved solids in excess of 35,000 parts per million have been classified as brines (Winslow and Kister, 1956). However, brines exploited for saline components usually exceed this concentration. In the United States brines are an important source of common salt, potassium compounds, bromine, borates, lithium, iodine, magnesium, sodium carbonate, and sodium sulfate.

In Arizona, highly saline waters are encountered in wells, springs, and in playa lakes, but there has been no known attempts in recent years to commercially exploit such waters. Regardless of exploitability, however, saline waters might lead to hidden saline deposits. Table 37 lists the principal brine occurrences in Arizona. The saline contents of water wells Nos. 3 and 4 (fig. *64*) in the Verde Valley are associated with the sodium sulfate deposits in the Verde Formation. Similarly, the association of the brines with "rock salt" in the water well at locality 5, west of Phoenix, has been mentioned. The source of the salt in Orange spring at the Salt Banks along Salt River just below the bridge on State Highway 77 (locality 1) is not known. The source of salines in the water well at locality 6 near Safford, in Graham County, may be from halite because discrete halite crystals within a muddy matrix were noted in samples taken from a nearby water well drilled in sec. 26, T. 7 S., R. 26 E. Brines are also present in some of the oil wells in northern Apache County (locality 7) on the Navajo Indian Reservation.

TABLE 37.—SELECTED BRINE OCCURRENCES IN ARIZONA

Locality No. in figure 64	Name and location	Total dissolved solids in parts per million	Remarks	Reference
1	Orange spring, Salt Banks on Salt River, sec. 13, T. 5 N., R. 16 E., Gila County.	37,300	Dissolved solids largely sodium and chloride.	Feth and Hem, 1963, p. 39.
2	6-foot augerhole, Willcox playa, sec. 4, T. 15 S., R. 24 E., Cochise County.	106,000	Dissolved solids largely sulfate, chloride, and sodium.	Brown and others, 1963, p. 82.
3	Water well, Camp Verde, sec. 32, T. 14 N., R. 5 E., Yavapai County.	176,893	Dissolved solids largely sulfate, chloride, and sodium.	Smith and others, 1963, p. 21.
4	Water well, Camp Verde, sec. 15, T. 13 N., R. 5 E., Yavapai County.	90,300	Dissolved solids largely sodium and chloride.	Twenter and Metzger, 1963, p. 92.
5	Water well, sec. 19, T. 2 N., R. 1 W., Maricopa County.	191,000	Dissolved solids largely sodium and chloride.	Stulik and Twenter, 1964, p. 25.
6	Water well, Safford, sec. 22, T. 7 S., R. 25 E., Graham County.	120,000	Dissolved solids largely sodium and chloride; sample taken from depth of 1,250 feet.	L. R. Kister, oral commun., 1968.
7	Oil wells in Four Corners region, northern Apache County.	(1)	Brines associated with oil	Arizona Oil and Gas Conserv. Comm.

[1] No information.

According to Arizona Oil and Gas Conservation Commission records, about 30,000 barrels of saline water are produced from these wells each month, but no information is available on the composition of the saline material. Relatively high bromine contents have been reported from brines in some wells in southeast Utah (Hite, 1964, p. 213) that are associated with evaporite deposits of the Paradox Member of the Hermosa Formation (Pennsylvania). Although some oil occurs where the Paradox Member extends into Arizona, evaporites other than minor gypsum-anhydrite are not known to be present.

Outlook

The potential for exploitation of Arizona's saline resources varies according to projected usage and the economic conditions surrounding each use. The development of a local sodium chloride industry is possible within the near future whereas the development of an industry to exploit potassium chloride in the Supai salt basin near Holbrook in the near future seems doubtful. The indirect use of halite deposits as storage sites for petroleum products, natural gas, helium, or radioactive wastes is a possibility, especially those near processing plants and existing transportation routes.

The possibilities for discovering new saline resources in Arizona are good, especially by accidental encounter during drilling operations in the basins of the Basin and Range province.

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SAND AND GRAVEL

(By S. B. Keith, Arizona Bureau of Mines, Tucson, Ariz.)

Introduction

Sand and gravel are the most common and important industrial rock products used, exceeding in total tonnage the production and use of any other rock material in the United States. In Arizona, the annual tonnage used outranks that of any other mineral resource and ranks second to copper in total value.

Sand and gravel consist of unconsolidated detritus ranging from the finest powdery silt and clay to large boulders and are defined by size as shown in table 38. In normal commercial usage, sand is commonly classified as "granular particles passing the ⅜-inch (aperture) sieve and almost entirely passing the No. 4 (4.76 millimeter or approximately 3/16-inch) sieve but predominantly retained on the No. 200 (0.074 millimeter or 74 micron) sieve." "Gravel is granular material predominantly retained on the No. 4 sieve" (Am. Soc. Testing Materials, 1967, pt. 10, p. 83). No upper size limit is specified for gravel but material over 2½ inches in diameter is usually rejected by screening or crushed to a smaller size. Although artificially crushed and pulverized stone is not reported as sand and gravel, the products from processing friable sandstone and weakly cemented conglomerate and the crushed oversize material from sand and gravel operations usually are so reported. Aggregate is a term commonly used for sand, gravel, and broken stone, particularly when mixed with cement, lime, or bituminous material to make concrete, mortar or asphalt surfacing. The physical characteristics and chemical composition of sand and gravel affect their use but are too variable to be included in any definition.

TABLE 38.—CLASSIFICATION OF DETRITAL PRODUCTS BY SIZE (AFTER C. K. WENTWORTH, 1922)

Material and size categories	Size of screen aperture						ASTM standard mesh No.	
	Larger than			Smaller than				
	Millimeters	Inches	Microns	Millimeters	Inches	Microns	Retain	Pass
Gravel:								
Boulders	256	10						
Cobbles	64	2½		256	10			
Pebbles	2	1/16		64	2½		10	
Sand:								
Very coarse	1	3/64	1,000	2	1/16		18	10
Coarse	½		500	1	3/64	1,000	35	18
Medium	¼		250	½		500	60	35
Fine	⅛		125	¼		250	120	60
Very fine	1/16		62	⅛		125	230	120
Mud:								
Silt	1/256		4	1/16		62		230
Clay				1/256		4		

Sand and gravel particles may be angular to rounded and elongated to spherical in shape, depending on the characteristics of the parent materials and the amount of disintegration and abrasion that has taken place. The sand grains and rock particles may consist of one or more minerals but crystalline quartz, one of the most common minerals, usually predominates and is the most desirable constituent. Other common minerals in sand and gravel are feldspar and mica. The presence of more than minor amounts of silt and clay or other soft, friable, unsound, and chemically active materials such as mica, kaolinized feldspar, amorphous silica, carbonaceous matter, iron oxides, and salts normally are undesirable. The specifications for sand and gravel for construction use have become increasingly strict in recent years and careful field checks and laboratory testing often are required to determine the suitability of a deposit for exploitation. The specifications for industrial sand, sand used for specialized purposes other than construction, are even more stringent. Table 39 lists the general uses and specifications for sand and gravel. For additional information on specifications and use see Lenhart (1960) and Cotter (1965).

Sand and gravel deposits result from the natural disintegration and abrasion of rock through the combined action of weathering and erosion. The character of the deposits depends on the original rock constituents, the type and duration of the disintegration and abrasion processes, the manner and distance of transportation, and the form and manner in which the products are deposited and, or, reworked. Most rocks can yield sand and, or, gravel but the products from different rocks vary greatly in quality and size and shape of particles. Sandstone and conglomerate are excellent source rocks for sand and gravel. Friable sandstone yields sand but little or no gravel. Dune and beach sandstone deposits are common sources of high quality industrial sands and some beach gravels make excellent aggregate. Limestone and dolomite can yield good sand and gravel deposits but shale and schist are poor sources. Quartz-rich, fine- and even-grained granitic rocks and diabase generally are good source rocks for sand and, or, gravel and, of the volcanic rocks, basalt is an excellent source of aggregate. Some gneisses yield good sand but most gneisses yield poor gravel due to their laminated structure and high mica content.

TABLE 39.—*General uses, specifications, and supplies of sand and gravel*

Use	Material	Physical properties	Chemical properties	Arizona supplies
Construction				
Concrete	Sand	Clean, well-sized, hard, durable particles. No weak, soft, friable, or coated material such as clay, loam, mica, salts, or oxides.	High silica content as crystalline quartz but low in amorphous silica (chert, opaline silica, and volcanic glass), alkali salts, and organic matter.	Plentiful, but sources vary as to accessibility and quality and require testing.
	Gravel	Clean, well-sized, hard, durable, and sound particles, cubical to spherical in shape.	do.	Vary between areas in quantity, quality, and accessibility.
Plaster and mortar	Sand	Sizing should be minus no. 4 mesh but not silty. Other properties similar as for concrete.	do.	Plentiful, but testing required.
Road base	Sand	Same as for concrete except sizing less important and small amount of clay often desirable.	Impurities are less important then for concrete, except for organic matter.	Plentiful.
	Gravel	Hard and durable particles of 1 to 1-1/2 inches in diameter with specified percentage of fines and clay.	do.	Adequate, but not equally available in all areas.
Bituminous road mix (black top)	Sand	Clean, well sized, fine grained; angular sand preferred as it provides maximum surface for oil absorption.	Generally not important.	Adequate, but can substitute crushed and broken stone and volcanic cinders.
	Gravel	Clean, angular, well-sized stone, 1 to 1-1/2 inches in diameter preferred.	do.	Adequate, but not equally available in all areas. Can substitute broken stone, volcanic cinders, and scoria.
Railroad ballast	Sand and gravel	Clean, angular, fairly coarse, well-sized material that will pack and set.	do.	Generally not used because crushed and broken stone is accessible and more suitable.
Fill	Sand and gravel	Depend on conditions and purpose of use. Vary from "as is" to specified qualities.	do.	Plentiful in most areas.
Industrial				
Abrasives				
Sandblasting	Sand	Sound, precisely sized, hard, tough grains. Depending on use, required shape may be rounded, subangular or angular and size may be fine to coarse.	Should be almost pure crystalline quartz and free of clay, coated grains, or other foreign material.	Adequate supplies, but sources require careful processing and testing.
Glass grinding	Sand	Clean, washed, evenly sized, sound, hard, rounded to subangular grains between 30 and 100 mesh.	Should be almost pure crystalline quartz very low in impurities, particularly iron.	Some suitable deposits but require careful processing and testing.

TABLE 39.—*General uses, specifications, and supplies of sand and gravel*—Con.

Use	Material	Physical properties	Chemical properties	Arizona supplies
Industrial—Continued				
Abrasives—Continued				
Stone sawing	Sand	Clean, hard, well-sized, tough, and durable grains, 12 to 100 mesh, free from flat fragments and fines.	Should be mainly crystalline quartz but chert sometimes used when readily available.	Some suitable deposits but careful preparation required.
Glass manufacture	Sand	Uniformly sized, 30 to 200 mesh, clean, high quality sand without fines or coarse grains. No ilmenite, iron oxides, spinels, aluminum silicates, manganese oxides, refractory minerals, or other colorants permitted.	Should be plus 99 percent crystalline quartz with extremely low iron, alumina, lime, magnesia, and alkali content. Many other elements allowable only in trace amounts.	No sources known.
Chemical manufacture (Sodium silicate or water glass, silicon carbide or carborundum, silicones, gels, and other chemicals)	Sand	Similar to glass sand except colorant materials are not as critical for some uses.	Same as for glass sand.	No known sources.
Metallurgical				
Silicon alloys (produced in electric furnace)	Gravel	Clean, well-sized, sound, and durable pebbles, generally 1/2 inch diameter or larger. Chert and opaline silica not desirable.	Should be almost pure quartz (plus 99 percent) with very low alumina, iron, base-metal oxides, and titanium and no phosphorous or arsenic.	Do.
Silcon metal (produced in electric furnace and used as deoxidizer in metallurgy)	Gravel	Well-sized, dense and tough pebbles, 1/2 inch or larger diameter.	do.	Do.
Furnace flux (for reduction of phosphate rock)	Gravel	Clean, well-sized pebbles, between 1/4 inch and 4 inches in diameter.	Should have more than 90 percent silica and low water, ferric oxide, alumina, carbon dioxide, and calcium oxide content.	Do.
Refractory				
Foundry molds for castings	Sand	Clean, well sized 40 to 100 mesh without clay that packs with high permeability but forms a sound strong mass under compression, shear, and tension.	High refractory silica with low impurity content.	Some deposits may be suitable but will require careful processing.
Furnace lining and patching	Sand	Crude silica sand, 3-mesh to silt size and containing some bonding clay, fines, and iron oxide.	Relatively high silica content desired; minor impurities not important.	Some deposits may be suitable.

TABLE 39.—*General uses, specifications, and supplies of sand and gravel*—Con.

Use	Material	Physical properties	Chemical properties	Arizona supplies
Refractory—Continued				
Ganister mix (lining, patching, and coating molten metal containers or furnaces)	Sand or gravel	Mixed, variable-sized 5/16 to 10-mesh gravel or 50- to 200-mesh sand and refractory clay. Chert also used.	Relatively high silica content.	Some deposits may be suitable.
Naturally bonded molding for light iron, brass and bronze castings	Sand	Crude sand naturally admixed with clay of desirable physical characteristics.	Should have uniform and specified silica, alumina, and iron content.	No known source.
Processed molding (to form cores and molds used for ferrous and nonferrous castings)	Sand	Well-sized clean sand with specified permeability.	Should have high silica content and limited alumina and iron.	Some processed sand may be suitable.
Refractory pebble for high-acid refractory	Gravel	Clean sized pebbles.	High silica but not amorphous, and very low alumina, iron, lime, and alkali and no titania.	No known source.
Runner lining and dams in foundries	Sand	Crude, coarse-grained sand with moderate amount of clay bonding to give plasticity.	Moderately high silica content.	Some deposits may be suitable.
Coal washing	Sand	Clean, well-sized, 30- to 100-mesh, subangular to rounded, sand with at least 2.64 sp. gr.	Relatively pure crystalline quartz.	Do.
Filter media for water supply systems	Sand and gravel	Clean, well-sized material with no clay or silt. Gravel should be durable and rounded with at least 2.6 sp. gr. and when emplaced as underdrain have at least 35 percent porosity. Sizing of gravel in successive layers, bottom to top, normally 3-1/2 to 3/32 inches. Overlying sand sizing may vary but uniformity desirable.	High silica content with no iron or manganese and low acid solubility.	Some deposits can be processed to meet specifications.
Hydrofrac (to facilitate the flow and extraction of water, gas, and oil)	Sand	Clean, sound, tough, rounded, 20- to 40-mesh, light-colored sand; no aggregated particles or clay, silt, or organic matter. High permeability most important.	Relatively pure crystalline quartz.	Some deposits meet the requirements.
Standard testing	Sand	Very clean dry sand of selected properties and characteristics.	Specifically defined.	Some sand suitable.
Traction (Particularly for railway engine and truck sand boxes)	Sand	Well-sized, 20- to 70-mesh, angular or subangular, sound, tough, free-flowing grains.	High quartz content most desirable.	Some suitable sources.

Residual sand and gravel deposits, which result from the disintegration of rock in place, are poor sources of sand and gravel because of chemical alteration and lack of good sizing. Talus deposits may locally contain poorly sorted, angular gravel, but little sand. Wind action produces dune sand and wave action produces beach sands and gravels. In Arizona the most important sand and gravel deposits are the ones formed by the transportation, deposition, and reworking of detritus by stream action. Such deposits occur in basin and valley fills, in stream terraces, in buried and active stream channels, and in alluvial fans.

Sand and gravel deposits are mined in open pits, and the materials are transported by truck or belt to stationary, portable, or combination processing plants where the material is cleaned and classified by washers and screens. Small amounts of sand and gravel are used in untreated form but most material is now processed before use. Construction-grade sand and gravel are low value materials which can be transported economically for only short distances. Stationary plants are installed at large deposits close to major markets such as cities, and portable plants are employed where the use is temporary, intermittent, or frequent moves are required as in highway construction. Combination plants offer flexibility to meet varying market conditions and to exploit different deposits. Industrial sand plants are stationary and are located near the deposits because the sources of such material are more restricted, the processing more specialized, and the higher value of the product permits costs of shipment to more distant markets.

Production and Use

U.S. producers used or sold 934 million short tons of sand and gravel valued at $985 million in 1966 (U.S. Bur. Mines, 1967, p. 556). The construction industry consumed almost 97 percent of the output, which was used mainly in concrete. Federal, state, county, and municipal agencies or their contractors accounted for over 25 percent of the total tonnage. Over 86 percent of the production was processed for use and the ratio of sand to gravel was 2 : 3. Industrial sand made up less than 3 percent of the total tonnage but accounted for about 9 percent of the total value; a minor amount was unclassified as to use. Most of the individual sand and gravel operations produced less than 200,000 tons during the year but collectively such operations accounted for more than one-third of the total output.

Figure 65 shows the estimated and recorded annual tonnage of sand and gravel produced and used in Arizona for the 1900–66 period and figure 66 shows the annual value of the production for the same period. The tonnage of sand and gravel produced in Arizona for the 1900–66 period totaled more than 212 million tons and had a value of more than $200 million. These figures are based on incomplete data, however, especially for the 1900–38 period. Prior to 1920, no published figures are available and annual estimates are based on information in the files of the Arizona Bureau of Mines. From 1920 to 1938, published figures are incomplete and since 1938 some company confidential data have been withheld.

Figure 67 shows the respective amounts of sand and gravel produced and used in Arizona since 1920 and illustrates the relatively greater

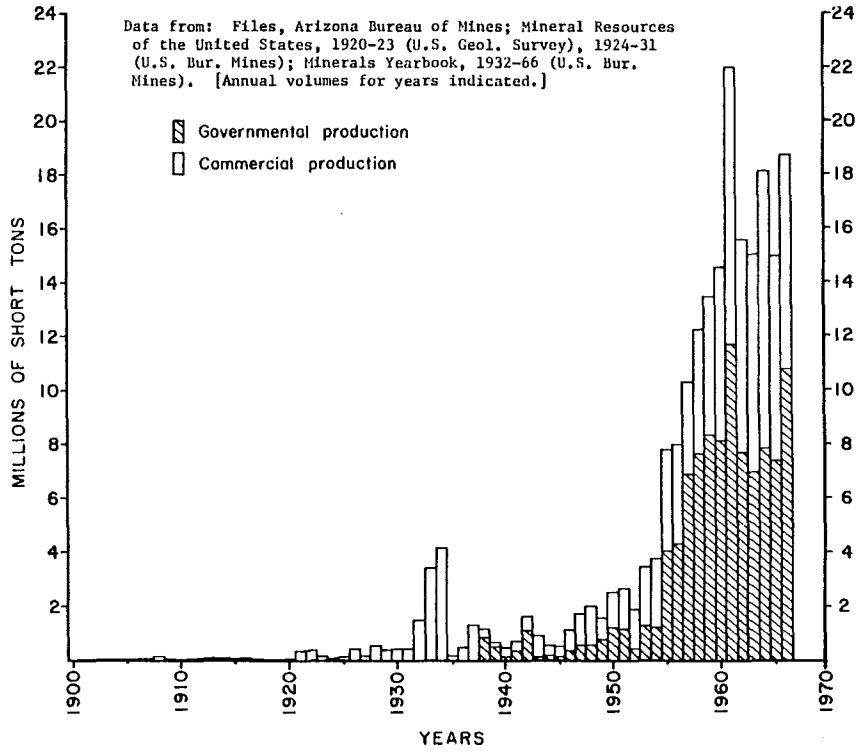

Figure 65.—Annual tonnage of sand and gravel produced and used in Arizona, 1900–66.

demand for gravel, particularly during the last 10 years when constructional activities in the State increased markedly.

Figure 68 shows the annual commercial and governmental production and use of sand in Arizona classified by principal uses for the years when recorded. As can be noted, commercial use was mainly for building purposes while governmental use was largely for highway construction (paving).

Figure 69 shows the annual commercial and governmental production of gravel in Arizona classified by principal uses for the years when recorded. Commercial use, particularly in recent years, has been divided about equally between building, paving, and fill and other purposes while governmental use was almost entirely in highway construction.

The yearly variations in figures 65 through 69 are related to changing levels in constructional activity as influenced by the installation of major dams, highways, irrigation ditches, airfields, defense establishments, and the building of commercial and residential structures. The Federal Aid Highway Act of 1956 stimulated road construction in Arizona and the expanding use of concrete was spurred by the construction of cement plants in the State. Both of these factors have had much bearing on the increased production of sand and gravel.

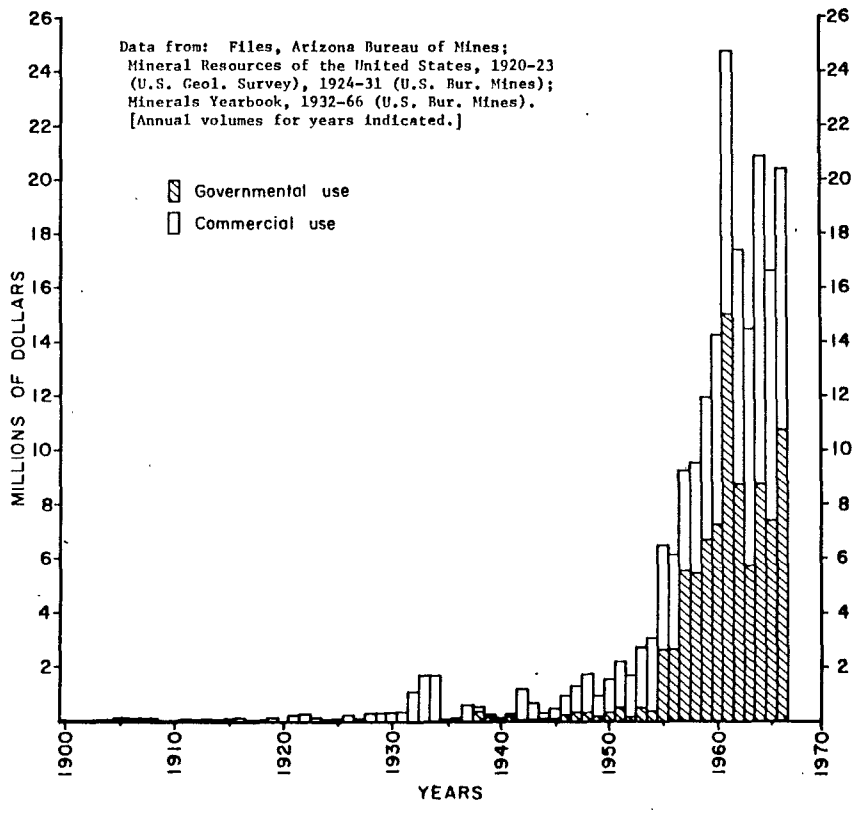

FIGURE. 66.—Annual value of sand and gravel produced in Arizona, 1900–66.

The State's annual production and use rose to 21.9 million short tons in 1961 but subsequently dropped because of strikes in the construction industry, temporary cutbacks in highway programs, and a slowdown in construction for lack of available financing. In 1966 the Arizona production and use of sand and gravel amounted to about 18.7 million short tons with a value of about $20.4 million (U.S. Bur. Mines, 1967, p. 557). Commercial construction activities accounted for about 43 percent of the total tonnage and 47 percent of the value.

Governmental production—that in which the entire production was used in government projects—consumed most of the balance. In this category, the Arizona Highway Department was the principal user with a large part consumed in interstate highway construction in northern and southern Arizona. Other governmental producers were the various county highway departments, U.S. Bureau of Indian Affairs, U.S. Bureau of Public Schools, U.S. Bureau of Reclamation, and the U.S. Forest Service, and some city street departments. There were more than 70 commercial sand and gravel operators in the State in 1966, about half of which were in the Phoenix and Tucson areas.

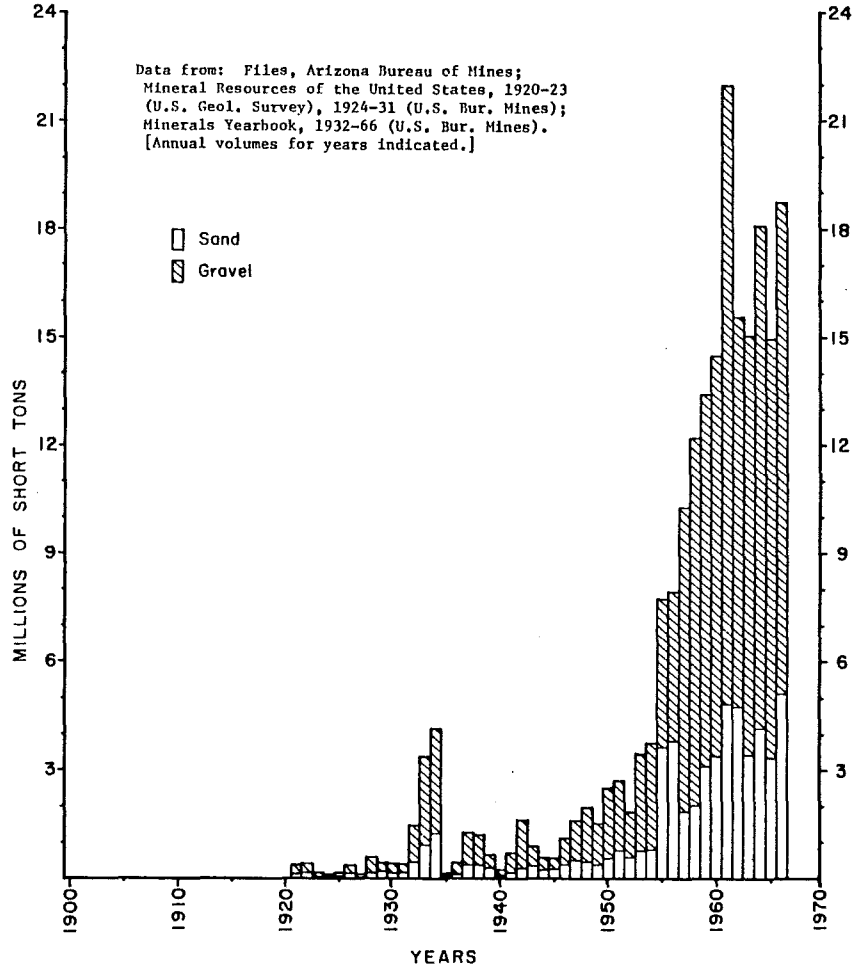

FIGURE 67.—Annual tonnage of sand and gravel produced and used in Arizona, 1920–66.

Industrial sand production amounted to considerably less than 1 percent of the total tonnage and contributed about 1 percent of the total value. Almost all sand and gravel was processed, the ratio of sand to gravel being 5:13.

Table 40 gives a breakdown of Arizona production and use by counties, showing the number of commercial and governmental operations, the total tonnages of sand and gravel produced and used, the ratio of sand to gravel, and the types of plants and products. Portable plants were used at several operations, so the number of plants listed in the "Notes" column in table 40 does not necessarily correspond with the number of operations listed in the second column.

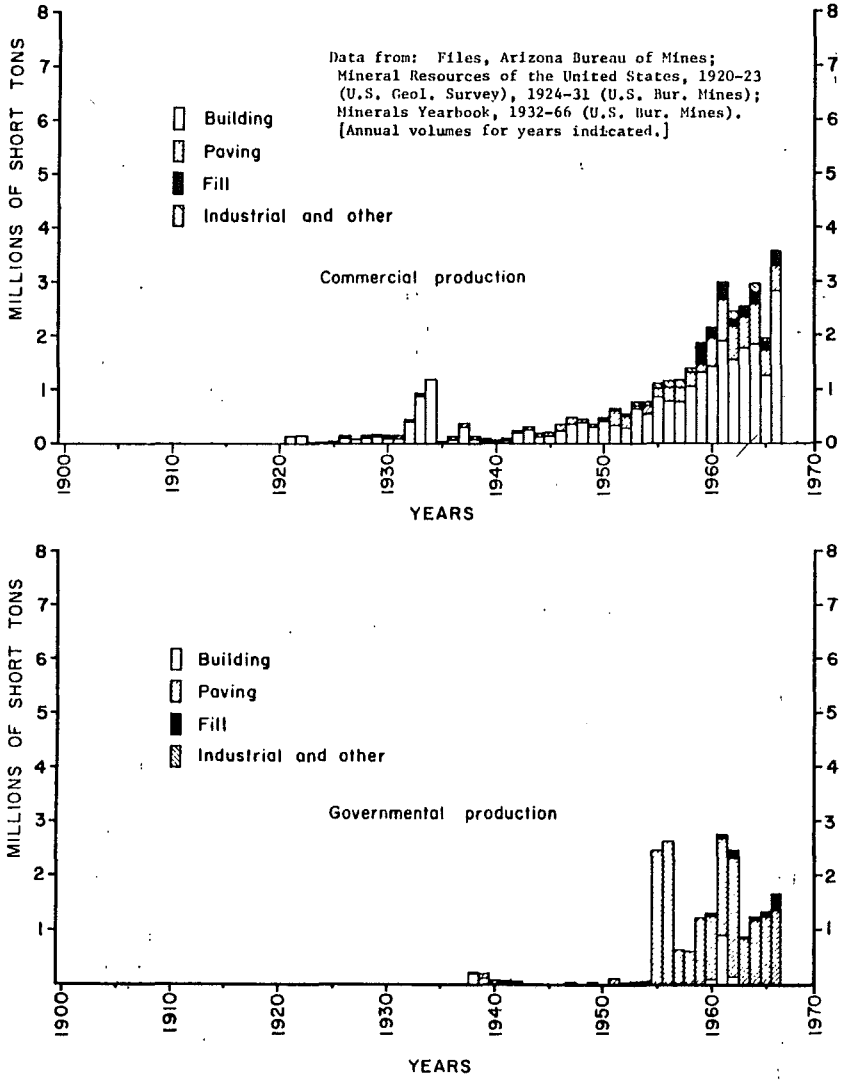

FIGURE 68.—Annual tonnage of sand produced and classified by principal uses in Arizona, 1920–66.

Figure 70 shows the general areas or locations of known commercial sand and gravel operations in Arizona, classified by 1966 annual production. As indicated in the figure and in table 40, the Phoenix area (fig. 70, No. 1), Maricopa County, accounts for a major share of the production; followed by the Tucson area (No. 2), Pima County; the Florence area (No. 3), Pinal County; the Camp Verde area (No. 4), Yavapai County; and the Yuma area (No. 5), Yuma County. Other

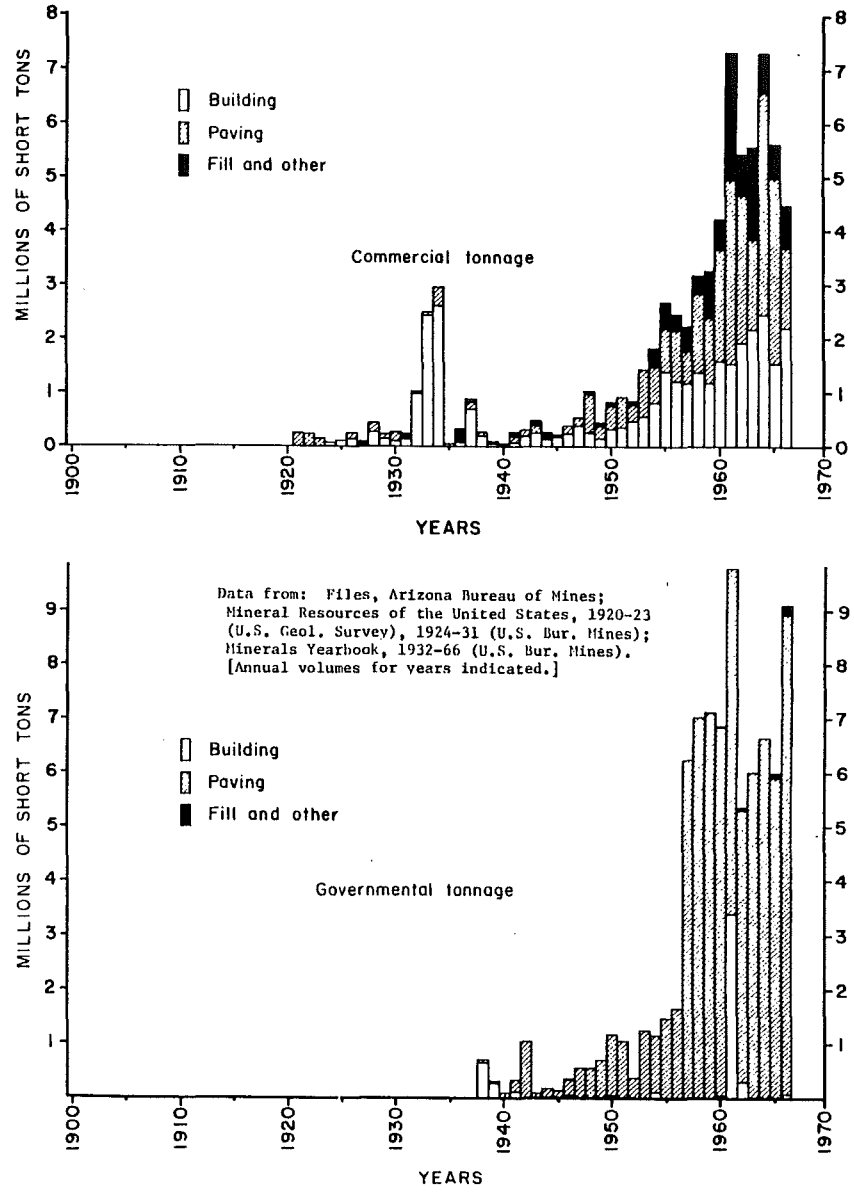

FIGURE 69.—Annual tonnage of gravel produced and classified by principal uses in Arizona, 1920–66.

TABLE 40.—*Tonnage of sand and gravel produced by counties in Arizona in 1966.*

[Data from Larson and Henkes, (1967), and unpublished file information, Arizona Bureau of Mines]

County	No. of operations (Commercial, C; governmental, G)	Short tons	Dollars	Sand:gravel ratio	Notes
Apache	1 (C) 8 (G)	554,000	761,000	1:13.6	Stationary commercial plant at Houck produced processed hydrofrac and blast sand. State and federal agencies processed sand and gravel in portable plants, mainly for Interstate Highway 40.
Cochise	3 (C) 4 (G)	1,465,000	1,474,000	1:7.4	Two stationary and one portable commercial operations supplied processed sand and gravel for building. State processed aggregate in a portable plant, mainly for Interstate Highway 10. Produced small amount of unprocessed fill.
Coconino	4 (C) 7 (G)	~795,000	~800,000	1:6.1	One stationary and two portable commercial plants supplied processed sand and gravel for building and paving. Some unprocessed sand and gravel used for miscellaneous purposes. One portable State plant used to produce aggregate, mainly for Interstate Highway 40.
Gila	2 (C) 5 (G)	246,000	292,000	1:5.3	One stationary and one portable commercial plants processed sand and gravel for building and paving. State and county agencies operated two portable plants for paving aggregate.
Graham	1 (C) 1 (G)	~114,000	~126,000	1:2.6	One stationary commercial plant processed sand and gravel for building. State operated one portable plant for paving aggregate.
Greenlee	0 (C) 5 (G)	113,000	112,000	1:3.9	State and county agencies operated two stationary and one portable plants to supply processed aggregate for paving.
Maricopa	20 (C) 18 (G)	6,654,000	7,474,000	1:1.6	Sixteen stationary and three portable commercial plants processed sand and gravel mainly for building but some used for paving and fill. State and County used one portable plant to supply paving aggregate.
Mohave	4 (C) 13 (G)	1,553,000	1,612,000	1:5.8	One stationary, one portable, and one combination commercial plants processed sand and gravel for building, paving, and miscellaneous uses. Federal, state, and county agencies operated two portable plants, mainly for paving aggregate for Interstate Highway 40.
Navajo	3 (C) 15 (G)	1,116,000	1,108,000	1:2.9	One stationary and two portable commercial plants processed sand and gravel for building and paving. Unprocessed sand fill also produced. Federal, state, county, and municipal agencies operated four portable plants for paving aggregate, building gravel, and fill.

TABLE 40.—*Tonnage of sand and gravel produced by counties in Arizona in 1966.*—Continued

County	No. of operations (Commercial, C; governmental, G)	Short tons	Dollars	Sand:gravel ratio	Notes
Pima	16 (C) 2 (G)	1,437,000	1,581,000	1:1.3	Thirteen stationary and two portable commercial plants produced sand and gravel mainly for building but some used for paving, fill, and other miscellaneous use. A few tons of blast and engine sand also produced. State and county agencies operated two portable plants for paving aggregate.
Pinal	8 (C) 5 (G)	596,000	841,000	1:1.4	Five stationary and three portable commercial plants processed sand and gravel, mainly for building and mine use, and for paving, fill, and miscellaneous other uses. State and county agencies operated two portable plants for paving aggregate and fill.
Santa Cruz	1 (C) 4 (G)	496,000	496,000	1:4.3	One portable commercial plant processed sand and gravel for building. State agency operated portable plant for highway construction aggregate.
Yavapai	7 (C) 10 (G)	1,756,000	1,819,000	1:3.6	Four stationary, one portable, and four combination commercial plants supplied sand and gravel, mainly for building and minor amounts for paving and fill. Federal, state, and county agencies operated one portable and two combination plants for paving aggregate, some fill, and miscellaneous other uses.
Yuma	8 (C) 7 (G)	1,835,000	1,952,000	1:4.5	Six stationary and two portable commercial plants processed sand and gravel for building and some material for fill and miscellaneous other uses. State and county agencies operated one portable and three combination plants for paving aggregate and fill for Interstate Highway 8 and other roads.
Total	78 (C) 104 (G)	18,730,000	20,448,000	1:2.6	

commercial productive areas and localities are Houck (No. 23), Apache County, for industrial sand; Bisbee (No. 16) and Wilcox (No. 17), Cochise County; Flagstaff (No. 9), Coconino County; Globe (No. 6), Gila County; Safford (No. 18), Graham County; Kingman (No 12), Lake Havasu (No. 13), and Bullhead City (No. 26), Mohave County; Taylor (No. 8) and Holbrook (No. 24), Navajo County; Mammoth (No. 7), Casa Grande (No. 20), Kearney (No. 19), Superior (No. 21) and Apache Junction (No. 22), Pinal County; Nogales (No. 15), Santa Cruz County; Prescott (No. 10), Perkinsville (No. 11), and Clarkdale (No. 25), Yavapai County; and Parker (No. 14), Yuma County.

The value of sand and gravel is variable and commercial competition in Arizona is strong. Contrary to the normal economic trend, prices generally are lower in times of high demand since many small producers only operate during such periods and thus provide increased

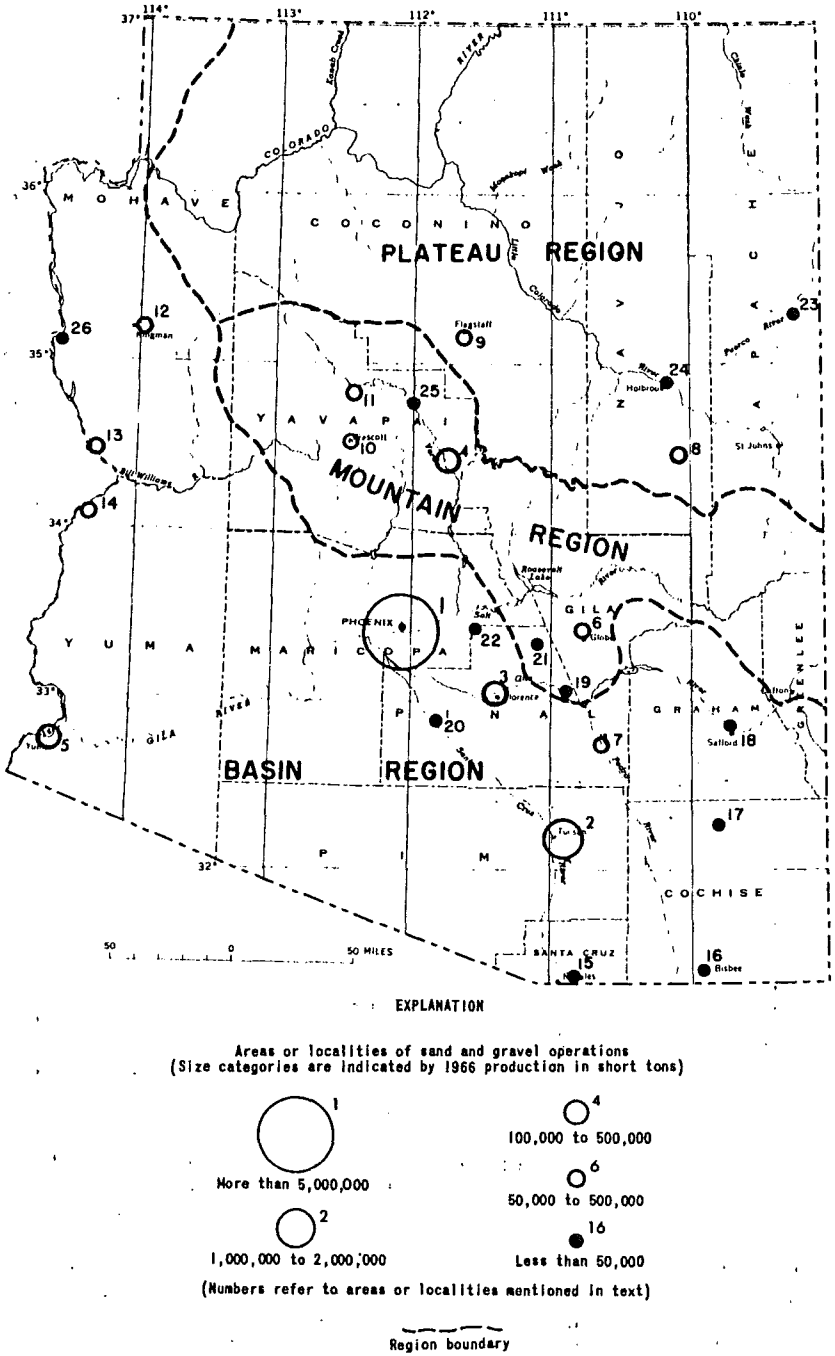

FIGURE 70.—Sand and gravel operations in Arizona.

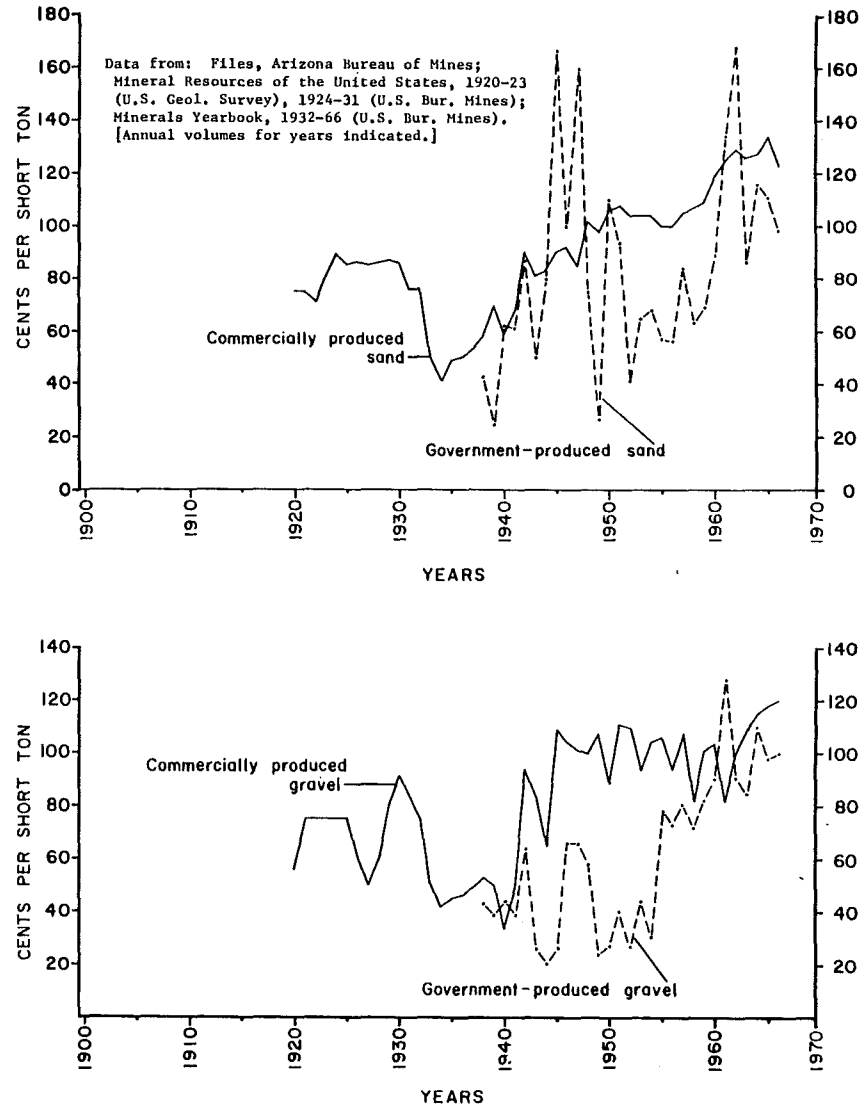

FIGURE 71.—Average annual values per ton for commercially produced and government-produced sand and gravel in Arizona, 1920–66.

competition in the available markets. Figure 71 shows the average annual values per short ton for commercial government-produced sand and gravel in Arizona since 1920. These values show considerable variation due to numerous factors such as the location of deposits with respect to markets, the quantity and availability of the desired material, and the transportation and processing costs.

Sources of Supply

Sand and gravel deposits occur in all counties of Arizona but the amount and quality of the deposits vary greatly between localities because of the different geologic, topographic, and climatic conditions.

Based on the characteristics of the sand and gravel deposits, Arizona can be divided into three regions—referred to here as the plateau, mountain, and basin regions, respectively.

The northeastern part, referred to as the plateau region, includes most of Apache, Navajo, Coconino, and northern Mohave counties (fig. 6), and is marked by wide plateaus drained by broad stream valleys, scattered buttes, mesas, and a few volcanic peaks and mountains. In the western part of the region, the plateau uplands are deeply incised by the canyons of the Colorado River system. The predominant rocks are essentially flat-lying sandstone and limestone but along the southern border, in southern Coconino, southern Apache, and southeastern Navajo Counties, extensive basaltic flows and cinder cones cover the sedimentary rocks. The average altitude is more than 5,000 feet and there is considerable daily and seasonal climatic variation. Except in local high elevations, rainfall generally averages less than 15 inches per year and the vegetation is sparse and scrubby.

Disintegration of rock is carried out mainly by diurnal changes in temperature, freezing and thawing, intermittent rainfall, and wind. Transportation of the disintegration products is mainly by stream flow, sheetwash, and wind. In general, the rocks produce sand but little gravel. The best commercial deposits occur along the streams and washes in local bars and terraces but they are rather thin and limited in area. Some industrial quality sand occurs mainly in the Bidahochi Formation, of Pliocene age, in the Navajo Indian Reservation, Apache and Navajo Counties (Kiersch, 1955, p. 95–98). In 1968, a sand deposit a few miles northwest of Houck (No. 23) was being mined and processed for hydrofrac and sand blasting purposes. The sand is unconsolidated, fairly coarse grained, well rounded and sized, and is nearly pure quartz. Local dune and terrace deposits, of Quaternary age, also are known. Although too impure for glass manufacture, many of these sands may be acceptable for other industrial uses (Kiersch, 1955, p. 95–98).

The mountain region is an irregular belt that trends diagonally across the middle of the State. The topography is rugged, remnants of plateau features are present locally on intervalley ridges, and a few areas such as the Chino and Tonto basins have topography that resembles the southern part of the State. Closely spaced steep sided ridges and valleys with relatively high stream gradients are characteristic of this region. The surface rocks range from Precambrian to Cenozoic in age and include sandstone, quartzite, shale, schist, limestone, dolomite, granitic and diabasic intrusives, and basaltic and dacitic flows. Altitudes generally are less than 5,000 feet.

Climatic conditions are similar to those of the plateau region except for higher rainfall and more abundant vegetation. Such conditions permit the accumulation of good quality, but generally small, alluvial deposits of sand and gravel along the stream channels and in terraces along the valley sides. Such deposits generally contain a high gravel to sand ratio with little or no silt or clay.

Most of southern and western Arizona, the basin region, is marked by scattered mountain ranges, containing numerous indurated rock types, separated by broad, flat, debris-filled valleys and plains. Thick and extensive beds of poorly consolidated gravelly and silty outwash, derived from the mountain ranges, are common in the basin areas. These valley and basin fills are mostly Cenozoic in age and consist mainly of sand and silt capped in many places by a thick, near-surface layer of caliche. Gravel, if present, is either sparsely scattered through the sand and silt or locally occurs in terraces and relatively small buried bars and old stream channels, generally near the mountain fronts.

Rainfall generally is sparse and occurs mostly in sporadic local thunderstorms and cloudbursts. Transportation and deposition of much fragmental material is by sheetwash. Vegetation is scanty and diurnal temperature changes are fairly extreme, except in the mountains. The best deposits of sand and gravel occur in alluvial fans along the mountain ranges where intermittent streams constantly supply new detritus and rework the older deposits. Stream channels and dry washes have yielded a large part of the sand and gravel production but in general the deposits have a high sand to gravel ratio and considerable washing and screening is required to produce acceptable high quality products.

Resource Summary

Arizona has ample reserves and resources of sand and gravel for constructional purposes but the remoteness from markets and the limited accessibility of many deposits limits their exploitation.

In the plateau region good sand is plentiful and some of it is of industrial quality, but good gravel is scarce, particularly near population centers or along main transportation routes. Fortunately, volcanic cinders and scoria are available and more accessible and, thus, are used extensively as a substitute for gravel. The production of industrial sand in Arizona presently is small but the resources are large and could supply a greatly expanded market.

In the mountain region are fairly abundant local resources of sand and gravel but the deposits in most parts are inaccessible and too far from the major markets.

In the basin region, particularly in the Phoenix and Tucson areas, where the principal markets exist, the best and most accessible alluvial deposits have been or are being exploited. These deposits generally are thin but are frequently recharged with new material by intermittent stream action. The sand content greatly predominates and gravel generally occurs only in local lenses and bars. Processing almost always is required and a large amount of material is rejected as waste. Another serious problem for producers is conflict with urban growth. As the cities expand, sources of sand and gravel are eliminated by restrictive zoning and increased land values. Thus, sand and gravel producers are forced to find deposits that are less satisfactory in quality or quantity or are more distant from the markets. Such problems in the Tucson area are described by Williams (1967) and in the United States by Davidson (1965). Generally, however, Arizona has great resources of

sand, but coarser aggregate is quite limited. With the large and increasing demand in the State for coarse aggregate, crushed and broken stone will likely become a major substitute for gravel in the near future.

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SANDSTONE

(By S. B. Keith, Arizona Bureau of Mines, Tuscon, Ariz.)

Characteristics and Specifications

Sandstone is a rock composed essentially of quartz grains compacted and cemented into a moderately indurated mass. By definition, size of grain varies from 1/16 to 2 millimeters in diameter and grain shapes generally are subangular to rounded. Quartz, with a hardness of 7, is one of the toughest and most durable minerals. In addition to quartz, variable amounts of other minerals such as feldspar, mica, garnet, magnetite, hematite, goethite, zircon, calcite, dolomite, and clay may be present and their relative amounts can affect the strength and quality of a sandstone. If the rock contains 10 to 25 percent feldspar it is called feldspathic sandstone and if more than 25 percent feldspar it is known as arkose. Both feldspathic sandstone and arkose can make good quality stone. Micaceous sandstone contains abundant mica flakes and is commonly weak. Ferruginous sandstone contains abundant iron oxide grains and if sizable amounts of clay particles are present the stone is called an argillaceous sandstone. Excessive amounts of either iron oxide or clay are detrimental.

The degree of compaction and the type and abundance of the cementing material play a large part of determining the density, porosity,

hardness, toughness, and durability of a stone. A carbonate cement may form a physically strong and easily worked sandstone but the bond between the grains is subject to chemical attack. A high clay content in the cement makes a weak and friable sandstone that can absorb water readily. Cement rich in ferric iron oxide may be strong whereas substantial ferrous iron makes a weak cement. Siliceous cement, usually quartz, is the most durable, physically and chemically. Sandstone that is so well cemented by silica that the rock breaks equally well through grains and cement is called quartzite. It is discussed in "Quartz and quartzite" (see p. 413).

The grain size and shape, the uniformity of grain size, the porosity, nature of impurities, and the color are important commercial considerations of sandstone. Fine- to medium-grained, uniformly sized, well-compacted siliceous sandstone of low porosity and pleasing color or color pattern is most favored. The porosity of sandstone ranges from about 1 percent to more than 20 percent. Relatively "wet" stone, which holds moisture in the pore space when quarried, is easier to split, cut and shape than "dry" stone. However, porous sandstone can resorb moisture if later exposed to a humid or rainy climate and this factor may be detrimental as far as durability is concerned, especially where exposed to freezing and thawing conditions. The color of sandstone depends largely on the presence of minerals or substances other than quartz, either as grains or as cement. Most commonly they are white to light gray or tan when relatively pure quartz and silica are present, and hues of yellow, brown, buff, and red are due to various iron oxides in the cement or as coatings on the sand grains. Hematite is a stable ferric oxide that produces hues of red, buff, and brown. Limonite, a mixture of hydrous ferric oxide minerals, generally produces yellowish colors that may change to browns and reds upon weathering. Stone containing limonite may be unsatisfactory because it develops irregular staining and discoloration when subjected to the weather.

Sandstone originates through the physical and chemical disintegration and decay of siliceous rocks by weathering and erosion; the transportation, abrasion, sorting, classifying and further disintegration of the mineral grains by water and wind; and the deposition of the more durable mineral grains, such as quartz, in limited to extensive beds of various thicknesses. Most sand deposition takes place in lake or marine basins in the form of sand bars, beaches, deltas, and channel deposits. It also occurs subaerially and produces sand dunes generally in wide flat areas. Burial by subsequent sediments causes compaction, and mineral-bearing water percolating through the beds precipitates cement between the grains. Most sandstone layers show distinctive bedding planes which represent more or less parallel planes of separation between individual layers or beds of various thickness. Bedding planes represent changes or interruptions in deposition and can be continuous over wide areas if horizontal or they may be local in extent as in cross-beds, which are sharply inclined to the horizontal, as in sand dunes. In dunes the cross-beds appear to be truncated by the general plane of stratification. Bedding planes, called "rift" by the sandstone industry, are important commercially because they determine the direction in which the stone can be split most easily. The spacing of the rift determines the thickness of the layer that can be quarried. Bed seams, joints,

cutters, reeds and run are other terms used in the commercial sandstone trade to describe other natural planes or directions in which the stone most easily splits or can be cut (Bowles and Barton, 1963).

Due to the uniformity of the stone and its resistance to weathering and abrasion, sandstone has been used widely in the United States as a building stone and for flagging, uses which are still popular. Large solid blocks, either rough or dressed, are extracted from massive sandstone beds. Smaller blocks and slabs used for facing, trim, steps, window sills, caps, and coping are produced from bedded sandstones that are easily split or cut into special shapes. Ashlar is a term used for cut or sawed and squared sandstone blocks similar to bricks, that can be used for facing in walls, chimneys, fireplaces and general decorative landscaping. Various color and textural patterns can be created from ashlar, so some producers sell it in unit amounts of various colors and sizes in order that the builder can readily follow set patterns and avoid wasting stone. Flagging, which is stone split to a thickness of 1–2 inches from thin-bedded sandstone, has long been popular for floor tile, stepping stones and sidewalks. Many of the former uses of sandstone for curbing, paving blocks, abrasive stone, laundry tubs and tanks, switchboard panels, and furnace linings have largely or completely disappeared due to the increased use of other less expensive natural or synthetic substitutes such as concrete and silicon carbide. Crushed and broken sandstone has little use except as fill rock and some other miscellaneous and minor uses.

Sandstone is extracted from quarries where it is split out in large sheets or blocks, the size depending on the spacing of the natural planes of weakness. These blocks or sheets may be further split, cut to desired sizes and shapes by hydraulic guillotines or wire saws, and left rough or dressed by grinding or polishing. Inherently, the quarrying and preparation of dimension sandstone wastes a large amount of the stone—as much as 60 percent in many operations.

Production and Use

In 1966 producers in the United States used or sold 405,000 short tons of dimension sandstone valued at about $10.1 million, most of it quarried in Ohio, Pennsylvania, New York, and Arkansas (U.S. Bur. Mines, 1967, p. 580). About a third of the amount was sawed building stone; about 85 percent of the total dimension sandstone product was utilized in building construction, and flagging accounted for most of the remainder. The average value for building stone in the United States in 1966 ranged from $16 per ton for rough construction to more than $37 per ton for dressed, sawed, and cut stone. The average value for flagging was about $23 per ton. For most commercial uses, sandstone is priced by cubic foot and an average of 13.3 cubic feet per short ton is often used.

In 1966 more than 7,000 short tons of dimension sandstone was used or sold by producers in Arizona (U.S. Bur. Mines, 1967, p. 580). This figure, however, included other siliceous rocks. A better estimate of the quarried stone is about 5,000 short tons valued at $69,000. Of this amount about 4,200 tons were sold or used to produce flagging, at an average price of about $13 per ton, and about 300 tons were sold or

used to produce rough architectural building stone (ashlar) at an average price of about $17 per ton. The products produced and sold from the stoneyards are valued at considerably higher prices, ranging from $25 to $32 per ton, depending on size, for ashlar veneer; $18 to $20 per ton for general flagstone, 1½ to 2 inches thick; and $22 to $27 per ton for select flagstone, ½ to 1 inch thick. The balance of the production was used for rough architectural construction and rubble at prices of $5 to $10 per ton. A list of the known producers of dimension sandstone is given in table 41.

Good dimension sandstone has been produced in northern Arizona since before 1900 and, up to 1966, has amounted to over 350,000 tons with a value of over $4 million. Burchard (1941, p. 1344–1346 and pl. 5) reported a number of quarry operations along the Santa Fe Railway between Flagstaff and Holbrook that produced a large amount of large, red sandstone blocks, probably from the Moenkopi Formation, that was shipped to California for building construction, and was utilized in various buildings, including the Federal buildings in Sacramento

TABLE 41.—*Production and use of dimension sandstone in Arizona in 1966*

County, area, and quarry	Producer	Production (short tons)	Source, type, and use
Coconino			
Ashfork and Drake areas[1]			
Bacon and Beans	John Bowman	~100	Coconino Sandstone; rough architectural stone and flagging.
East Shot Gun	R. K. Hamilton	~100	Coconino Sandstone; flagging.
Grand Canyon	Hyslip Stone Co.	~3,000	Do.
Not specified	Charles R. Ray	>400	Coconino Sandstone; rough architectural building stone and flagging.
Not specified	A. B. Ross	~200	Coconino Sandstone; flagging.
Bennett	Donald Norman	~100	Coconino Sandstone; rough construction building stone and flagging.
Rainbow	W. R. Mitchell	~10	Coconino Sandstone; flagging.
Not specified	Pete Ross	>500	Do.
Gila			
Near Pine			
Yellow Stone	George O. Gould	>60	Do.
Navajo			
South of Holbrook in			
Taylor area	Roy Reidhead	~500	Coconino and Moenkopi sandstones; rough construction building stone, rubble, sawed building stone, flagging.
Yavapai			
South of Flagstaff in			
Sedona area	Sedona Concrete Co.	~455	Coconino Sandstone; rough construction building stone, rubble, flagging.

[1] The Western States Stone Co., Grand Canyon Quarries, Inc., Dunbar Stone Co., and possibly others in Ashfork and the Maesta Stoneyard in Williams purchase rough blocks and slabs to cut or saw into finished stone products.

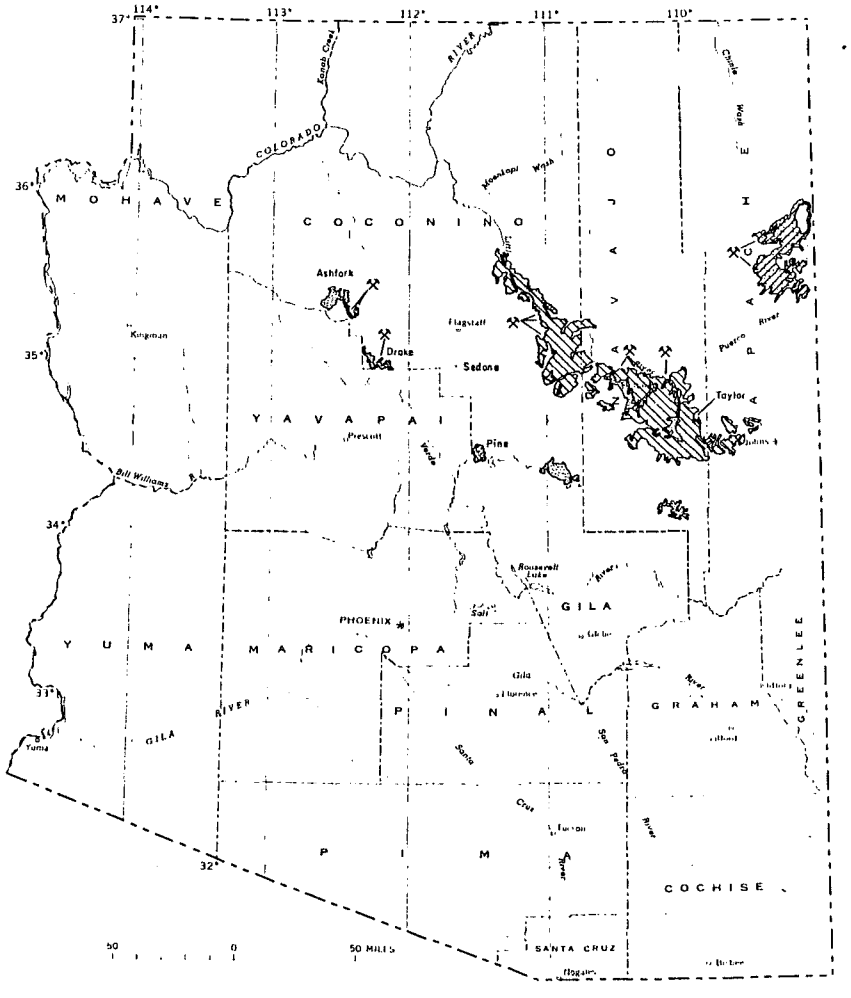
and Los Angeles. Wilson and Roseveare (1949, p. 46–47) noted that considerable amounts of sandstone had been used in railway bridges and that "commercial shipments of sandstone have been made chiefly from Coconino, Navajo, and Yavapai Counties," with the out-of-state shipments going mainly to California. In more recent years, production has fluctuated sharply from practically none during the 1940's and early 1950's to a range from 22,000 to 42,000 tons a year between 1954 and 1960. Since then the annual production has varied between 5,000 and 15,000 tons. Since 1954, flagging has been the major product and continues to be in good demand with a large part shipped to the West Coast.

Sources of Supply

Good standstone for dimension stone is abundant in northern Arizona. The highest quality stone and the principal source of production at present is the Coconino Sandstone of Permian age (McKee, 1934). This stone is eolian in origin and has medium- and uniformly-sized quartz grains, well cemented with silica. It underlies the Kaibab Limestone and from place to place overlies either the Hermit Shale or the Supai Formation throughout a large part of the Colorado Plateaus province in Arizona. The formation ranges from less than 30 feet thick in northwestern Coconino County to more than 1,000 feet thick in the Mogollon Rim along the Coconino-Gila County line northeast of Pine. Further to the southeast it decreases to about 250 feet thick. There it loses its characteristic cross-stratification and thus is less favorable for commercial use.

As can be noted on the geologic maps of Mohave (Wilson and Moore, 1959), Coconino (Moore and others, 1960), Yavapai (Ariz. Bur. Mines, 1958), Navajo and Apache (Wilson and others, 1960), and Gila Counties (Wilson and others, 1959), the Coconino Sandstone is well exposed along the rim of the Grand Canyon, in the canyon walls of tributary streams of the Colorado River, along the Mogollon Rim, and in some of the tributary valleys of the Little Colorado River. These outcrops, however, are usually relatively narrow and inaccessible due to the resistant capping of the Kaibab Limestone and the steep erosional slope on the underlying soft Hermit Shale and Supai Formation. Thus only the more accessible and better exposed outcrops can be shown on the geologic maps. In these areas, such as north of Seligman and Ashfork, east of Drake, and south of Holbrook, outcrops of sandstone are readily accessible and well enough exposed over wide areas to permit quarry operations (see fig. 72). The Ashfork area, in particular, is now the center of the dimension sandstone industry in Arizona.

The De Chelly Sandstone (Permian) of the Defiance Plateau and Monument Valley regions of northeastern Arizona, seems to occupy a stratigraphic position similar to that of the Coconino Sandstone but differs from it in some physical and chemical aspects (Peirce, 1958, 1964). The stratigraphic relations of the De Chelly Sandstone and its thickness and extent are still under study. The upper part of the De Chelly Sandstone has been quarried locally on the Navajo Indian Reservation and used as building block, flagging, table tops,



EXPLANATION

Principal and most accessible outcrops of formations containing dimension stone

Moenkopi Formation — Coconino Sandstone — De Chelly Sandstone

Quarry

Figure 72.—Sandstone in Arizona.

steps, and for sign monuments (Peirce, 1955). For purposes here, the Coconino and De Chelly Sandstones are treated together, only noting their differences. Figure 72 shows the major outcrops of the Coconino and De Chelly Sandstones that could be of commercial importance. For the most part, sandstones in the Coconino and De Chelly are relatively flat lying with prominent cross-bedding and generally widely spaced joints, permitting the extraction of large slabs. The Coconino Sandstone has a high silica content, almost everywhere over 90 percent SiO_2 with minor feldspar, mica, and iron oxide. It is white to shades of red and brown and the porosity ranges from about 7 percent to 19 percent (Townsend, 1962). Weathered Coconino is poorer in quality than fresh stone. The De Chelly Sandstone, on the other hand, is more variable, consisting of interbedded siltstone and thick layers of cross-stratified sandstone, and has a wider range of grain size, a significant feldspar content, a greater porosity, and is less well cemented. Some localities of De Chelly Sandstone in the southern part of the principal outcrop area north of Sanders could produce stone approximately equivalent to the Coconino in quality (Peirce, 1955).

The other Arizona sandstone of major commercial importance occurs in the Moenkopi Formation (Triassic). The principal accessible exposures are shown in figure 72. The Moenkopi furnished most of the stone produced prior to the 1930's, and was quarried mainly in large blocks as building stone. Several of the buildings at Northern Arizona University, at Flagstaff, as well as several buildings in Flagstaff, are constructed of blocks of Moenkopi sandstone. Its production has diminished due to the substitution of concrete for building purposes and the substitution of sandstone from the Coconino for decorative purposes. The Moenkopi Formation crops out extensively over northern and northeastern Arizona (see Moore and others, 1960; Wilson and others, 1960) and consists of nonmarine, sandy and silty red beds that interfinger with thin, marine, calcareous sediments to the northwest. It is thickest in northwestern Mohave County (854 feet thick at Fredonia), thins eastward (330 feet thick at Flagstaff, 168 feet thick at Snowflake) and pinches out in eastern and southeastern Apache County.

The best stone is reported to be in a lower massive sandstone in the basal part of the formation (McKee, 1954). This sandstone is described as a poorly to fairly well-sorted, very fine- to fine-grained, lenticular bed, 20 to 40 feet thick, cross-bedded at places, and having uniform maroon and chocolate-colored beds a few inches to several feet in thickness, commonly separated by thin to thick beds of shale. The sandstone beds are generally massive and do not split readily into flagging but large solid blocks can be quarried and cut and shaped for building stone, masonry dams, foundations, and riprap. Although having adequate strength for building stone, the sandstone contains only about 80 percent silica, and as much as 4 percent iron and aluminum oxide, and 13 percent calcium carbonate. It is only moderately hard and does not retain sharp lines and angles (Burchard, 1914, p. 1344–1345).

Other sandstones in northern Arizona which locally may be used for good dimension stone are beds in the Supai Formation of Permian age and in other formations in the Fort Apache Indian Reservation (Moore, 1967) and the Chinle Formation, of Triassic age, in the Window Rock-Fort Defiance area of the Navajo Indian Reservation (Peirce, 1955). Other sandstones of northern Arizona such as the Wingate, Navajo, Entrada, and Morrison sandstones (Triassic-Jurassic), and the Dakota Sandstone (Cretaceous) at best yield only fair dimension stone. They might be used locally but cannot be considered as commercial sources.

Outlook

Sandstone production in Arizona is a relatively small industry but it is important in both intrastate and interstate commerce, the products being shipped both by rail and truck. Reserves and resources are extremely large and there appears to be a continuing good market for high quality dimension sandstone products. Careful selection of textures and colors, better methods of selective quarrying at lower costs, development of a wider variety of high quality prepared stone products, and good salesmanship should increase the profitability, popularity, and sale of Arizona sandstone for building and decorative purposes.

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SHALE, SLATE, AND MISCELLANEOUS STONE PRODUCTS

(By S. B. Keith, Arizona Bureau of Mines, Tucson, Ariz.)

Introduction

Various types of stone not described elsewhere in this report are or have been produced in Arizona for construction, industrial, and ornamental use. The tonnages and values of these stone products are not always recorded in production records but they are a part of Arizona's mineral resources and, thus, are described below.

Shale

Shale is a fine-grained, laminated, slightly indurated, fissile sedimentary rock composed essentially of clay particles. Lamination and fissility are generally related to original bedding but may be influenced by pressure from the weight of overlying sediments, or by plastic flow. Shale originates from mud so has a wide variation in chemical and mineralogical composition. In general it ranges from 50 to 60 percent silica, 15 to 20 percent alumina, 1 to 4 percent iron and the balance is composed of oxides of calcium, magnesium, sodium and potassium with water, carbonaceous matter, and other minor substances. Besides the clay minerals, some mica, quartz, and other durable minerals are usually present. Shale is soft, brittle, and crumbly and ranges widely in color due to various combinations of iron oxide, organic matter, and other impurities. Also, it may contain carbonates, gypsum, and other salts, or hydrocarbons.

Shale and clay are so closely related in chemical and physical properties that they are often used for the same purposes (see "Clay," p. 324). Only some of the specific and potential uses of Arizona shale are reviewed here. The silica, alumina, and iron content of shale make it suitable as one of the raw ingredients of portland cement. The interbedded limestone and shale of the Naco Formation (Pennsylvania) at Picacho de Calera, near Rillito in Pima County, makes a natural raw mix for the Rillito portland cement plant. Clayey shale of the Verde Formation (Cenozoic) is quarried near Clarkdale for blending with the Redwall Limestone (Mississippian) at the Clarkdale cement plant.

Some ground shale, when heated to incipient fusion, is suitable to produce expanded, bloated, or sintered lightweight aggregate of high structural strength and insulating value. Concrete made with such aggregate provides large savings in weight without sacrificing strength. It is favored for long structural concrete spans such as floor slabs for long bridges and multistoried buildings, and in domed roofs. The use of expanded shale, as well as expanded clay and slate, is growing rapidly in the United States where other natural lightweight aggregate is not available. In Arizona, however, volcanic cinders, scoria, pumice, or perlite are readily accessible substitutes and the use of expanded shale as a lightweight aggregate has not developed.

For 1966, in the United States, more than 11 million short tons of clay and shale were consumed in producing portland cement (figures are not listed separately for slate) (U.S. Bur. Mines, 1967, p. 442, 463). The Arizona Bureau of Mines estimated that at least 55,000 tons were so used in Arizona. The value of this clay and shale is not revealed because the production is usually a captive operation of the cement manufacturer. In 1966 the U.S. production of shale and clay for expanded lightweight aggregate was more than 8 million short tons (U.S. Bur. Mines, 1967, p. 463) with an estimated value of more than $9 million.

Arizona has large and varied shale resources. The Paleozoic, Mesozoic, and Cenozoic sedimentary sequences all contain shale beds in almost all parts of the State. No detailed study of their potential use has been made but with rapid technical development of shale as a lightweight aggregate, the shale resources of the State may become increasingly important to the construction industry.

Slate

Slate is a fine-grained, argillaceous, metamorphic rock having a natural, well-developed cleavage in one plane which permits the stone to be split into thin, smooth plates. Slate originates from the compaction of clay and shale beds by the weight of overlying sediments or by the induration of the beds by heat and pressure. Like clay and shale, slate may have a wide variation in chemical and mineralogical composition. In general, the main constituents are quartz, sericite, chlorite, and graphitic or carbonaceous matter. Most commonly, slate is dark gray to black but red, brown, yellow, and purple colors also are common and caused by the iron content. Some slate is green, which is caused by chlorite. Slate is firm but soft enough to be readily cut and shaped.

In the past, much dimension slate was used for roofing, blackboards, electrical panels, laundry tubs and sinks, floor tile, and flagging but such uses have decreased in recent years due to rising costs in quarrying and preparing the stone and due to the development of lower cost substitutes.

In the United States the 1966 production of dimension slate was 166,000 short tons valued at $9,173,000 of which 39 percent was used for flagging; 32 percent for aquarium bottoms, buildings, fireplaces, flooring, and miscellaneous items; 14 percent for roofing; 13 percent for electrical, structural, and sanitary millstock; and 2 percent for blackboards, bulletin boards, and billiard table tops (U.S. Bur. Mines, 1967, p. 581). The value of these products ranged from about $24 per ton for flagstone to more than $300 per ton for blackboard and bulletin board material. The principal producing states of dimensional slate, in order of importance, are Virginia, Pennsylvania, Vermont, and New York.

The production and use of crushed and broken slate in the United States has more than doubled in the past five years and amounted to 1,190,000 short tons with a value of $4,507,000 in 1966 (U.S. Bur. Mines, 1967, p. 590). Lightweight aggregate production consumed 64 percent of this amount, granules for composition materials, 24 percent,

and slate flour for filler, 12 percent. The respective average values for these products were $2.25, $5.70, and $6.90 per ton. Virginia, Georgia, and Pennsylvania were the principal producing states. The sale of these products is important to the slate industry since only 10 percent of the slate extracted is suitable for dimension stone and the disposal of nondimensional material becomes a problem and an expense unless it can be marketed.

Slate has been quarried in Arizona at intermittent periods in the past but none was produced in 1966. Blake (1903, p. 127–128) noted that there were large areas containing mica and clay slate in the Precambrian rocks in western Arizona and argillaceous slate on Cave Creek, Maricopa County; near Walnut Grove, Yavapai County; on the east side of the Rincon Mountains, Pima and Cochise Counties; 7 miles north of Phoenix (used for the State Capitol foundations), Maricopa County; and in the Bradshaw Mountains, Yavapai County. Some of these localities are referred to by Burchard (1914, p. 1342 and pl. 5). Wilson and Roseveare (1948, p. 49) cited slate in schist areas in the Phoenix, Estrella, and Mazatzal Mountains of Maricopa County, and in the Sierra Ancha Mountains of Gila County. They suggested that the small local demand, low market value, and transportation costs had discouraged commercial production. Townsend (1962, p. 32) considered that good slate was scarce in Arizona and that most of the reported occurrences were actually phyllite, and argillaceous rock intermediate in metamorphic grade between slate and schist, or mica slate of poor quality. He did note that some excellent green, brown, and black slate—hard, smooth, and with good cleavage—was reported southwest of Walker in the Bradshaw Mountains of Yavapai County; that micaceous, but hard and firm, blue-black and green slate had been quarried near Sunnyslope, Maricopa County, for rough masonry walls; and that hard, banded, dark-red, gray, and purple "ribbon" slate occurred in the Sierra Ancha district, north of Globe, Gila County.

It appears doubtful if good dimensional slate can be economically exploited from Arizona deposits except as flagstone or for special decorative purposes; even these products would have to compete with the more abundant and well established stone substitutes such as sandstone. A more likely market might be developed for crushed and broken slate as granules, flour, and expanded lightweight aggregate but even these materials would encounter severe competition from available substitutes. Thus, slate is an Arizona resource of doubtful value.

Schist

Schist is medium- to coarse-grained metamorphic rock having a foliated structure due to the subparallel orientation of the constituent minerals of which the micaceous minerals are most prominent. Schist can be split into thin irregular plates but the cleavage is irregular and does not yield large flat sheets. It can originate from almost any type of rock and thus has a wide variation in physical texture and chemical and mineralogical composition. Schist generally is defined specifically by various adjectives, which denote the predominant character or composition, such as mica, chlorite, augen, or ferruginous schist.

Although schist is sometimes used as an abrasive, in rough construction, and as a source of ground mica, there are no data available on production or use. In recent years, thousands of tons of variously colored schist, mainly mica schist, have been produced in Arizona for use as a decorative wall facing for buildings and sold both in and outside the State. The more ferruginous mica schist is red, pink, yellow, or brown; the chlorite-mica schist is green; and other mica schists are gray to silver or display variegated colors or shades of colors. In 1966, the Arizona Bureau of Mines estimated that 1,500 short tons of schist valued at about $13 per ton were produced in Arizona. The production came from various localities, but mostly from Precambrian rocks in Maricopa, Mohave, Yavapai, and Yuma Counties. Townsend (1962, p. 34) mentioned the Sunnyslope area north of Phoenix and the highly colored schist at New River, Maricopa County, and near Mayer, and other locations south of Prescott in Yavapai County.

Arizona resources of colorful and decorative schist are almost unlimited and with the growing demand for its use in facing stone in private and public buildings, the production of schist has become an important business in the State.

Copper-Stained Stone

Any firm solid rock containing or coated with the blue and green stains of oxidized copper minerals has been in increasing demand in recent years as a rough building stone for wall facing, fireplaces, and ornamental construction. The copper minerals generally are the bluish-green hydrous silicate, chrysocolla; and the green and blue hydrous carbonates, malachite and azurite. The value of such rock as stone often exceeds the value of the contained copper. Large quantities of copper-stained rocks occur in the dumps of many mines in the State where it has been stockpiled until an economic process for recovery of the copper can be found. Figures are not available nor can they be estimated for the amounts of such rock that have been sold and used but a considerable tonnage has been used in Arizona and also shipped out of the State. Such stone has become an important Arizona mineral resource.

Other Minor Stone Products

Other types of stone occurring in Arizona have had local and minor usage in construction and for decorative purposes. Some light-colored, somewhat banded, red and brown rhyolite and rhyolite tuff has been used locally in masonry walls and landscaping when it could be cut or trimmed into blocks or when found as weathered boulders. Sources of such stone are in the Tucson Mountains of Pima County; near Kingman, Mohave County; northeast of Douglas, Cochise County; south of Wickenburg, Maricopa County; and several locations in Yavapai County. Some jasper, a red, brown, or green, impure and finely crystalline silica rock that is generally banded, occurs in Arizona in sufficiently large deposits to be exploited, such as in northeastern Maricopa County, northwestern Yavapai County, and in Mohave County. It has been shipped out of the State for special decorative use. Near Rock Springs, on the border between Maricopa and Yavapai Counties, a white to light-yellow, silicified carbonate rock, locally

called "magnesite," has been exploited, and some serpentinized rock in Gila County has been quarried, both as a decorative and as a construction stone. No one type of these miscellaneous rocks is of major economic significance in the State at the present time but they have added a significant amount to the growing use of different stone for decorative construction and ornamental purposes. In aggregate they constitute an increasingly important resource.

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STRONTIUM SALTS

(By Richard T. Moore, Arizona Bureau of Mines, Tucson, Ariz.)

Introduction

Strontium is a member of the alkaline earth group of elements and thus, is closely related to calcium, with which it is frequently associated in nature. Metallic strontium has a specific gravity of 2.6, a melting point of 757° C. (1,395° F.), and a strong affinity for oxygen and several other gases. Because of this last property, small quantities of elemental strontium are used as "getters" to remove residual traces of gas from electronic tubes (Ambrose, 1965, p. 847), one of the few uses that have been found for strontium metal.

Various salts of strontium, on the other hand, have important commercial and military applications, particularly in the manufacture of pyrotechnic devices. When ignited, various strontium salts burn with a vivid red flame, and large quantities of the nitrate, oxalate, and peroxide of strontium are used in the manufacture of military material, including signaling and illuminating flares, and tracer ammunition. Peaceful applications include marine distress flares, motor vehicle and railway warning flares (fusees), and fireworks of many types. Some strontium salts, principally the carbonate, are used in ceramics and ceramic glazes. Other uses are found in medicine, optics, metallurgy, and in the plastics industry.

No domestic production of strontium minerals was reported during the 1960's, although large reserves are known in the United States. Celestite ($SrSO_4$) and strontianite ($SrCO_3$), the principal minerals of strontium, are imported from the United Kingdom, Mexico, and, in minor quantities, from Italy. During the period 1960 through 1966, an average of 11,800 short tons per year of strontium minerals was imported for domestic consumption (U.S. Bur. Mines, 1962–1967). These imports had a total value of $1,942,500.

Domestic deposits of celestite and strontianite are known to occur in Arizona, California, Ohio, Texas, and Washington. Major production from these deposits, however, was almost entirely during wartime, when foreign supplies were not available.

Strontium is found in minor quantities in many igneous rocks, especially the alkalic rocks, and is commonly associated, in the mineral celestite, with such sedimentary rocks as limestone, dolomite, and calcareous shale. In a few areas, moderately large deposits of fairly pure celestite occur as beds, veins, and irregular masses in sedimentary terranes and such deposits comprise the major commercial source of the metal and its salts. In the Southwestern United States, bedded deposits of celestite that intermittently have been exploited are found intercalated with tuffaceous lake sediments. It has been suggested that the strontium was introduced into the lakes by volcanic emanations from adjacent areas (Harness, 1949, p. 980).

Arizona Deposits

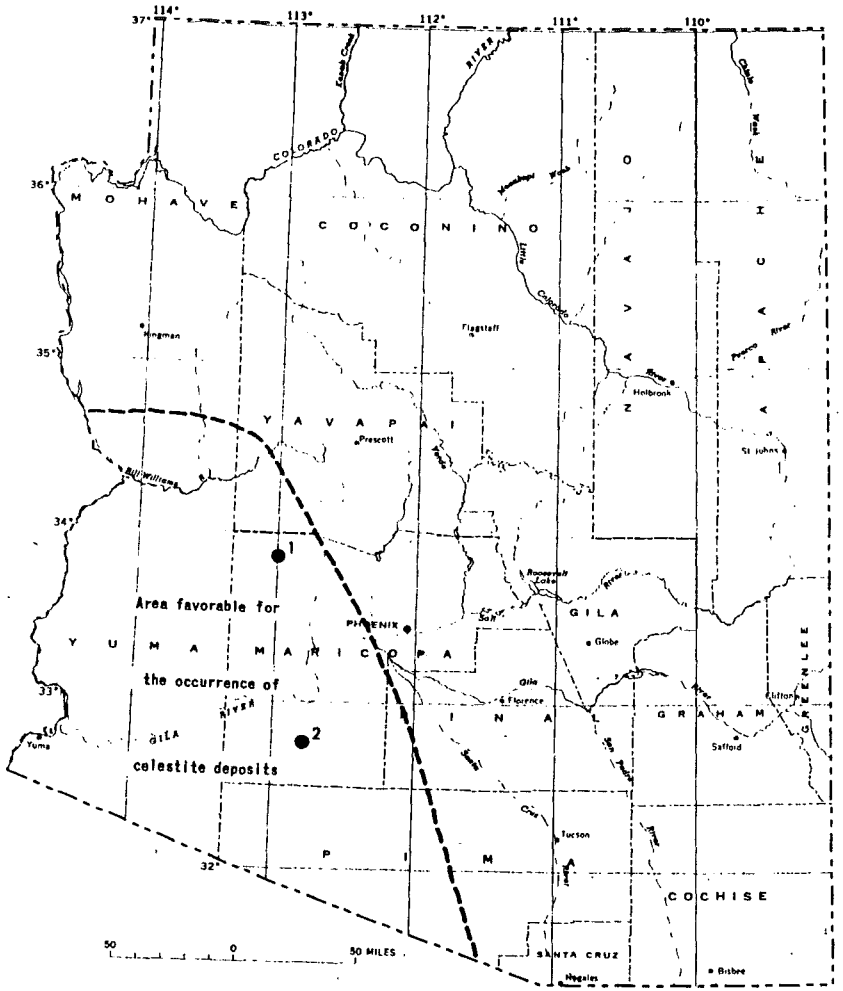
In Arizona, two deposits of celestite have been known for many years, and were described in detail by Moore (1936). The larger of the two deposits is in the Vulture Mountains, about 10 miles southeast of Aguila, Maricopa County (fig. 73, No. 1). In this deposit, celestite-bearing rock occurs in beds up to 2 feet thick interbedded with thin-bedded, olive-buff to light-brown shaly tuff of Tertiary age. The interval containing the celestite rock is about 160 feet thick and underlies an area of about 5 acres. The deposit contains more than 180,000 short tons of celestite rock (Moore, 1936, p. 153).

The smaller of the two deposits is about 15 miles south of Gila Bend, Maricopa County (fig. 73, No. 2). Similar to the Aguila deposit, here also the principal strontium mineral is celestite. The celestite occurs in beds associated with gypsum, sandstone, and conglomerate in a zone 40 to 50 feet thick and about 1 mile long (Phalen, 1914, p. 532). Igneous flows and intrusions also are associated with the series. Moore (1936, p. 154), on the basis of actual exposures determined that the deposit contains more than 9,000 short tons. If the celestite extends along strike farther than exposed, which seems probable, the tonnage is much greater.

Outlook

In much of southwestern Arizona, as outlined in figure 73, the geologic conditions are similar to those at the two known deposits, and, therefore, are considered favorable for the occurrence of celestite. Large volumes of volcanic rocks which could have served as sources of strontium are present in the several mountain ranges in the area, and these are commonly flanked by sediments of early Cenozoic age, composed of fine-grained volcanic detritus, interbedded with calacareous siltstone and silty limestone of lacustrine or, possibly, lagoonal origin. These Cenozoic sediments are the most favorable rocks for the occurrence of celestite.

Under present economic conditions, Arizona's strontium deposits are not competitive with foreign supplies, and there is no indication



EXPLANATION

●1 Celestite deposit
(Number refers to locality mentioned in text)

Approximate boundary of area that is favorable for the occurrence of celestite deposits

FIGURE 73.—Strontium salts in Arizona.

this situation will change in the near future. If, however, foreign supplies for some reason should become unavailable, or the price for strontium salts should markedly increase, the Arizona deposits might become economically attractive.

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SULFUR

(By Alfred J. Bodenlos, U.S. Geological Survey, Washington, D.C.)

SULFUR INDUSTRY

Arizona has large potential resources of sulfur in its metallic sulfide mineral deposits and in gypsum (and anhydrite) beds, but both materials require relatively costly processes to convert them into usable sulfuric acid or sulfate fertilizer compounds. Recent price trends in the cost of elemental sulfur, however, which rose in 1968 to its highest point in history, may permit increased use of sulfide and sulfate minerals as a source of sulfur compounds within the near future.

Sulfur and its most common industrial derivative, sulfuric acid, are extensively used throughout industry and agriculture; in fact, their level of consumption probably indicates levels of national industrial activity. Less than 15 percent of consumption is used in nonacid form for such purposes as making paper pulp, carbon disulfide, insecticides, fungicides, and in vulcanizing rubber. More than 85 percent is used as sulfuric acid, in the manufacture of soluble fertilizers, chemicals, pigments, iron and steel pickling, plastics, petroleum refining, and in small amounts in a host of other processes requiring acid (Ambrose, 1965, p. 908). The fastest growing use has been that of fertilizer manufacture; in 1967 such use consumed half the sulfur or acid equivalent available, and it is anticipated that larger tonnages will go into this segment of industry in future years (Oil and Gas Jour., 1968, p. 31).

Sulfur is a widespread element, occurring in native form associated with sedimentary rocks and in volcanic terrane; as sulfide minerals in all types of rocks and metallic mineral deposits; as the sulfate minerals anhydrite and gypsum in sedimentary rocks of evaporite origin; as a constituent of hydrocarbon molecules in petroleum, oil shale, coal, and tar sands; and as hydrogen sulfide gas in volcanic emanations and contained in "sour" natural gas. It is recovered in elemental form, as hydrogen sulfide or sulfur dioxide gas, or as sulfate compounds in one part of the world or another from all these types of occurrence, either as a principal product or as a coproduct or byproduct (Fogarty and Mollison, 1960, p. 819–827).

Native, or elemental, sulfur is relatively inert and can be shipped any distance to consuming centers, whereas sulfuric acid is a relatively dangerous chemical and is shipped at most for only several hundred miles. Elemental sulfur thus is the more desirable product for shipment, which coupled with the large volume of production and relatively low mining or recovery costs, it forms the base of the sulfur industry. Most of the elemental sulfur of the world is produced from deposits in Louisiana and Texas and hence its price, f.o.b. Gulf Coast ports, is the world base price. Due to a relatively tight supply situation in recent years its price has been rising, particularly since early 1966, from a rather stable level of $25 per long ton to $42–$43 per long ton in early 1968 (Ambrose, 1965, p. 910–913). Hence, the more expensive sources of sulfur or sulfuric acid, such as pyrites, cuprous pyrites, and sulfur dioxide recovered during base-metals smelting, are close to becoming competitive with elemental sulfur at present (1968) price levels. Recent developments also indicate that the manufacture of sulfate fertilizers from anhydrite or gypsum may become competitive in the near future (Chem. and Eng. News, 1968, p. 11–12).

This country's position in the sulfur industry stems from the discovery and development of an elemental sulfur deposit in Louisiana in the 1890's, which led to production in 1901; by 1912 this country was the world's leading producer, a position it has held since then (Haynes, 1942, p. 47, 322–323). By far the largest part of our production still comes from the elemental sulfur in the Gulf Coast but is supplemented by elemental sulfur recovered from sour natural gas and by sulfuric acid, sulfur dioxide, and hydrogen sulfide recovered in pyrite roasting, base-metals smelting, and petroleum refining (Ambrose, 1965, p. 905–908, and table 2, p. 911).

The U.S. Bureau of Mines (1967, p. 595) reports domestic production as follows:

	Thousands of long tons (contained sulfur)
Frasch-process mines (elemental sulfur deposits)	7,001
Recovered elemental sulfur (largely from hydrogen sulfide contained in sour natural gas)	1,238
Pyrites	356
Byproduct sulfuric acid (produced at base-metal smelters)	424
Other byproduct sulfur compounds (hydrogen sulfide and sulfur dioxide, probably mostly from petroleum refining)	134
Total	9,153

An additional 500 tons of material, containing from 10 to 70 percent sulfur, was produced from volcanic deposits.

The United States both exports and imports sulfur and also draws from or adds to mined stocks. Production and consumption thus differ, but in recent years stocks have been drawn upon to satisfy domestic demand. The U.S. Bureau of Mines (1967, p. 595) published the following statistics for 1966 (in thousands of long tons):

Production, all forms	9,153
Exports	2,373
Imports	1,674
Apparent consumption	9,158
Stocks on hand, Dec. 31, 1966	2,704

The difference between exports and imports equals to within a few tons the amount of sulfur drawn from mined stocks during the year. In 1967, the major sulfur companies put their customers on allocation

to avoid further drawdown of stocks, which were at their lowest levels in years (Gittinger, 1968, p. 154A). Imports consist largely of elemental sulfur recovered from sour gas and pyrites produced in Canada, and elemental sulfur mined in Mexico.

Free world production in 1966 totaled 16,440,000 long tons of elemental sulfur and 9,700,000 long tons of pyritic sulfur. Some countries produce appreciable tonnages from volcanic deposits; small amounts of sulfuric acid or sulfur compounds are obtained from anhydrite and gypsum deposits and from oil shale.

Sulfur in the United States

In Texas and Louisiana, deposits of elemental sulfur occur in lenses of calcite and anhydrite that overlie intrusive salt masses (known as domes or stocks), penetrating to within several thousand feet of the surface (Murray, 1961, p. 269–271)); the anhydrite lenses, because of their position above the salt are called cap rock. Sulfur occupies openings in brecciated calcite and forms as much as 25 percent of the rock mass (Taylor, 1938, p. 71–80). Deposits are tabular and range in size from several thousand to tens of millions of tons of sulfur. About 26 deposits have been discovered, of which 10 are being mined and 4 are being developed (Hawkins and Jirik, 1966, p. 35). They are mined from wells by injecting superheated water to melt the sulfur and injecting compressed air to lift the molten sulfur to the surface (Fogarty and Mollison, 1960, p. 828–830). Sulfur mined in this manner (Frasch process) contains at most only a few tenths of a percent of impurities. Recently two sulfur deposits were found in bedded evaporite strata on the southeast side of the Permian Basin in West Texas, but little is known of their geology. In 1967 both were being developed for Frasch mining.

Deposits of sulfur occur in volcanic rocks in many parts of the western United States and some sulfur also is associated with solfataras or hot spring deposits (Wideman, 1957, p. 2–13, 16–22, 28–32, and 37–39; Kinkel and Broderick, 1966, p. 411–413). At present they furnish only small amounts of sulfur but were worked more extensively in the past. Volcanic rock or gangue material deposited by hot springs must be treated to separate sulfur from its gangue, a relatively expensive process.

Second in rank in sulfur production in the United States is sulfur recovered from the hydrogen sulfide contained in sour natural gas, a source developed in the 1950's and 1960's as demand for sweet gas was rising. Hydrogen sulfide is separated from natural gas at the surface by use of a chemical absorbant and then one-third is burned to convert it to sulfur dioxide (Fogarty and Mollison, 1960, p. 827; Ambrose, 1965, p. 906–908). The remaining hydrogen sulfide and the sulfur dioxide then react in the presence of a catalyst to form elemental sulfur and water. The process is less costly than Frasch mining but can only be carried on to the extent that markets for natural gas are available. Most such sulfur is produced from sour gasfields in Texas, New Mexico, Wyoming, and Arkansas but other states produce lesser amounts of sulfur from sour gas (Oil and Gas Jour., 1967, p. 113–132).

Despite increasing demand for sulfuric acid, production from the sulfur dioxide generated in pyrite roasting and base-metals smelting

has been relatively stable in recent years, in part the result of the economics and in part due to the problems of shipping the commodity. The costs of installing special equipment to recover sulfur dioxide from stack gases and the costs of acid manufacturing are relatively high, perhaps three times that of the cost of installations to make acid from the burning of elemental sulfur (Caldwell, 1968, p. 76; Haynes, 1942, p. 267–270). Chemically the sulfur dioxide is converted to the trioxide, and the trioxide is combined with water to make sulfuric acid. Some smelters produce liquid sulfur dioxide (Kinkel and Broderick, 1966, p. 413). Arizona is one of several states producing either acid or the dioxide from pyrites.

The sulfur contained in petroleum is being recovered during refining in increasingly larger amounts. Refineries recovering sulfur are located both in petroleum producing and nonproducing states and some treat imported sulfur-bearing petroleum (Oil and Gas Jour., 1967). It is said that comparable recovery is feasible from sulfur-bearing shale oil.

As yet, gypsum (or anhydrite) has not been used in the United States as a source for sulfur or sulfur compounds but one plant is being built for this purpose near Van Horn, Tex. Processes for recovery of sulfur from gypsum (or anhydrite) are more costly than mining sulfur by the Frasch process but the sulfur prices prevailing in 1968 perhaps are nearly high enough to permit their development (Chem. and Eng. News, 1968).

An unknown factor in the future sulfur supply is the potential resource provided by coal, where the element occurs as the sulfide in pyrite and marcasite (known as coal brasses), and as a constituent of hydrocarbon compounds (known as organic sulfur). (Walker and Hartner, 1966, p. 1–4; Williams and Keith, 1963; Reidenour and others, 1967, p. 632–644). The brasses can be separated physically from coal, unless they are exceedingly fine grained; organic sulfur can only be released upon combustion as sulfur dioxide in stack gases. Public demand for control of air pollution may result in its large-scale recovery in the not-too-distant future, regardless of cost. The possible effect on the sulfur industry of large tonnages of sulfur derived from coal is still unknown; the stack gases of thermoelectric plants annually emit millions of tons of sulfur and even partial recovery from this source would add appreciably to the national supply.

Sulfur-Bearing Minerals in Arizona

Only small occurrences of elementary sulfur have been found in Arizona, none large enough to be minable (Galbraith, 1941, p. 8). The State evidently does not contain rocks favorable to concentration of elementary sulfur in commercial quantities and to the present neither sulfur-bearing petroleum nor sour gas have been found. Notwithstanding, Arizona contains large deposits of sulfide minerals and several parts of the States are underlain by beds of gypsum and anhydrite, as described in more detail in other parts of this report (see "Copper," "Lead and zinc," "Iron," "Gypsum and anhydrite," and figs. 18, 24, 27, 28, and 57).

Major deposits of sulfide ores occur in the following districts or mines: Jerome, Bagdad, Agua Fria, Globe-Miami-Inspiration, Magma

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(Superior), Ray, Silver Bell, Clifton-Morenci, San Manuel, Ajo, and Bisbee (Warren) (Wideman, 1957, p. 43–61; Kelly, 1962, p. 6, 11, and 17–19). Other sulfide ores occur at Mission, Pima, Esperanza, Twin Buttes, and Ithaca Peak. Those containing substantial resources of pyrite are the United Verde mine at Jerome and mines at Magma, Ray, Iron King, Miami-Inspiration, and Morenci (see "Iron" and "Copper," p. 168 and 117). Total potential resources of sulfur are large, both in contained ore and in mine dumps and mill tailings.

Only a fraction of the sulfur resources in the form of sulfide minerals is being recovered. A detailed study made in 1958 showed that a minimum of 700,000 tons of sulfur was generated as sulfur dioxide in the smelters of Arizona, of which only 10,000 tons was recovered and used to manufacture sulfuric acid (Kelly, 1962, p. 16 and 22). The same study found that it was less expensive in most parts of the State to use elemental sulfur than smelter gases in manufacturing sulfuric acid. However, the sharp rise in the price of elemental sulfur since that study was made may make use of pyrite or sulfur dioxide in smelter gases more attractive for such use; in 1958 the base price of elemental sulfur was $23.50; in 1968 it was $42.50 per long ton. But as Kelly noted, freight costs on sulfuric acid shipment from smelters to consumers may offset the advantages of using the sulfur dioxide in smelter gases (1962, p. 13).

Pyrite is used in recovering sulfuric acid and sponge iron at the Kennecott Copper Corp. plant at Hayden. Pyrite from the Magma and Ray mines provides the feed, which after concentration and thickening is processed in a fluid-bed roaster. The plant has a reported capacity of 100 tons of sulfuric acid per day (Harrer, 1964, p. 164; Kelly, 1962, p. 19), but is being enlarged. The Phelps Dodge acid plant at Morenci produces 600 tons per day and supplies acid to Inspiration as well. Three sulfuric acid plants, which use elemental sulfur shipped from Texas, are located at Inspiration, Benson, and Chandler; the first operates only when it cannot get acid from Morenci. The bulk of the acid manufactured in the State is used to leach copper and uranium ores; smaller amounts are used in the manufacture of fertilizers, explosives, and in miscellaneous industrial and commercial processes (Kelly, 1962, p. 22–25).

Acid produced from sulfide ores in Arizona contains selenium and cannot be used for fertilizer without further refining. This matter is being studied and might lead to changes in acid production operations.

As noted in "Iron" (p. 181), pyrite in tailings dumps at the Iron King mine, Humboldt, Yavapai County, is acidulated and ammoniated to produce a ferrous sulfate-polysulfide soil conditioner.

Gypsum crops out mainly in the southeast quarter and the extreme northwest corner of Arizona, and is described in "Gypsum and Anhydrite," p. 371. These and subsurface occurrences of anhydrite are listed and summarized in table 31, p. 375. Anhydrite occurs in subsurface in the Supai Formation, of Pennsylvanian-Permian age, in a basin of the same name near the New Mexico boundary. A small segment of the Paradox Basin extends into the northeast border of Arizona, where gypsum of the Paradox Member of the Hermosa Formation, of Pennsylvanian age, is in the subsurface (Withington, 1962, p. 2–3.

Although gypsum has been mined from five deposits in Pinal, Yavapai, and Yuma Counties, it is used as construction material,

cement additive, and as a soil conditioner rather than as a source of sulfur (Larson and Henkes, 1965, p. 98, 110–111, and 113). Should the price of elemental sulfur remain at levels reached in 1968, the higher-grade occurrences of gypsum perhaps can be processed as a source of sulfur or sulfur compounds and should be considered as a potential resource of that commodity.

Reserves and Resources

Although data are insufficient to accurately appraise the national sulfur reserves and resources, the amounts are large, not only in elemental deposits but in sulfide deposits, sour natural gas, and petroleum. Even larger amounts will be available should the sulfur in coal and the sulfate in gypsum and anhydrite be recoverable on a significant scale (President's Materials Policy Comm., 1952, p. 83–87 and table 3, p. 85; Ambrose, 1965, p. 909; Landsberg and others, 1963, p. 483–486). These various sources will be mined or recovered only under competitive conditions, which at present are governed by the cost of elemental sulfur mined by the Frasch process.

Of the sources listed, Arizona contains large resources of sulfur in base-metal sulfide deposits and associated pyrite masses, not only in place but also in accumulated waste. The contained sulfide is recovered during smelting as needed for sulfuric acid manufacture, but only a fraction of the supply is used. As noted above, deleterious elements in the acid restrict its use to nonagricultural applications, largely the leaching of low-grade ores. Use also is limited by the availability of sulfuric acid manufactured at lower cost from plants burning elemental sulfur.

Rising prices of elemental sulfur may make gypsum competitive in the manufacturing of sulfur or sulfate compounds. The new sulfur-recovery plant in West Texas is designed to process gypsum from the Permian Basin for this purpose. On a long-range basis, therefore, the gypsum of Arizona may constitute a resource for sulfur recovery but this will rest on its competitive position with sulfuric acid produced at base-metals smelters.

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VERMICULITE

(By Richard T. Moore, Arizona Bureau of Mines, Tucson, Ariz.)

Characteristics, Use, and Occurrence

Vermiculite is a micaceous hydrated silicate formed by the low temperature alteration of other sheet silicate minerals, chiefly biotite. The chemical composition of vermiculite depends largely upon the composition of the original mineral and the degree of alteration. About 20 varieties of vermiculite have been described, differing slightly in cation and hydroxyl content, in hydration, and in optical properties; the general name, vermiculite, is now preferred, and is applied to all the commercial product.

Crude vermiculite ranges in color from light yellow-brown to green, greenish brown, dark brown, and black. It retains most of the original ability of its parent mica to cleave or split into very thin parallel leaves. Some varieties contain as much as 20 percent water and, when heated, expand and separate or exfoliate into very thin, loosely attached silvery to golden flakes. Crude vermiculite, which weighs about 100 pounds per cubic foot, will expand 20 times or more its original volume with a proportionate reduction in weight.

More than 50 percent of all exfoliated vermiculite is used in the building and construction industry, as an effective fireproof insulator against heat and sound. For such purposes, it can be used either directly in loosely packed form, or mixed as an aggregate in various plasters, bricks, and cements. It is also used in ornamental stucco and wallpaper. Important quantities of exfoliated vermiculite are used as a soil conditioner to lighten clay soils and to improve their moisture retention. When finely ground, vermiculite serves as an extender for gold and bronze printing inks, a vehicle for agricultural chemicals, and as a filler in plastics and rubber products (May, 1965; Wilson and Roseveare, 1949, p. 31).

U.S. production of crude vermiculite has come entirely from Montana and South Carolina in recent years. In 1964 over 226,000 short tons were produced domestically, and another 18,000 tons were imported from the Republic of South Africa. Exfoliated vermiculite, on the other hand, was produced at 51 plants in 33 states (May, 1966) because it is cheaper to ship crude vermiculite to market areas for treatment than to ship expanded vermiculite. An example is the exfoliating plant operated by the Ari-Zonolite Co. at Glendale, Ariz. (see fig. 61) which treats crude vermiculite shipped from deposits in Montana.

Vermiculite occurs intermingled with other rock-forming minerals in many altered igneous and metamorphic rocks. Commercially important deposits are often found where masses of dark-colored mafic rocks, such as peridotite, pyroxenite, amphibolite, and serpentine, have been intruded by dikes and sills of acidic composition, such as pegmatite and aplite. Until about the time of World War II, it was generally believed that the vermiculite formed by hydrothermal alteration of the mafic host rock or of biotite and phlogopite in the host rock. Since then there has been increasingly conclusive evidence that weathering or supergene alteration is probably the most important process in the formation of many deposits.

Arizona Deposits

Comparatively little is known about possible commercial vermiculite deposits in Arizona. Although the mineral has been identified in samples submitted to the Arizona Bureau of Mines from many parts of the State, no large, relatively high-grade deposits are known. According to Wilson (1940, p. 2), in 1940, the Micro-Cell Insulation Co. began development of a deposit located 15 miles southeast of Kingman, in the Hualpai Mountains, Mohave County (No. 12, fig. 61), and started to install a pilot mill to prepare the raw vermiculite for shipment to California. This project, however, did not reach the production stage. North and Jensen (1958) reported that in 1954 a small quantity of vermiculite was mined for experimental purposes from an occurrence near Aguila, Maricopa County, but that no commercial production was made. The exact location of this occurrence was not reported. A deposit on the Bar FX ranch, southwest of Wickenburg (No. 13), has been opened but not commercially worked (Wilson and Roseveare, 1949, p. 32). An occurrence near Oracle, Pinal County (No. 14), has been worked for mill-test material but not commercially mined.

Present suppliers of crude vermiculite outside of Arizona appear to have sufficient reserves to supply market needs for many years at the present rate of growth of the industry. There seems to be little likelihood that crude vermiculite will be mined in Arizona, unless deposits are found that are of markedly better quality or are both large tonnage and amenable to low cost mining.

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ZEOLITES

(By Richard A. Sheppard, U.S. Geological Survey, Denver, Colo.)

Characteristics, Use, and Occurrence

Zeolites are crystalline hydrated aluminosilicates of the alkali and alkaline earth elements. They have a framework structure that encloses interconnected cavities occupied by the relatively large cations and water molecules (Smith, 1963). The cations and water have considerable freedom of movement which gives the zeolites their cation exchange and reversible dehydration properties. The porous character of the zeolites enables them to act as molecular sieves for the separation of molecular mixtures based on the size and shape of the molecular compounds or for the selective adsorption of gases.

These unique properties of the zeolites suggest diverse industrial uses in processes such as purification and drying of liquids and gases, chemical separations, catalysis, and decontamination of radioactive wastes (Brown, 1962). Zeolitic rock can be used as a pozzolan in cement (Mielenz, 1950, p. 5–7) or as a soil conditioner to increase the effectiveness of chemical fertilizers. Industry now uses synthetic zeolites almost exclusively, but as economic methods are developed to convert natural material into a commercial product (Barrer and Makki, 1964), large natural deposits may become important.

Zeolites occur chiefly as cavity fillings in igneous rocks and as authigenic rock-forming constituents in sedimentary rocks, particularly altered silicic vitric tuffs (Hay, 1966). The bedded deposits are a potential resource because they can be extensive and high in purity. Most, if not all, of the potentially valuable zeolite deposits in Arizona occur in Cenozoic continental tuffs and tuffaceous sedimentary rocks that originally consisted of silicic vitric ash. The zeolites formed after deposition of the rock mainly by reaction of the ash with interstitial water, which may have originated as either meteoric water (Hay, 1963) or connate water of a saline lake (Hay, 1964). Of the more than 30 naturally occurring zeolites, only 6 occur in bedded deposits of Arizona. These include analcime, chabazite, clinoptilolite (an alkali- and silica-rich variety of heulandite), erionite, mordenite, and phillipsite.

The zeolites occur in nearly monomineralic beds or, more commonly, occur associated with other zeolites, clay minerals, silica minerals, or feldspars.

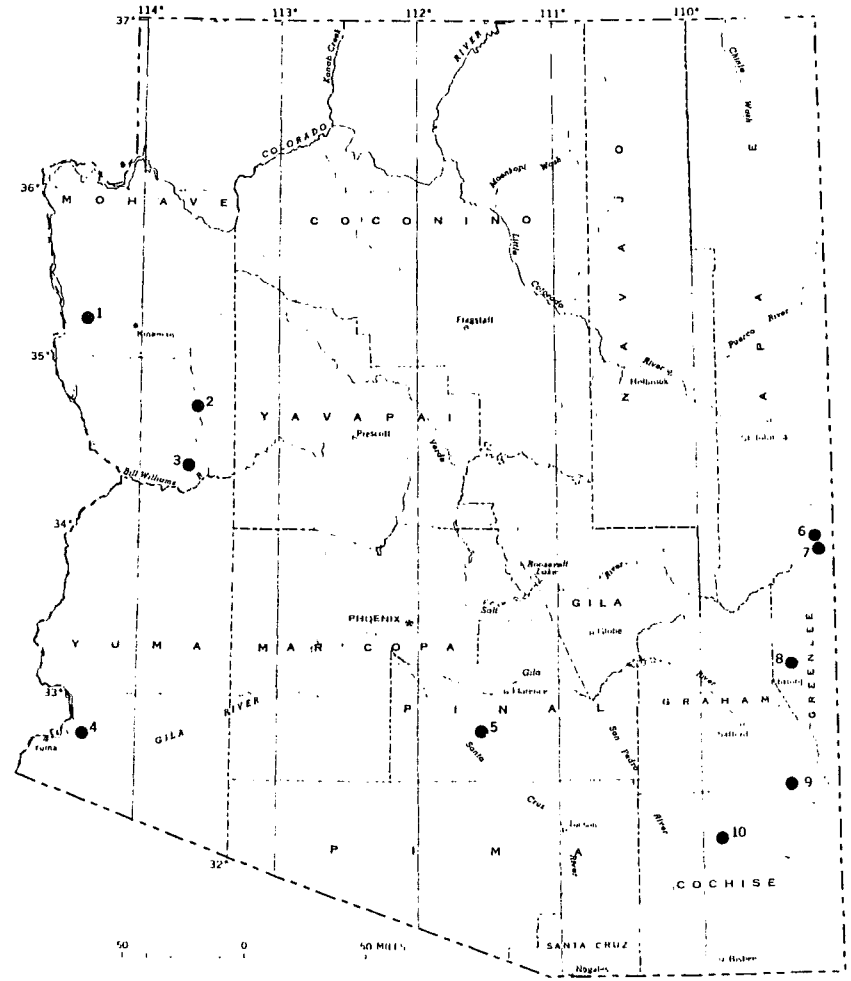
Arizona Deposits

Bedded zeolite deposits have been reported mainly from the west-central (table 42 and fig. 74, Nos. 1–3) and southeastern (Nos. 5–10) parts of Arizona. The only other deposit reported from Arizona is clinoptilolite (No. 4) in a bentonite at Dome (Bramlette and Posnjak, 1933, p. 169–170).

Analcime and clinoptilolite are reported as minor constituents in predominantly clastic rocks (Nos. 3, 5, 6, and 10). Inasmuch as these deposits contain less than 25 percent zeolite, they probably cannot be considered minable resources. The clinoptilolite near Alpine (No. 7) makes up about 80 percent of the tuff, but the bed is thin and discontinuous.

Table 42.—*Bedded zeolite deposits in Arizona*

Locality No. in fig. 74	Location	Zeolites	Occurrence	References
1	Sec. 11, T. 21 N., R. 20 W., north side of Union Pass, Mohave County.	Mordenite	Tuff and lapilli tuff in the Golden Door Volcanics of Tertiary age.	A. J. Gude, 3d, oral commun., 1967.
2	E½ T. 16 N., R. 13 W., chiefly east of the Big Sandy River, Mohave County.	Analcime, chabazite, clinoptilolite, erionite, phillipsite	Tuff in unnamed lacustrine formation of Pliocene age.	Ross, 1928; 1941; Sheppard, unpub.
3	Sec. 30, T. 12 N., R. 13 W., Maggie Canyon, Mohave County.	Analcime	Cement in sandstone of the Chapin Wash Formation of Pliocene age.	Lasky and Webber, 1949, p. 30, 59.
4	Near Dome, Yuma County.	Clinoptilolite	Bentonite.	Bramlette and Posnjak, 1933, p. 169–170.
5	Sec. 25, T. 7 S., R. 8 E., drill hole near Eloy, Pinal County.	Analcime	Silty claystone of late Tertiary age.	P. D. Blackmon, oral commun., 1966.
6	Secs. 2, 15, and 16, T. 6 N., R. 30 E., near Nutrioso, Apache County.	Analcime, clinoptilolite	Cement in sandstone of unnamed formation of Tertiary age.	Wrucke, 1961, p. H17–H19.
7	Sec. 11, T. 5 N., R. 30 E., near Alpine, Apache County.	Clinoptilolite	Tuff in unnamed formation of Tertiary age.	Sheppard, unpub.
8	Sec. 16, T. 3 S., R. 29 E., about 6 miles N. of Morenci, Greenlee County.	Clinoptilolite, mordenite	Tuff and lapilli in tuff in unnamed formation of Tertiary age.	Do.
9	Sec. 2, T. 12 S., R. 29 E. northwest to sec. 12, T. 11 S., R. 28 E., along San Simon Creek, Cochise County.	Analcime, chabazite, clinoptilolite, erionite	Tuff in unnamed lacustrine formation of late Cenozoic age.	Sand and Regis, 1966; Regis and Sand, 1967.
10	Sec. 12, T. 15 S., R. 24 E., drill hole at Willcox Playa, Cochise County.	Analcime	Mudstone of Pleistocene age.	Pipkin, 1967.



EXPLANATION

1 Zeolite occurrence

(Number refers to locality described in text and listed in table 42)

Figure 74.—Zeolites in Arizona.

High-grade deposits of zeolites occur in altered silicic tuffs at several localities (Nos. 1, 2, 8, and 9) where the beds are at least 1 foot thick and consist of more than 90 percent zeolite. Thick beds of nearly monomineralic mordenite occur at Union Pass (No. 1) and near Morenci (No. 8). Some beds at the latter locality contain clinoptilolite and quartz as well as mordenite. Beds of nearly pure analcime, chabazite, and erionite occur east of the Big Sandy River near Wikieup (No. 2). Some zeolitic tuffs at this locality also contain trace to major amounts of clinoptilolite, phillipsite, or potassium feldspar. Along San Simon Creek north of Bowie (No. 9), zeolitic tuff about 4 feet thick consists of thin layers of analcime, chabazite, clinoptilolite, and erionite—some of which are nearly monomineralic (Sand and Regis, 1966).

Although the size and purity of most of the above deposits are not adequately known, large volumes of silicic vitric tuffs have obviously been altered to zeolites. Large additional volumes of zeolitic tuff probably occur in other Cenozoic basins of Arizona. As of 1968, only locality No. 9 is known to be undergoing commercial exploitation (U.S. Bur. Mines, 1968, p. 4), although preliminary exploration and sampling have been done on several. The bedded zeolites of Arizona are potentially exploitable, but studies to determine their size and value await further industrial development and the establishment of suitable markets.

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