MINERAL FUELS AND ASSOCIATED RESOURCES

COAL

(By Paul Averitt and R. B. O'Sullivan, U.S. Geological Survey, Denver, Colo.)

INTRODUCTION

The coal resources of Arizona are concentrated primarily in the Black Mesa field of northeast Arizona and secondarily in the Pine-dale field of southern Navajo and northeast Gila Counties, and the Deer Creek field of eastern Pinal County (fig. 10). These and other minor occurrences of coal have been known since the days of earliest settlement. However, Arizona has been used only on a small local, scale because of the relatively small population of the State, because of the lack of coal-based industries, and because coal and electricity are imported from New Mexico and Colorado. Consequently, Arizona coal has been mapped and studied only on a reconnaissance basis and the information available is not as abundant as that in other Rocky Mountain States.

All the economically important coal in Arizona is found in rocks of Cretaceous age, but at least one occurrence of thin-bedded coal in rocks of Paleozoic age, which is discussed under a separate heading, is of considerable scientific interest.

BLACK MESA FIELD

The coal-bearing rocks in the Black Mesa field are of Cretaceous age. They cover an area of about 3,500 square miles near the center of the Navajo Indian Reservation, in Apache, Navajo, and Coconino Counties. The coal-bearing rocks form the rim and the relatively flat top of Black Mesa.

STRATIGRAPHY

The sequence of Cretaceous rocks exposed on Black Mesa comprises, in ascending order, the Dakota Sandstone, which is coal bearing at many places, particularly on the southern rim of the Mesa; the Mancos Shale, which is noncoal bearing; and the Mesaverde Group. The Mesaverde Group is subdivided into the Toreva Formation at the base, the Wepo Formation in the middle, and the Yale Point Sandstone at the top. Both the Toreva and the Wepo Formations are coal bearing. The stratigraphic relations of the Cretaceous rocks on Black Mesa are shown diagrammatically in figure 11. The distribution of these units is shown in a small-scale map compiled by O'Sullivan (1958, p. 170). A part of the field has been mapped in detail by Beaumont and Dixon (1965). A complete description of the units is contained in a report by Repenning and Page (1956).

The Dakota Sandstone ranges in thickness from about 50 to 120 feet (Repenning and Page, 1956, p. 261). It consists of interbedded tan, fine- to medium-grained sandstone, siltstone, and dark-gray and brown shale, and coal. At most localities the Dakota consists of a lower and an upper ledge-forming sandstone bed, separated by coal-bearing shale. One or more units may be absent locally.

FIGURE 10.—Coal in Arizona.
The available information for the 1916, 1947, and 1958 reviews of the coal in Black Mesa was conducted by Campbell and Gregory (1911, p. 229-238), Gregory (1917, p. 142-144), and Kiersch (1956, p. 50-63). The coal in Black Mesa was reviewed and summarized by Rubel (1916), Andrews, Hendricks, and Huddle (1947, p. 1-4), and O'Sullivan (1958). An archaeological study by Brew and Hack (1939) records use of Black Mesa coal by the Hopi Indians as early as 1300 which predates the use of coal in Europe. A report on the Cretaceous stratigraphy of Black Mesa by Repenning and Page (1956) provides information that will aid in prospecting for coal. In recent years the Navajo and Hopi Indian Reservations have been mapped geologically as part of a study of the underground water resources. A report by Cooley, Harshbarger, Akers, and Hardt (1964) includes a geological map of the region on the scale of 1:125,000 and a detailed discussion of the regional stratigraphy. This report does not include data on coal, but it shows the distribution of coal-bearing units and will aid anyone interested in the economic development of the region.

**Areas of coal occurrence**

Sequences of coal-bearing rock crop out in the Dakota Sandstone, the Toreva Formation, and the Wepo Formation.

Coal is contained in the middle shale member of the Dakota Sandstone, which crops out around the entire perimeter of Black Mesa, and in outliers northwest and south of the Mesa. Although coal is present at most places in the middle shale member of the Dakota, the thicker and more extensive beds are confined to the eastern half of Black Mesa as shown by the darker stippled area in figure 10. According to Kiersch (1956, p. 50) the coal beds in the southern part of the Mesa are 2 to 4 feet thick at most localities, but are conspicuously thicker at the Tuba City mine (No. 3, fig. 10) and at a locality at the southeast corner of the Mesa. At the Tuba City mine the coal is 6 feet thick divided into several benches as shown in the following section taken from the report by Campbell and Gregory (1911, p. 254):

<table>
<thead>
<tr>
<th>benches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
</tr>
<tr>
<td>Shale</td>
</tr>
<tr>
<td>Coal (middl)</td>
</tr>
<tr>
<td>Reef</td>
</tr>
<tr>
<td>Coal</td>
</tr>
<tr>
<td>Reef</td>
</tr>
</tbody>
</table>

It is composed of interbedded light-gray, fine- to coarse-grained sandstone, olive-gray and brown siltstone and shale, and coal.

The Yale Point Sandstone conformably overlies the Wepo Formation, and is the youngest formation of the Mesaverde Group exposed on Black Mesa. It crops out only on the northeast side of the Mesa, where it attains a maximum thickness of 300 feet (Repenning and Page, 1956, p. 280). It consists of tan medium- to coarse-grained sandstone.

**COAL DEPOSITS**

**Previous investigations**

Reconnaissance investigations of the coal in Black Mesa were conducted by Campbell and Gregory (1911, p. 229-238), Gregory (1917, p. 142-144), and Kiersch (1956, p. 50-63). The coal in Black Mesa was reviewed and summarized by Rubel (1916), Andrews, Hendricks, and Huddle (1947, p. 1-4), and O'Sullivan (1958). An archaeological study by Brew and Hack (1939) records use of Black Mesa coal by the Hopi Indians as early as 1300 which predates the use of coal in Europe. A report on the Cretaceous stratigraphy of Black Mesa by Repenning and Page (1956) provides information that will aid in prospecting for coal. In recent years the Navajo and Hopi Indian Reservations have been mapped geologically as part of a study of the underground water resources. A report by Cooley, Harshbarger, Akers, and Hardt (1964) includes a geological map of the region on the scale of 1:125,000 and a detailed discussion of the regional stratigraphy. This report does not include data on coal, but it shows the distribution of coal-bearing units and will aid anyone interested in the economic development of the region.

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<tr>
<td>Reef</td>
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<td>Coal</td>
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<tr>
<td>Reef</td>
</tr>
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At the locality on the southeast corner of Black Mesa the coal in the middle shale member of the Dakota is 9 feet thick. The Chinle No. 1 mine (No. 5, fig. 10) and the Montezuma mine (No. 7, fig. 10) have also been opened on areas of reasonably thick coal in the Dakota.

A Dakota coalbed locally as much as 6 feet thick has been reported by Williams (1951, pl. 18, fig. 2) at a locality about half way between mines Nos. 2 and 3, figure 10. This locality is shown by darker shading in figure 10. This locality and the thick coal at the Chinle No. 1 mine (No. 5, fig. 10) probably represent the northernmost extent of minable coal in the Dakota Sandstone. The coalbeds in the Dakota are typically lenticular, and relatively high in ash. They are also divided into several benches by partings of shale or bone, and at most places are not suitable for large-scale mining.

The thickest and most extensive coal in the Toreva Formation is in the middle carbonaceous member in the southeastern corner of Black Mesa. This area is shown by darker lined shading in figure 10. The Keams Canyon mine (No. 4, fig. 10) and the Chinle No. 2 mine (No. 6, fig. 10) both operate on coalbeds in this area. The coal at the Chinle No. 2 mine is 6 to 7 feet thick (Kiersch, 1956, p. 63). The coal at the Keams Canyon mine is about 5 feet thick, divided into several benches as shown by the following section recorded by Kiersch (1956, p. 58):

<table>
<thead>
<tr>
<th>Coal</th>
<th>6.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>4.0</td>
</tr>
<tr>
<td>Coal</td>
<td>6.0</td>
</tr>
<tr>
<td>Shale</td>
<td>4.5</td>
</tr>
<tr>
<td>Coal</td>
<td>6.0</td>
</tr>
</tbody>
</table>

The important coal deposits in the Wepo Formation are restricted to the northern part of Black Mesa as shown by the darker shading in figure 10. The thickest and most continuous beds are in the upper half of the formation. Both the Maloney and the Kayenta No. 1 mine (No. 1, fig. 10), and the Cow Spring mine (No. 2, fig. 10) operate on beds in the Wepo Formation. At the Maloney mine the coal is 6 feet thick (Williams, 1951). At the Cow Springs mine the coal is 4 feet 7 inches thick without observed partings (Kiersch, 1956, p. 59). The coal at the Cow Springs mine probably represents the southernmost extent of minable coal in the Wepo Formation.

The Wepo Formation contains at least 10 coal beds that individually exceed 3 feet in thickness. Most of these beds underline massive, cliff-forming sandstone beds, and are easily traced and mapped in the field. The thickest bed thus far observed is 14 feet thick at one locality, but it thins in both directions along the outcrop (Williams, 1951).

The substantial amount of coal in the Wepo Formation on the north side of Black Mesa has long been known, but its relative inaccessibility, the availability of competing coal from the Gallup field of the nearby San Juan Basin, N. Mex., and the lack of an assured, continuous market have deterred exploration and use. In the early 1960's, however, the rising demand for electric power in southern California and Ariz. focused attention on Black Mesa coal, and a period of mapping and exploratory drilling ensued.

In 1966, the Peabody Coal Co. announced plans to open a large modern strip mine on a block of ground on the Wepo Formation leased from the Navajo and Hopi Indian Tribes. The block is estimated to contain 350 to 400 million tons of coal. The mine will supply coal to the projected 1,500,000 kilowatt Mohave electric powerplant to be located below Davis Dam on the Colorado River in southernmost Clark County, Nev. The plant is to be financed and built by a group of 17 private and public utilities known as the Western Energy Supply and Transmission Associates (WEST Associates), and is scheduled for completion in 1970 or 1971. The contractual agreement between the Peabody Coal Co. and WEST Associates calls for the delivery over a period of 35 years of at least 117 million tons of coal at a delivered cost of $500 million, which will include $30 million in royalty payments to the Navajo and Hopi Tribes. This is the largest long-term coal mining and delivery contract ever signed. The mining and delivery of this coal over the 275-mile distance between the mine and the powerplant represents many jobs; an increase in the industrial tax base; and a powerful economic stimulus to the Navajo and Hopi Tribes, to Arizona, and to the Southwest.

Quality of coal

Analyses of coal at individual mines, outcrops, and prospect pits on Black Mesa have been published by Campbell and Gregory (1911, p. 237), the U.S. Bureau of Mines (1947, p. 32, 54), and Kiersch (1956, p. 52-53). This information has been summarized according to the stratigraphic position of the beds by O'Sullivan (1958, p. 171), as shown in the following tabulation:

<table>
<thead>
<tr>
<th>Formation</th>
<th>Number of samples averaged</th>
<th>Percent content</th>
<th>B.t.u.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Moisture</td>
<td>Volatile matter</td>
</tr>
<tr>
<td>Dakota</td>
<td>6</td>
<td>10.1</td>
<td>38.4</td>
</tr>
<tr>
<td>Toreva</td>
<td>6</td>
<td>6.3</td>
<td>34.7</td>
</tr>
<tr>
<td>Wepo</td>
<td>4</td>
<td>7.6</td>
<td>40.1</td>
</tr>
</tbody>
</table>

Assuming that the average sulfur content of all these coals is 1 percent, and further assuming that the averaged analyses are truly representative of coal in the respective stratigraphic units, the Dakota coals are of subbituminous B rank, and the Toreva and Wepo coals are of high-volatile C bituminous rank, according to the recommended definitions of the American Society for Testing and Materials (1966). The lower ash and the higher Btu contents of the Wepo coals make them more desirable for large-scale mining and commercial use.

Pinedale Field

The Pinedale field was examined on a reconnaissance basis by Veatch (1911) and was discussed briefly by Reagan (1911; 1929), and a part
of the field has been mapped by Finnell (1966). The coal occurs in two areas of Cretaceous rock, covering about 175 square miles near Pinedale in southern Navajo and northeast Gila Counties (fig. 10). The Cretaceous sequence is as much as 500 feet thick. It consists mainly of nonmarine rocks, but locally includes two thin sandy limestone beds that contain marine fossils of early Late Cretaceous age. In a zone 50-100 feet above the base the sequence includes two beds of subbituminous coal, 10 to 15 feet apart. The upper bed attains a maximum thickness of 12 feet at one locality in the NE¼NE¼, sec. 38, T. 11 N., R. 18 E. Of this total, only about half is coal and even the coal is high in ash. The lower coal is 2 to 3 feet thick and contains fewer partings. On the Fort Apache Indian Reservation, near Cottonwood Creek, the local office of the Bureau of Indian Affairs formerly operated a mine in the lower bed. At this locality the bed is 31 feet thick, of which two-thirds is coal and one-third partings. This coaly horizon has been traced and sampled at intervals over a distance of about 25 miles and found to be consistently thin and high in ash (Moore, 1967, p. 77-78).

The coal-bearing rocks are essentially flat lying and the coal is suitable for mining locally on a small scale to supply a modest local demand. Analyses of coal from the Pinedale field are contained in a report by the U.S. Bureau of Mines (1947, p. 32).

**DEER CREEK FIELD**

The small and unimportant Deer Creek field is in eastern Pinal County far removed from other Rocky Mountain coalfields. It was examined on a reconnaissance basis by DeVereaux (1981), Walcott and Bannom (1885), Campbell (1904), and Ross (1925). The field is a small synclinal basin, 10 or 12 miles long east-west, and 3 to 4 miles wide, in which coal-bearing rocks of Cretaceous age have been preserved. These Cretaceous rocks consist of a lower, unnamed sedimentary formation as much as 500 feet thick containing coalbeds in the basal 50 feet, and an upper unnamed volcanic and sedimentary formation as much as 3,000 feet thick (Wildren, 1964, p. E25-E27). The lower sedimentary formation is mainly of nonmarine origin, but locally contains thin beds of marine rock of early Late Cretaceous age (Simons, 1964, p. 37). The Cretaceous rocks dip 30 to 60 degrees at the outcrop, but flatten to approximately horizontal in the center of the basin. They are also cut by many andesite dikes.

The coal-bearing sequence at the base of the Cretaceous contains two impure coalbeds individually 24 to 30 inches thick, and several additional thin beds of no commercial importance. The two best coalbeds commonly contain several partings, and benches of pure coal are typically no more than 10 to 15 inches thick. The coal is also high in ash. Of five analyses presented by Campbell (1904, p. 254-256) the ash contents range from 18.7 to 24.4 percent. The lower figure was from a selected 10-inch bench of "clean" coal. The coal is of bituminous rank and will make a low-grade coke, which is of no current commercial value because of its high ash content. This coal will probably not be developed except for local use because of the thinness of the beds, the high ash content, and the relative inaccessibility of the area.

**GALLUP-ZUNI FIELD**

The Gallup-Zuni field, which is the southwestern part of the vast San Juan coal basin of New Mexico, extends into eastern Apache County, Ariz. at several places, mostly as small outliers (see fig. 10). Some of these outliers in central Apache County have been described briefly by Aker (1964). The Gallup field of New Mexico has been described by Sears (1925) and a summary of the geology of the San Juan basin, including a bibliography, has been prepared by Read, Duffner, Wood, and Zapp (1950). The coal in the Gallup-Zuni field and its minor extensions into Arizona is contained in rocks of Cretaceous age. As in the Black Mesa field, the thicker and more continuous coals in the Gallup-Zuni field are in the Mesaverde Group and thinner and less continuous coals are present in the Dakota Sandstone.

A great deal of coal has been mined from the Gallup field and from the western edge of the San Juan basin for use directly or indirectly in Arizona.

For many years the mines around Gallup supplied the local needs of the Santa Fe Railway, and much coal was hauled westward into Arizona.

In 1962, the Pittsburg and Midway Coal Co. opened the McKinley mine, a new, modern strip mine in New Mexico about 21 miles north of Gallup for the specific purpose of supplying coal on a long-term contract to the 155,000 kilowatt Cholla electric generating plant of the Arizona Public Service Co., near Joseph City, Ariz. The McKinley mine has a potential capacity of 1 million tons annually. In 1965 it produced 368,611 tons, most of which was moved by unit train to Joseph City. The principal customers of the McKinley mine in addition to the Arizona Public Service Co. are the Phelps Dodge and Kennecott Copper Corps. (See Coal Age, 1962; 1966, p. 83, 97).

The Navajo strip mine of the Utah Construction and Mining Co. in the Four Corners area has increased its output almost annually to supply the needs of the huge Four Corners electric generating plant, which also supplies a large amount of power to Arizona. (See Coal Age, 1963). The Navajo mine produced nearly 2 million tons in 1966, and production is expected to increase in the future.

**SOUTHWESTERN COLORADO FIELD**

The Dakota Sandstone is locally coal bearing over many hundreds of square miles in southwestern Colorado and adjoining parts of Utah. A small tongue of this field extends across the Four Corners into the extreme northeastern corner of Arizona. In this area the coals are lenticular, and are rarely more than 14 inches thick. Although some mining has been carried on in the Dakota coals near Cortez in Colorado, this part of the field in Arizona has not been mined.
KAIPAROWITS FIELD

The Kaiparowits coalfield covers an extensive area in southwest Utah. Near the Colorado River, two small outliers of this field extend a short distance into Arizona. Thin beds of coal are present in the Dakota Sandstone but have no economic value.

COAL IN ROCKS OF PALEozoIC AGE

In Arizona, all the economically important coal is found in Cretaceous rocks, but one occurrence of coal in Paleozoic rocks although of no commercial value is of some scientific interest. Coal, reported to be as much as 20 inches thick (Ransome, 1916, p. 160) occurs in the Supai Formation of Paleozoic age in Fossil Creek (locality 1, fig. 10). The extent of the coal is not known; an analysis of the coal showed a yield of about 10,000 Btu (McGoon, 1969). The coal is noteworthy because it is the westernmost occurrence of coal in Paleozoic rocks in the United States and indicates that conditions suitable for the formation of coal existed this far west in Paleozoic times. A previous report (Dumble, 1902) of Carboniferous coal in the Chiricahua Mountains (locality 2, fig. 10) is now believed to be of Cretaceous age (P. T. Hayes, oral commun., 1968).

PRODUCTION OF COAL

In the period 1300 to 1600, the Hopi Indians probably mined and used about 100,000 tons of coal (Brew and Hack, 1939, p. 14). Between 1600 and 1925 there is no official or historical record of the use of coal in Arizona, though, of course, small amounts must have been mined annually for local use. In 1926, the Arizona Bureau of Mines recorded production of 624 tons. For the years 1926-34, 1942, and 1943 the total recorded production was 88,730 tons valued at $358,000 (Wilcox and Roseveare, 1949, p. 16). The greatest production in any one year during this period was 11,373 tons. Most, if not all, of this coal came from the Black Mesa field.

Since 1943 production in the Black Mesa field has been no more than about 10,000 tons annually, most of which was mined and used locally at schools in the Navajo Indian Reservation, but some of which was shipped to Holbrook, Winslow, and Flagstaff.

When plans for the large-scale production of strip coal from the northern part of the Black Mesa field are put into effect, annual production will jump abruptly to several million tons a year.

COAL RESOURCES

With the very small amount of factual data available, it is impossible to estimate the coal resources of Arizona with the degree of accuracy comparable for resources in states where the coal has been mapped and studied in greater detail. Table 6, however, shows the order of magnitude of coal resources in each of the three main fields, based on data currently available.

<table>
<thead>
<tr>
<th>TABLE 6.—ESTIMATED ORIGINAL COAL RESOURCES OF ARIZONA</th>
</tr>
</thead>
<tbody>
<tr>
<td>[in millions of short tons]</td>
</tr>
<tr>
<td>Field</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Black Mesa</td>
</tr>
<tr>
<td>Peinesdale</td>
</tr>
<tr>
<td>Deer Creek</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

*Includes subbituminous coal in the Dakota Sandstone, and bituminous coal in the Toreva and Wepo Formations.

The figures in table 6 represent coal in the ground, about half of which may be considered to be ultimately recoverable. The figures for bituminous coal in the Deer Creek field include coal in beds to a minimum thickness of 14 inches. The figures for subbituminous coal in the Peinesdale field include coal in beds to a minimum thickness of 30 inches. The figures for subbituminous and bituminous and in the Black Mesa field include coal in beds to a minimum thickness of 50 inches. Most of the coal included in the estimates is less than 1,000 feet below the surface, though some coal in the center of the Deer Creek field may be more than 1,000 feet below the surface.

CONCLUSIONS

Since statehood, Arizona has depended on oil and gas, and on coal and electricity imported from New Mexico and Colorado for its main sources of fuel and energy. With the opening of the new, modern strip mine on Black Mesa, it is likely that coal production will increase to several million tons annually. This output will be an economic boon to Arizona and California, and might well encourage increased Arizona coal production and, consequently, less dependence on outside sources of supply.

SELECTED REFERENCES

Deer Creek, Arizona: Coal Age, v. 67, no. 6, p. 60-64.
— 1963, Navajo mine: Coal Age, v. 68, no. 11, p. 59-64.
**INTRODUCTION**

Crude oil is a naturally occurring liquid composed of compounds of hydrogen and carbon (hydrocarbons) commonly containing minor amounts of oxygen, nitrogen, and sulfur as impurities. Hundreds of different hydrocarbons are recognized and each has special physical and chemical properties. One widely accepted standard for classifying crude oil is gravity expressed on a scale adopted by the American Petroleum Institute (API). The lighter gravity oils have greater value because they contain larger quantities of gasoline and other valuable products. Crude oils containing such impurities as sulfur are less valuable because they are more expensive to handle and refine.

Crude oil supplies about one-third the total energy requirements of the United States, principally in the form of energy for power and heat. In 1965, the value of crude oil produced in the United States was about $7.8 billion, or about 36 percent of the total value of all minerals produced in that year. There are over 5,000 crude-oil producing units but about 90 percent of them are various kinds of gasolines and fuel oils. Other products include lubricants, solvents, wax, asphalt, coke, chemical, petrochemicals, and a wide variety of specialty products.

Geological evidence strongly suggests that crude oil is derived from the organic matter of living organisms. During deposition, plant and animal remains were enclosed in sediments as they accumulated in lakes, swamps, and oceans. As the sediments were buried, the organic matter was subjected to heat, pressure, and various chemical processes and was gradually transformed into crude oil. Subsequently, the disseminated crude oil was either retained in the source rocks or was forced to migrate short or long distances through porous rocks. The migration of crude oil away from the source rocks is caused by a number of forces, including gravity and water and gas pressure as the enclosing rocks are compacted, folded, faulted, or tilted. Under certain favorable conditions, the migration or movement of crude oil is interrupted where a suitable trap forms a barrier to further migration. The crude oil then accumulates in the trap by filling the cracks, pore spaces, and other voids in the rocks. The accumulation of crude oil is called a pool, field, or reservoir. Typical traps or barriers that collect crude oil include anticlinal or domes, which are upwarps in the rock layers; fault traps, where a break in the rock layers causes porous rocks to abut against nonporous rocks; and stratigraphic traps, where porous rocks pass laterally into nonporous rocks.

**HISTORY**

Early test holes in Arizona were apparently drilled in a haphazard manner in part because surface indications such as oil and gas seeps and oil-stained outcrops of rocks were unknown (Allen, 1917, p. 32). Some test holes may have been located in areas where there were shows or at least rumors of shows of oil and gas in wells drilled for water. However, the most important incentive to drill appears to have been the presence of oil and gas in nearby areas. As stated by Allen (1917, p. 32): "It is a fact that the possibility of oil in Utah and New Mexico
is being more realized every day. That oil exists in great quantities in southern California still more enhances the possibilities of there being oil in Arizona.”

In Arizona, the first well drilled for oil and gas was completed in 1903 (Pye, 1967, p. 108), the first commercial natural gas well was completed in 1954, and the first commercial oil well was completed in 1955. Records of early test holes are incomplete, but about 164 wells (including some drilled primarily for water) are known to have been completed in Arizona in the half century between the first test and the discovery well (Stipp and Beikman, 1959). This averages out to only a little over three test holes a year. In the 50-year period from 1903 to 1953, drilling activity started slowly and gradually increased as shown below:

<table>
<thead>
<tr>
<th>Period</th>
<th>Wells completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1903 to 1909</td>
<td>8</td>
</tr>
<tr>
<td>1910 to 1919</td>
<td>0</td>
</tr>
<tr>
<td>1920 to 1929</td>
<td>25</td>
</tr>
<tr>
<td>1930 to 1939</td>
<td>22</td>
</tr>
<tr>
<td>1940 to 1949</td>
<td>0</td>
</tr>
<tr>
<td>1950 to 1953</td>
<td>29</td>
</tr>
</tbody>
</table>

After the discovery of oil, as would be expected, drilling activity increased markedly. The most recent count (Pye, 1967) shows that a total of 548 wells have been drilled in the search for oil, gas, and helium, as well as for potash in Arizona since 1903. This number of wells in a period of over 60 years is still small in comparison with such a large oil-producing state as Wyoming, where a total of 987 wells were completed in the year 1966 alone.

**Production**

In comparison with the larger oil-producing states or with the metal mining industry of Arizona, production of crude oil in Arizona has not been as important. Cumulative crude oil production in Arizona through the year 1966 amounted to about 570,000 barrels with a value of $1,219,800 at the wellhead. In 1967, a new oilfield—Dineh-bi-Keyah—increased cumulative production more than sixfold. In the future, it can be expected that crude oil production will be a consistent and growing contributor to the economy of Arizona.

The following summary (table 7) of petroleum production in Arizona has been prepared mainly from D’Amico (1961, p. 11; 1964, p. 10; 1967, p. 9). The value of crude oil is calculated at $2.83 per barrel of crude oil at the wellhead in Arizona (Kirby and Moore, 1967, p. 399, table 34). Production for the year 1967 is from

<table>
<thead>
<tr>
<th>Year</th>
<th>Oil in barrels</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958</td>
<td>12,000</td>
<td>$25,880</td>
</tr>
<tr>
<td>1959</td>
<td>25,500</td>
<td>53,500</td>
</tr>
<tr>
<td>1960</td>
<td>72,000</td>
<td>156,270</td>
</tr>
<tr>
<td>1961</td>
<td>73,500</td>
<td>156,270</td>
</tr>
<tr>
<td>1962</td>
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<td>255,880</td>
</tr>
<tr>
<td>1967</td>
<td>2,924,267</td>
<td>6,529,931</td>
</tr>
</tbody>
</table>

Total . . . . . 3,454,267 7,477,731

**DINEH-BI-KEYAH FIELD**

The largest oilfield in Arizona is the Dineh-bi-Keyah field (No. 1, fig. 12), located about 36 miles south of the Four Corners Monument and about 5 miles west of the New Mexico boundary. The discovery well was the Kerr-McGee Navajo 1 in the SE1/4SW1/4 sec. 32, T. 36 N., R. 30 E. It was completed in February 1965 and formally abandoned in June 1965. After a study of electric logs, the test hole was reentered in January 1967. The well was then completed in February 1967 for an initial production of 611 barrels of 43.5° (API) oil per day between depths of 2,860 and 2,885 feet in an igneous sill intruded into the lower part of the Hermosa Formation. Production from the discovery well climbed to 1,400 barrels of oil per day until July 19, 1967, when an additional zone was opened between depths of 2,885 and 2,942 feet. The daily production on July 23, 1967 was 1,851 barrels of oil and 135,000 cubic feet of gas (Pohlmann, 1967, p. 64).

The unusual reservoir is a sill of igneous rocks injected between the layers of sedimentary rocks that make up the lower part of the Hermosa Formation. The igneous rock has been classified as a diopsid-rich melite, a variety of the syenite lamprophyre group of igneous rocks. The sill ranges in thickness from 18 feet near its north edge to about 70 feet near its south edge, a distance of nearly 80 miles (Pohlmann, 1967, p. 67). The base of the sill apparently is irregular, as the distance from the sill to the top of the Redwall Limestone differs from well to well. The igneous rock is sufficiently porous to serve as a suitable trap for the oil which migrated into it after the sill was emplaced.
Figure 13.—Stratigraphy of oil- and gas-bearing rocks of the northern Apache County area, Arizona.

**TABLE 1: PERIOD, FORMATION, LITHOLOGY, MEMBER**

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>FORMATION</th>
<th>LITHOLOGY</th>
<th>MEMBER</th>
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<td>Chinle Formation</td>
<td>Shinarump Member</td>
<td>DeChelly Sandstone Member</td>
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<td></td>
<td></td>
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<td>middle member</td>
</tr>
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<td>PENNSYLVANIAN</td>
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<td></td>
<td>Paradox Member</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tertiary igneous sill of Dineh-bi-Keyoh field</td>
</tr>
<tr>
<td>DEVONIAN</td>
<td>Molos Formation</td>
<td></td>
<td>McCracken Sandstone Member of Knight and Cooper (1955)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Aneth Formation of Knight and Cooper (1955)</td>
</tr>
<tr>
<td>CAMBRIAN</td>
<td>Topeka Sandstone</td>
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</tbody>
</table>

**EXPLANATION**

- Crude oil field
- Crude oil field and natural gas field
- Natural gas field
- Helium field

Boundary between northern (No. 1), southeastern (No. 2), and southwestern (No. 3) areas (see text)

Figure 12.—Areas of Arizona ranked by order of oil and gas potential, and crude oilfields and gasfields of the State.
Cumulative production at Dineh-bi-Keyah through the year 1967 is 2,815,169 barrels of crude oil from 13 producing wells. The ultimate recovery of the field is estimated to be 50 million barrels (John Banister, as cited in World Oil, 1968, p. 86).

**EAST BOUNDARY BUTTE FIELD**

The East Boundary Butte field (No. 2, fig. 12) is about 15 miles west of the Four Corners Monument and less than 1 mile south of the Utah boundary. The Boundary Butte field is the largest gasfield and third largest oilfield in Arizona. The discovery well for the field is considered to be the Shell Oil Co. East Boundary Butte 2 in the SE1/4 NW1/4 sec. 3, T. 41 N., R. 28 E. The well, completed in December 1954, had an initial production of 3,150,000 cubic feet of gas and 3.6 barrels of 41° (API) oil per day from between depths of 4,540 and 4,585 and between depths of 4,650 and 4,690 feet in the Paradox Member of the Hermosa Formation. About one-half mile to the west, the Humble Oil and Refining Co. Navajo Tribal 1 was completed in 1955 in the NE1/4 SE1/4 sec. 4, T. 41 N., R. 28 E. The Humble well had an initial production of 47 barrels of 30.4° (API) oil and 4,141,000 cubic feet of gas per day. Two other producing wells were completed later—one in 1958 and the other in 1959. The well completed in 1958, the Humble Oil and Refining Co. Navajo 1-E in the SW1/4 NE1/4 sec. 10, T. 41 N., R. 28 E., had an initial production of 562 barrels of oil per day, the highest of the four wells in the field. The cumulative production of crude oil from the East Boundary Butte field through the year 1967 amounted to 225,765 barrels of oil.

**UNNAMED FIELD**

About 6 miles south of the East Boundary Butte field is an unnamed field (No. 3) that also produced from the Paradox Member of the Hermosa. The discovery well of the one-well field was the Pan American Petroleum Co. Navajo 1-A in the SW1/4 SW1/4 sec. 6, T. 40 N., R. 28 E. The well, completed in December 1954, had an initial production of 50 barrels of 38° (API) oil from between depths of 6,422 and 6,467 feet. After producing 6,900 barrels of oil, the field was abandoned in March 1965.

Crude oil has been produced from the Redwall Limestone of Mississippian age at two fields in northeastern Arizona—both located on a west-trending anticline and both related to an old buried landmass. Subsurface studies by J. D. Strobell (U.S. Geol. Survey, 1960) show that the Tapeats Sandstone (1) and Elbert Formation lap out on an old Precambrian highland in the western part of the Carrizo Mountains area. The younger Redwall and Ouray Limestones thin across this old buried landmass. Crude oil in the Redwall Limestone is found in solution cavities just beneath the relatively impermeable Molas Formation and in porous crystalline zones in the lower part of the limestone.

**DRY MESA FIELD**

The discovery well of what is now the second largest oilfield (No. 4) in Arizona was the Texas Pacific Coal and Oil Co. Navajo 188-1 in the center of NE1/4 NE1/4 sec. 11, T. 40 N., R. 28 E. The discovery well, completed in June 1959, produced 240 barrels of 40° (API) oil per day from between depths of 5,566 and 5,589 feet in the Redwall Limestone. A total of five wells have been completed in the field; three wells produced oil and two were dry holes. At the end of 1967, two wells were still producing oil. Cumulative production through 1967 is 369,648 barrels of oil.

**WALKER CREEK FIELD**

The discovery well of the Walker Creek field (No. 6) was the Texaco Inc. 1AG in the NW1/4 SE1/4 sec. 16, T. 41 N., R. 25 E., Apache County. The discovery well, completed at the end of 1967, initially produced 182 barrels of 40° (API) oil per day from between depths of 6,370 and 6,384 feet in the Elbert Formation. The producing zone is near the base of the McCracken Sandstone Member of Knidt and Cooper (1955), and an unnamed unit. Crude oil is produced from a zone near the lower part of the McCracken Sandstone or from the upper part of the Aneth Formation. The Aneth Formation is as much as 275 feet thick in the northern Apache County area (Strobell, 1958, p. 66) and consists of dolomite and black shale. The McCracken Sandstone is 100 to 150 feet thick (Strobell, 1958, p. 66) and consists of fine- to coarse-grained, light-colored sandstone containing some interbedded dolomite.

**UNNAMED FIELD**

Small production was obtained from the Elbert Formation in an unnamed one-well field (No. 7) about 6 miles southwest of the Four Corners Monument and about 31 miles east of the Walker Creek Field. The discovery well was the Texaco Inc. Navajo I-Z in the NW1/4 SW1/4 sec. 38, T. 41 N., R. 30 E. The well, completed in July 1960, had an initial production of 8 barrels of 41° (API) oil per day from between depths of 6,758 and 6,793 feet. Cumulative production amounted to 733 barrels before the field was abandoned in 1962.
RESERVES AND RESOURCES

Inasmuch as crude oil and natural gas are closely related, the reserves and potential resources of these two commodities are discussed together under "Natural gas" which follows.

SELECTED REFERENCES


NATURAL GAS

(By B. B. O'Sullivan, U.S. Geological Survey, Denver, Colo.)

INTRODUCTION

Natural gas consists of a variety of gaseous hydrocarbons in which the paraffin series of hydrocarbons (CH₄) predominates. Natural gas may contain such contaminants as nitrogen, carbon dioxide, hydrogen sulfide, helium, and some other gases. Small amounts of contaminants reduce the heating value of natural gas, but large amounts of some of the contaminants are recoverable as byproducts. Natural gas is found associated with crude oil either as solution gas or as free gas in a gas cap. Natural gas also occurs in what might be termed a primary gas accumulation, in which there is no associated crude oil. Primary natural gas accumulations are classified as "wet" or "dry," depending on the amount of liquid the gas contains. Wet gas is believed to be in a gas cap, such as at reservoir pressures, but as the pressure declines during production some of the gas liquifies and is then collected at the wellhead as condensate.

Natural gas supplies about one-third the total energy requirements of the United States, principally as fuel for all forms of heating. In 1965, the value of natural gas at the wellhead was about $2.5 billion or about one-third the value of crude oil produced in the United States in that year. Natural gas furnishes fuel for space heating of commercial and residential buildings and for a variety of industrial uses that include crude oil well, pipeline and refinery fuel, and raw material for carbon black and petrochemicals. Condensate is used as a chemical raw material or as a fuel.

The origin of natural gas is the subject of considerable speculation (Hedberg, 1964; Tiratsoo, 1967) between the views that it has an origin either similar to or entirely different from that of crude oil. As all crude oil accumulations have some associated natural gas, it has been suggested that oil and gas are merely liquid and gaseous phases of hydrocarbons derived from the same source material. By this concept, it is believed that natural gas may be a beginning, accompanying, or final stage in the formation of crude oil. However, some natural gas accumulations have no crude oil associated with them, and this has led some geologists to believe that natural gas is generated by plants or land source material. Other theories include the separation of natural gas and crude oil during migration; differences in temperature, pressure and other geological conditions during the formation of hydrocarbons; and metamorphism with depth converting oil to gas. Although the origin of natural gas is open to question, it seems clear that in some areas both natural gas and oil were formed originally and in other areas only natural gas.

HISTORY

Natural gas was discovered in Arizona in 1954 on the Boundary Butte anticline, a large structural feature about 18 miles long that lies partly in Utah and partly in Arizona. A well completed in 1929 on this anticline in Utah, about 3 miles north of Arizona, found a small amount of oil in the Shinrump Member of the Chinle Formation (fig. 13) and a reported flow of 15 million cubic feet of gas per day from the Hermosa Formation (Sheffer, 1958, p. 265). The remoteness of the area when the test was drilled and the lack of a market, however, prevented production from this well. This anticline was first tested in Arizona by the Shell Oil Co. East Boundary Butte 1 in sec. 6, T. 41 N., R. 29 E., that began to drill in December 1953. Drillstem tests of the Hermosa Formation showed substantial amounts of natural gas and shows of oil, but the well was suspended in March 1954. Shell Oil Co. then moved west about 3½ miles and higher on the structure to drill the East Boundary Butte 2 in sec. 3, T. 41 N., R. 28 E. This well, completed in December 1954, marks the discovery of commercial natural gas in Arizona.

PRODUCTION

Production of natural gas in Arizona has not been important in comparison with the large gas-producing states. Natural gas production, however, can be expected to increase in the future with a growing contribution to the economy of Arizona. For a period after natural gas was discovered in 1954, the wells were shut in until pipeline facili-
ties were constructed. A reported 122,116,000 cubic feet of gas was produced in 1954 and 1955 during production tests on wells drilled at East Boundary Butte, but the gas was not used commercially. The following summary (table 8) of natural gas production in Arizona was prepared from data supplied by John Bannister, Chairman of the Arizona Oil and Gas Conservation Commission (oral commun., 1968). The value of natural gas is calculated at 13.8 cents per 1,000 cubic feet, the average value of natural gas at the wellhead in Arizona (U.S. Bur. Mines, 1967, p. 769).

<table>
<thead>
<tr>
<th>Table 8—Production of Natural Gas in Arizona, 1962-67</th>
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<tbody>
<tr>
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</tr>
<tr>
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</tr>
<tr>
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<td>1964</td>
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<td>1965</td>
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<td>1966</td>
</tr>
<tr>
<td>1967</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>

**Natural Gas in Arizona**

All the marketed natural gas accumulations are in the Paradox Member of the Hermosa Formation (fig. 13) in northeastern Apache County. Natural gas is also present in the Redwall Limestone and in the Tertiary igneous sill intruding the Hermosa Formation at the Dineh-bi-Keyah field but this gas has not been marketed. The Paradox Member in northeast Arizona consists of limestone, black shale, some dolomite, and thin interbedded gypsum. Details of the geology of natural gas accumulations in rocks of Pennsylvanian age in northeastern Arizona are discussed by Picard (1960).

There are six fields in Arizona that produce gas, and of these, four are without any associated crude oil. One field—East Boundary Butte—produces both oil and gas. The other field—Dineh-bi-Keyah—also produces both oil and gas, but the gas was not being marketed at the end of 1967. The distribution of the fields is shown in figure 12. In addition to the natural gas, the four gas fields have produced a cumulative total of 44,078 barrels of condensate. Cumulative and other production figures used in the description of the gas fields are from production statistics compiled by the Oil and Gas Conservation Commission of the State of Arizona (written commun., 1968).

**Bita Peak Field**

The discovery well of the second largest gasfield (No. 8, fig. 12) in Arizona was the El Paso Natural Gas Co. and Stanolind Oil and Gas Co. Bita Peak 1, in the SW\(^{1/4}\)NW\(^{1/4}\) sec. 19, T. 41 N., R. 31 E. Initial production was 20,878,000 cubic feet of gas a day and some condensate from a zone about 22 feet thick in the Paradox Member of the Hermosa. Cumulative production of gas through the year 1967 is 2,478,977,000 cubic feet and 12,314 barrels of 60° (API) condensate. In 1967, production of gas at the Bita Peak field declined by over 500 million cubic feet from 1,050,287,000 cubic feet in 1966 to 508,114,000 cubic feet in 1967. The drop in production at Bita Peak accounts for the decrease in total production of natural gas in Arizona in 1967 (see table 8).

**Dineh-bi-Keyah Field**

Dineh-bi-Keyah is primarily an oilfield but it also produces some gas. It is shown as an oilfield (No. 1) in figure 12 because pipeline facilities have not been constructed into the field and the gas therefore is not being marketed commercially. The discovery well for the field—the Kerr-McGee Navajo 1 in the SE\(^{1/4}\)SW\(^{1/4}\) sec. 32, T. 36 N., R. 30 E.—produced oil containing small amounts of gas between depths of 2,800 and 2,885 feet in an igneous sill intruded into the lower part of the Hermosa Formation. The well, completed in February 1967, had an initial production of 611 barrels of oil per day and gas amounting to 73 cubic feet per barrel of oil (Pohlmann, 1967, p. 64). The gas, at present, is in solution but, as the pressure in the field declines, a gas cap is expected to form (Pohlmann, 1967, p. 68). Cumulative production through the year 1967 is 271,046,000 cubic feet of gas. Currently, the gas is used as a fuel to run pumps in the field or is being flared.

**East Boundary Butte Field**

East Boundary Butte (No. 2) is an oilfield and is also the largest gas producer in Arizona. The discovery well was the Shell Oil Co. East Boundary Butte 2 in sec. 3, T. 41 N., R. 28 E. The well, completed in December 1954, had an initial production of 3,150,000 cubic feet of gas and 36 barrels of oil per day from the Paradox Member of the Hermosa. The other wells in the field also produce from the Paradox. According to Sheffer (1958) the Humble Oil and Refining Co. Navajo 1 gaged an estimated 9 million cubic feet of gas per day from the Redwall Limestone, but the well was plugged back to a productive zone in the Paradox Member. Cumulative gas production at East Boundary Butte through the year 1967 is 2,950,766,000 cubic feet of gas.

**Toh-Atin Field**

The Toh-Atin gasfield (No. 9) is about 3 miles south of the East Boundary Butte field. The discovery well of the field was the Franco Western Oil Co. Navajo 1 in the SW\(^{1/4}\)NW\(^{1/4}\) sec. 22, T. 41 N., R. 28 E. The well, completed in August 1956, had an initial production of 7,450,000 cubic feet of gas and 20 barrels of condensate per day from between depths of 5,360 and 5,392 feet in the Paradox Member of the Hermosa Formation. Cumulative production from the one-well field through the year 1967 is 634,002,000 cubic feet of gas and 6,315 barrels of 61° (API) condensate.

**Twin Falls Creek Field**

The Twin Falls Creek gasfield (No. 10) is about 4 miles west of the Bita Peak field. The discovery well of the field was the Superior Oil Co. Navajo 2–H in the SW\(^{1/4}\)SW\(^{1/4}\) sec. 16, T. 41 N., R. 30 E. The well, completed in December 1967, had an initial production of 4,002,000 cubic feet of gas per day and 65° (API) condensate at the rate of 31 barrels a day from between depths of 5,063 and 5,071 feet in the
Paradox Member. Cumulative production from the one-well field through the year 1967 is 201, 963,000 cubic feet of gas and 660 barrels of 65° (API) condensate.

**Unnamed Field**

An unnamed field (No. 11) is about midway between the Bita Peak and the Twin Falls Creek fields. The discovery well of the field is the Pan American Petroleum Co. Navajo 1-JQ7 in the SE1/4 SW1/4 sec. 23, T. 41 N., R. 30 E. The well, completed in July 1965, had an initial production of 4,559,000 cubic feet of gas per day from depths between 5,122 and 5,140 feet in the Paradox Member. Cumulative production from the one-well field through the year 1967 is 570,694,000 cubic feet of gas and 24,789 barrels of condensate.

**Reserves and Potential Resources of Crude Oil and Natural Gas**

Reserves of oil and gas in Arizona are difficult to estimate. In the past the crude oil and natural gas reserves have been so inconsequential that the Arizona estimates have been included with several “other states” (Oil and Gas Jour., 1967). By apportioning these figures among the several “other states,” based on past production, the crude oil reserves of Arizona would be about 1.2 million barrels of oil as of January 1, 1967. However, the Dineh-bi-Keyah field, discovered in 1967, boosted the Arizona crude oil reserve estimate to over 50 million barrels and demonstrates how quickly reserve estimates can change. By apportioning out the natural gas reserves of the “other states” (Oil and Gas Jour., 1967) based on past production, the reserves of Arizona are an estimated 125 billion cubic feet of gas as of January 1, 1967.

The ultimate oil and gas resources of Arizona are also very difficult to assess because of the scarcity of drilling data. According to Pye (1967, p. 168) a total of 548 wells have been drilled in Arizona which represents a density of about one well for each 207 square miles. However, the drill holes are not distributed equally over the State and of the total number of wells, 384, or about 70 percent, have been drilled in Apache and Navajo Counties. In addition, many of the wells were shallow and did not test the entire section of sedimentary rocks above the Precambrian or crystalline basement.

Arizona, however, can be subdivided into three areas, northern, southeastern, and southwestern (fig. 12), each having a different potential for discoveries of oil and gas. Northern Arizona (area No. 1, fig. 12) consists for the most part of gently dipping strata and essentially includes the Arizona part of the Colorado Plateau province with the exception of the Tonto section (see fig. 4, p. 36). Northern Arizona contains the State’s only known oil and gas and has by far the greatest potential. Southeastern (area No. 2) and southwestern (area No. 3) Arizona make up the remainder of the State. These areas have produced no oil and gas and the potential appears to be much less than that of northern Arizona. Furthermore, large areas of southeastern and southwestern Arizona are underlain by igneous and metamorphic rocks of Precambrian, Paleozoic, Mesozoic, and Cenozoic ages and Precambrian sedimentary rocks (see “Geologic map,” fig. 5, facing p. 38). These rocks generally form the cores of mountain ranges and have little or no oil and gas potential.

The oil and gas possibilities of different parts of northern Arizona have been discussed by Brown and Lauth (1961), Pye (1961), and Swapp (1961). Production has already been established in the Hermosa Formation, Redwall Limestone, and Elbert Formation (fig. 13), and future exploration will be directed towards finding additional production from the same rocks in northeastern Arizona. Shows of oil and gas have been recorded in most of the Paleozoic rocks in drill holes in other parts of northern Arizona away from the present producing areas which indicates that a wide area is underlain by potential oil and-gas resources. In addition, other less important potential resources might be found in the Chinle Member of the Chinle Formation, the Moenkopi Formation, the Cutler Formation, and the Rico Formation, that so far have not yielded oil and gas in Arizona but have yielded small quantities of oil and gas in nearby areas. In Utah, for example, the Moenkopi Formation, the Rico Formation, and the Shinarump Member have yielded oil 15 miles, 10 miles, and 3 miles, respectively, north of the Arizona boundary and gas was discovered in the Butler Formation in a recently drilled well in New Mexico, less than 2 miles east of Arizona.

In the southern half of the State, southeastern Arizona has the greatest oil and gas potential (Buck, 1961). Most of southeastern Arizona (area No. 3, fig. 12) consists of Cretaceous rocks exposed they commonly are metamorphosed or severely altered. Thick Cretaceous and Mesozoic and have little or no oil and gas potential. The Cenozoic rocks generally form the cores of mountain ranges and have little or no oil and gas potential. These rocks generally form the cores of mountain ranges and have little or no oil and gas potential. The Cenozoic fill in the basins conceals the underlying bedrock and the fill is very thick at places. According to Pye (1967, p. 172) a well drilled in one of the basins near San Simon passed through 7,500 feet of alluvium without penetrating the underlying bedrock. In summary, the southeast section has some potential for oil and gas because it contains possible source rocks but has little or no oil and gas potential.

Southwestern Arizona (area No. 3, fig. 12) apparently has little oil and gas potential; the oil and gas possibilities have been discussed by McCarthy (1961). The area consists of low mountain ranges, composed for the most part of igneous and metamorphic rocks, separated by desert basins filled with Cenozoic alluvium and volcanic rocks. The area is structurally complex and where the sedimentary rocks are exposed they are mineralized and metamorphosed. The Cenozoic fill obscures any possible sedimentary bedrock in the desert basins and would make exploration difficult and hazardous. In addition, information from water wells and stratigraphic studies suggest that marine sedimentary rocks are thin or absent in much of the area (Pye, 1961).
OTHER ASSOCIATED GASES

(By R. B. O'Sullivan, U.S. Geological Survey, Denver, Colo.)

Other gases are associated with natural gas (p. 77) and include carbon dioxide, helium, hydrogen sulfide, and nitrogen. These non-combustible gases occur at widely scattered localities in northeastern Arizona most commonly as components of the hydrocarbon gases. Some of the occurrences and analyses of the associated gases are given in table 9. Helium at present (1968) dollar value is the only important associated gas and probably will continue to be the only important gas.
Helium is a light inert gas with a wide variety of critical uses. Currently over 80 percent of the helium produced in the United States is used (1) for pressuring rockets and missiles; (2) as an inert shield in arc welding; (3) as a controlled atmosphere for growing transistor crystals; and (4) for research (Lipper, 1965). The remainder is used as a lifting gas for balloons and lighter-than-air craft, as part of a breathing mixture for deep-sea divers, for heat transfer purposes, leak detection, cryogenics and other purposes. The helium consumed in the United States in 1965 amounted to 757 million cubic feet (Thomasson, 1967, p. 457-460) and at the established Bureau of Mines price of $35 per 1,000 cubic feet, the value of helium consumed in 1965 amounts to about $26.5 million.

The source of helium in natural gas accumulations is not completely understood (Pierce, 1960). It is commonly believed that helium forms through the decay of uranium and thorium present in sedimentary rocks. Accumulations of helium in natural gas accumulations are believed to come from four main sources: (1) by direct magmatic emanations; (2) by oxidation of hydrocarbons by mineralized waters; (3) by contact metamorphic action of hot igneous rocks intruding limestone; and (4) by the dissolving action of ground water on limestone (Dobbin, 1935, pp. 106-1069).

Most of the carbon dioxide consumed in the United States is obtained as a byproduct at coke, chemical, cement, and metallurgical plants. Minor amounts are supplied by naturally occurring accumulations of carbon dioxide. The adjacent State of New Mexico is the largest producer of naturally occurring carbon dioxide; in 1965 the State produced 833,819,000 cubic feet but valued at only $62,000 at the wellhead (Burleson and Henkes, 1967, p. 551). The carbon dioxide content of the gas in New Mexico is as much as 98 percent (Anderson and Hinson, 1951). In Arizona gas from only one well showed a high concentration of carbon dioxide. That well—the Great Basin Oil Co. Taylor-Fuller 1 (sample No. 26, table 9)—showed a concentration of almost 80 percent carbon dioxide. The rest of the wells (table 9) show a concentration of less than 16 percent and most are less than 6 percent. The occurrences of carbon dioxide in Arizona do not have the purity or quantity to warrant economic exploitation at this time. The presence of carbon dioxide gas at so many localities, however, indicates a favorable potential for discovering future resources of carbon dioxide.
mentary rocks and in the underlying basement rocks. Dobbin (1935, p. 1064) noted that natural gas with the highest helium content generally occurs in sedimentary rocks relatively close to the basement, which supports the theory that helium is derived at least in part from the disintegration of radioactive elements in the basement rocks.

HISTORY

Helium was first reported in Arizona at the Great Basin Oil Co. Taylor Fuller 1 drill hole a few miles south of Holbrook. The well, completed in 1927, had an open-flow potential of 100,000 cubic feet a day (Anderson and Hinson, 1951, p. 49) and the gas contained 1.12 percent helium (sample No. 26, table 9). The productive zone was in Cambrian rocks, Tapeats Sandstone (?), at a depth of 2,500 feet. Since 1927, helium has been found at a number of other localities in northeast Arizona (table 9).

PRODUCTION

The following summary (table 10) of helium gas production in Arizona was prepared from Lipper (1965) for 1962, Larson (1964, p. 119) for 1963, Larson and Biggs (1965, p. 121) for 1964, Larson and Henkes (1967, p. 99) for 1965, and the production for 1966 and 1967 has been calculated from production figures compiled by the Arizona Oil and Gas Conservation Commission (written commun., 1968). Some helium was produced in 1961 but it cannot have been as much as the helium extraction plant near the Pinta Dome field did not begin operations until December 1961 (Smith and Pylant, 1962).

<table>
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<th>Year</th>
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</tr>
<tr>
<td>1967</td>
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<td>$900,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td><strong>10,650,000</strong></td>
</tr>
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</table>

**OCCURRENCES IN ARIZONA**

In Arizona, helium is present in rocks of Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, and Triassic ages (table 5) and the highest concentration of helium is found in rocks of Permian and Triassic ages. Helium is found in most of the gasfields and some of the oilfields in northern Apache County, but thus far, it has not been extracted for commercial use. The occurrence and origin of gas with a high helium content in rocks of Mississippian age in northeastern Arizona and adjacent areas is described by Picard (1962).

All production of helium in Arizona has been from the Pinta Dome and Navajo Springs fields (Nos. 12 and 13, fig. 13) in central Apache County. Helium has also been discovered at an unnamed field (No. 14, fig. 12) in Navajo County but that field is currently shut in. The distribution of the fields is shown in figure 12 and the stratigraphic sequence that contains productive helium zones is shown in figure 14.

Helium is produced from the Coconino Sandstone of Permian age and the Shinarump Member of the Chinle Formation of Triassic age. The Shinarump Member is as much as 100 feet thick in central Apache County and consists of fine- to coarse-grained sandstone and conglomerate with some thin interbedded shale. The Coconino Sandstone is as much as 200 feet thick (H. W. Peirce, written commun., 1968) in central Apache County and consists of fine- to coarse-grained sandstone.

**Pinta Dome field**

The largest producing helium field in Arizona is the Pinta Dome field (No. 12, fig. 12) located about 35 miles northeast of Holbrook. The field covers parts of Tps. 19-20 N., R. 26 E. The discovery well was the Kipling Petroleum Co. Macie 1 in the SW 1/4 SW 1/4 sec. 34,
METALLIC MINERAL RESOURCES

ANTIMONY AND OTHER MINOR METALS

(By G. H. Roseweare, Arizona Bureau of Mines, Tucson, Ariz.)

INTRODUCTION

Antimony, arsenic, bismuth, cadmium, selenium, and tellurium occur primarily as accessory elements in many metallic ores and thus their production is largely as byproducts. Antimony is recovered mainly by concentration and smelting of antimonial, lead, and lead-silver ores and concentrates and by refining intermediate lead smelter products. Arsenic is mainly a byproduct of the smelting of copper and concentrate. Bismuth is recovered principally as a byproduct in the refining of intermediate metallurgical products, such as lead bullion. Cadmium occurs with zinc deposits and is recovered in the processing of zinc ores and concentrates. Selenium is derived from the electrolytic refining of copper, from lead smelter flue dust, and from selenium-bearing sulfur residues of chemical plants. Tellurium is recovered as a byproduct in the electrolytic refining of copper and lead.

Most of Arizona's lead ores and concentrates are shipped to El Paso, Tex., for smelting and the lead bullion containing most of the antimony, bismuth, and tellurium content is shipped to the electrolytic refinery in Omaha, Neb., where the byproducts are recovered from the lead. Arizona zinc concentrates are normally shipped to zinc plants outside the State where cadmium is recovered as a byproduct. Anode copper from Arizona copper smelters is shipped to several different refineries and the residue slimes from the refineries are shipped to plants in the eastern United States for recovery of selenium and tellurium. No arsenic is recovered from Arizona ores and concentrates.

The smelters and refineries treating copper, lead, and zinc ore products from Arizona sources do not normally record the amounts of the byproduct commodities received from individual sources. Shippers are penalized by the smelters if appreciable amounts of some of these byproducts, such as 1 to 2 percent antimony and arsenic, are present in the ores or concentrates. In a few cases, payments have been made for the cadmium in zinc concentrates but payments are not made for the other byproduct metals. In general the mines, mills, smelters, and refineries do not check each shipment but depend mostly on past experience and composite assays to determine the byproduct content. Thus the production, value, and resources of the minor or byproduct metals of Arizona cannot be determined within any reasonable accuracy and their recovery will depend on the exploitation of the copper, lead, and zinc ores in the State.

Antimony is a relatively common element in the earth's crust but it seldom occurs in large concentrations. In its elemental state it may have several forms but usually is a brittle, tin-white material with a metallic luster. Most commonly it occurs in stibnite, a generally bladed, steel gray, crystalline form of antimony trisulfide; in antimony oxides; and in complex sulfosalts of copper, lead, and silver.

The major use of antimony is in antimonial lead for storage batteries and type metal. It also is used in the manufacture of ammunition, bearing metal, solder, and collapsible container tubes. Antimony oxides and compounds are used in flame-proofing compounds, paints, ceramics, rubber, and plastics (Moulds, 1965, p. 68-69). In 1966, the United States produced 927 short tons of antimony from primary mine ore, mainly from Idaho, and 14,539 short tons of antimony as a smelter byproduct of antimonial lead. Secondary recovery from scrap metal accounted for an additional 24,258 short tons. Antimony imports amounted to 19,712 short tons of metal, in the form of metal, ore, and concentrates; exports amounted to only a few tons (U.S. Bur. Mines, 1967, p. 164). Consumption from primary and sec-

(93)
Arizona is considered to be an area of low antimony content (R. F. Welch, oral commun., 1968). No primary antimony ore is produced in the State and the average antimony content of Arizona lead and lead-silver ores and concentrates seldom reaches 1 percent. The main producing areas of antimony-containing lead ore in the past 10 years are the Big Bug (fig. 15, No. 11) and Patagonia (No. 55) districts. Other districts in which antimony-containing lead ores have been noted are Wallapai (No. 3), Castle Dome (No. 24), Pima (San Xavier mine, No. 41), Warren (No. 56) and Tombstone (No. 49).

Arizona lead production, the only commercial source of antimony, has decreased sharply in recent years and unless new sources are found and developed, Arizona's output of antimony will continue to decline. Based on the possible lead resources in the State, the antimony resources may amount to as much as 1,500 short tons but how much of this amount will be recovered cannot be predicted.

**Arsenic**

Arsenic is a brittle, tin-white to silver-gray element that is widely distributed in the earth's crust but rarely occurs in large concentrations. The most common arsenic-bearing minerals are the silver-white to steel-gray arsenopyrite (iron arsenide-sulfide); the orange-red resinous realgar (arsenic monosulfide); and the yellow, resinous, to pearly orpiment. These minerals are found in Arizona but are not mined for arsenic. Appreciable quantities of arsenic, with or without sulfur, commonly occur elsewhere in copper, lead, zinc, cobalt, and nickel ores. When such ores are smelted the arsenic volatilizes at temperatures between 400°C and 700°C and is collected from the flue gases as crude arsenic dust in cooling flues, baghouses, or Cottrell precipitators. The crude arsenic dust may be refined further by volatilization with controlled air to produce relatively pure arsenic trioxide which is marketed as white arsenic.

The soluble compounds of arsenic are very poisonous and calcium and lead arsenates have been used extensively in insecticides. Organic insecticides, such as DDT, however, have been replacing this commercial use of arsenic compounds. White arsenic is used in glass making, and recently has been used in Arizona as a metallurgical flotation agent for separating molybdenum and copper concentrates. It is used also in wood preservatives and in the manufacture of lead shot. Arsenides are being used in small quantities in the recently developed masers and lasers (Lansche, 1965, p. 76-77).

The United States relies heavily on foreign supplies of white arsenic for domestic requirements. During 1967, about 19,000 short tons of white arsenic was imported and during the 1963-66 period 67 percent came from Mexico, 20 percent from France, and 13 percent from Sweden (U.S. Bur. Mines, 1968, p. 6). Domestic arsenic production has decreased in recent years due to the general change in copper mining from vein deposits to porphyry-type deposits which have a relatively low arsenic content. Also, in present metallurgical practices every effort is made in milling to depress with lime, and thus eliminate, the pyrite and arsenopyrite from the copper concentrates. Until recently there were two arsenic trioxide recovery plants in the United States, at Tacoma, Wash., and Butte, Mont., but the latter has been closed because of the low arsenic content of the ore received. Arsenic recovered at the Tacoma smelter is derived primarily from copper concentrates imported from the Philippine Islands. In April 1968, only crude arsenic was being produced at Tacoma. Some arsenious oxide may be recovered from chemical waste products in a process now being studied by the chemical industry.
Arizona ores are notably low in arsenic (R. F. Welch, oral commun., 1966) and no figures on the contents in the base-metal ores and concentrates are available. Arsenic in ores has been noted principally in the silver-lead deposits in the Wentworth (No. 9) and Big Bug (No. 11) districts; the copper deposits at Verde (No. 9) and Pioneer (No. 27); and in the silver deposits at Tombstone (No. 49), Pioneer (No. 27), White Hills (No. 2), and the mining districts in the Bradshaw Mountains (Nos. 12, 13, 15, and 16).

The generally low concentration of arsenic in the base-metal ores and the lack of any definitive assay data precludes making a meaningful estimate of arsenic resources in the State. However, it is doubtful that much, if any, arsenic will be recovered as a byproduct of the metallic ores in which it occurs.

BISMUTH

Bismuth is a brittle, reddish-white metal that has unusual properties such as a low melting point, resistance to corrosion and acids, and expansion on solidification from a melt. It is a relatively rare element in the earth's crust, being present in only about 0.1 part per million, and it seldom occurs in sufficient concentrations to be mined alone. The most common bismuth minerals are: bismuthenite, a bismuth trisulfide, that occurs in foliated or fibrous masses or in needlelike, gray metallic crystals; and bismite, a bismuth trioxide, a yellow, pulverulent, generally impure, oxidation product. Bismutite, a bismuth carbonate, also occurs locally. Native bismuth is rare but is found in small quantities in some sulfide deposits.

U.S. consumption of bismuth has increased rapidly in recent years, and reached a high of about 3.2 million pounds in 1966 (U.S. Bur. Mines, 1967, p. 181). Pharmaceuticals and chemical compounds account for over 50 percent of the consumption, in such uses as in digestive remedies, in making waterproof material less flammable, in vitreous ceramics, and in research. Fusible alloys making use of the low melting point and other alloys requiring other unusual bismuth properties have consumed increasing amounts in recent years (Moulds, 1965, p. 113-114).

The major producing countries of the world are Peru, Japan (from imported ores and concentrates), Mexico, Bolivia, Canada, and the United States, although for the latter no production figures are available. About half of the U.S. requirements are imported, mainly from Peru (70 percent), Mexico (19 percent) and Canada (6 percent) (U.S. Bur. Mines, 1965, p. 16-17). Three companies in the United States produce all the domestic bismuth from the processing of intermediate metallurgical products containing minor amounts of the element. With the increased demand, the price of bismuth has almost doubled in recent years, rising to as much as $5.00 per pound and averaging $4.00 per pound in the 1965-67 period.

The copper, lead, and silver deposits of Peru; the lead deposits of Mexico; the tin and tungsten deposits of Bolivia; the lead-zinc deposits of western Canada; and the tungsten deposits of the Republic of Korea are the principal foreign sources. The domestic sources of bismuth in the United States are the lead-silver ores of Colorado, Idaho, and Utah; and the copper-lead-zinc ores of Arizona, Idaho, Montana, New Mexico, Nevada, and Utah. A small amount has been mined from small high-grade pockets in pegmatite dikes, quartz veins, and contact metamorphic deposits.

Arizona production has been mainly a byproduct from the treatment of lead ore and concentrates. Arizona copper ores are extremely low in bismuth and the smelters do not recover it. The San Xavier mine in the Santa district (No. 42) produced some lead concentrates assaying 0.25 percent bismuth (E. H. Crabtree, oral commun., 1948) and lead ores and concentrates from the Patagonia (No. 55) and Wallapai (No. 3) districts and the Big Bug and Tiger districts (Nos. 11, 17) contained more than 0.02 percent bismuth. Cooper (1962, p. 2-4), in a listing of bismuth occurrences in the United States, included the mines and prospects in Arizona that reportedly contained at least 0.02 percent bismuth in the base- and precious-metal ores and concentrates.

Bismuth also occurs in pegmatite at the Williams mine in the Aquarius district (No. 8), and Midnight Owl and Outpost mines (No. 19) in the White Picacho district. Johns (1932, p. 73) reported that the distribution and extent of the bismuth in pegmatite was spotty, but localized in zones rich in massive quartz. More than 10 tons of bismutite-bismuthinite ore was taken from one large pod at the Outpost mine but the entire district has produced only about 12 short tons of bismuth-bearing ore.

Inadequate data on the bismuth content of Arizona ores and concentrates make it difficult to estimate the bismuth resources of the State. With lead production decreasing and with only negligible amounts present in the copper ores, it is unlikely that more than a few hundred tons of bismuth can be considered a recoverable resource.

CADMIUM

Cadmium is a soft, ductile, bluish-white metal that is recovered as a byproduct in the processing of zinc ores and concentrates (Chizhikov, 1966, p. 89-116). Cadmium occurs either in the greenockite (cadmium sulfide), a yellow to orange mineral, associated with zinc minerals, or in solid solution in sphalerite (zinc sulfide).

The major use of cadmium is in electrolytic coating. Cadmium also is used in alloys for antifriction bearings, low melting alloys, in copper wire, in lead cable sheathing, as a deoxidizer in metal casting, in rubber, in medicine, and as a paint colorant. Cadmium-nickel and silver-cadmium batteries are increasing in demand in the electrical energy field (Schroeder, 1965, p. 167-168).

World production of cadmium has increased at a faster rate than U.S. production but in recent years nearly 40 percent of the world supply has been refined in the United States with more than half the supply derived from imported zinc and base-metal concentrates and cadmium flue dust (U.S. Bur. Mines, 1965, p. 22-23). In 1966, U.S.S.R., Japan, and Canada were the major foreign producers (U.S. Bur. Mines, 1965, p. 185). U.S. annual consumption of cadmium has doubled during the past 20 years (Schroeder, 1965, p. 170) and during the 1963-67 period averaged about 11,740,000 pounds per year (U.S. Bur. Mines, 1968, p. 22). The demand is expected to increase.

All zinc concentrates produced in Arizona are treated outside the State and no data are available on the cadmium content for most of
the concentrates. In 1965, the Iron King mine in the Big Bug district (No. 11) produced 44,855 tons of concentrates containing 71,570 pounds of cadmium and 27,247,360 pounds of zinc (U.S. Bur. Mines, 1967, p. 112), an average content of 5.3 percent of zinc metal. Schroeder (1965, p. 169) noted that 11.4 pounds of cadmium were recovered per ton of slabs zinc produced in the United States during the 1959–63 period.

Cadmium production in Arizona closely follows the output of zinc concentrates and at present appears to be decreasing. The Iron King mine, a major producer of zinc concentrates in the past, closed down in 1967. Although now leased to other operators, plans for any future operations are unknown. The Big Dick and Copper Queen mines in the Eureka district (No. 8) also have been sizable producers of zinc concentrates but the known ore bodies are about exhausted. The Patagonia (No. 55) and Cochise (No. 44) districts have had intermittent zinc production but future operations are uncertain. Other districts or mines which have produced cadmium-bearing zinc ores and might again be productive are the Wallanai (No. 3), Verde (No. 9), Silver Bell (No. 39), and Bisbee (No. 56). The Mission mine in the Pima district (No. 41) continues to produce zinc concentrates from zones associated with the copper ore body and the Antler mine in the Cedar Valley district (No. 5) anticipates the production of zinc concentrates containing cadmium.

A rough estimate of the amount of recoverable resources of cadmium in Arizona is about 1,000 short tons. The amount that will be recovered, however, will depend on the future production of zinc ores and the economics of cadmium recovery.

**Selenium**

Selenium is an allotropic element closely allied in chemical properties to sulfur. Chemically pure selenium may occur in either of three amorphous forms (black vitreous, red, or red colloidial), or in either of two crystalline forms (monoclinic, a metastable form, or hexagonal, a stable form). The element may act as a metal or nonmetal, as an electrical conductor or insulator, as a hydrogenator or dehydrogenator, a colorant or decolorizer, and as a poison or a nutrient. Selenium compounds are poisonous to animal life either from ingestion or from contact with the skin but some plant life requires or tolerates selenium.

Selenium has a wide range of applications in electrical, metallurgical, and chemical industries, such as in rectifiers, photo-electric cells, lasers, chrome plating, stainless steel, pigments, vulcanizing, insecticides, lubricants, and pharmaceuticals. It is an essential part of Factor 3 in vitamin E and in extremely low concentrations helps increase infant growth (Muth and others, 1967, p. 205–206). Other miscellaneous uses are in blasting caps, decolorizers in glass and production of clear red signal glass (Lanshe, 1965, p. 794–795).

U.S. consumption of selenium in recent years has averaged about 1 million pounds per year of which about 70 percent was supplied by domestic production and about 30 percent by imports, mainly from Canada (U.S. Bur. Mines, 1968, p. 132). In 1966 U.S. production was 620,000 pounds valued at $4.50 to $6.00 per pound for commercial grade material (U.S. Bur. Mines, 1967, p. 348). Ninety percent of domestic production is a byproduct from the electrolytic refining of copper and the remainder is recovered from lead smelter flue dust or selenium-bearing sulfur residues. Four copper refineries and one chemical company accounted for almost all U.S. production.

Selenium is widely but sparsely disseminated throughout the earth's crust but its occurrence in the form of the native element is uncommon. However, crystals of the red variety are rather common in oxidized seleniferous uranium ores, and the writer has found slender selenium crystals in the siliceous smelter flux above an old fire zone in the United Verde open-pit copper mine at Jerome, Ariz. Both red and gray forms have been identified in many uranium mines. The principal occurrences of selenium are in sulfide deposits where it generally occurs as a selenide and perhaps locally in elemental form (Davidson, 1967).

Potential resources of selenium in the United States are mainly in the disseminated copper deposits but the selenium in the uranium deposits in the sedimentary rocks of the Rocky Mountain region, although generally low, is an additional resource, should the demand and prices for selenium increase (Squyres, 1963, p. 160; Clark and Havens, 1963, p. 111; Bhappu, 1961, p. 25–26). The massive, highly pyritic, sulfide copper deposits, such as in the United Verde mines, Verde district (No. 9), with a range of 0.001 to 1.0 percent selenium in the copper ore appear to have a higher content than the less pyritic porphyry deposits, such as San Manuel mine, Mammoth district (No. 35) with a range of only 0.01 to 0.1 percent selenium in the concentrates (Everett, 1964, p. 19).

As the major copper producing state, Arizona is also a major producer of selenium, but the mines and smelters normally do not assay for, or report on, the selenium content of the ores, concentrates, or anodes. Thus, the electrolytic anode refinery slimes, which contain the selenium, are a composited material and the origin of the selenium cannot be traced to individual mines or even states.

Although the Arizona reserves and resources of selenium cannot be accurately estimated, the potential resources may total at least 8,000 short tons of selenium. In any event, Arizona will continue to supply substantial amounts as a byproduct from copper production for many years to come.

**Tellurium**

Tellurium is one of the least abundant elements in the earth's crust. Although found rarely in native form, it more generally is combined in minerals with gold, silver, copper, lead, bismuth, and antimony. It is never found in large quantities and its distribution is quite limited. All current supplies of tellurium are derived from slimes resulting from the refining of copper and lead, with copper ores accounting for 80–95 percent of the tellurium production.

The major uses of tellurium are in metallurgy, chemical coloring, vulcanizing, and thermoelectrics (Lanshe, 1965, p. 337).

The U.S. production of tellurium in 1966, principally from primary sources, was 199,000 pounds and apparent consumption was 215,000 pounds. Some of the U.S. production came from imports of unrefined copper and lead bullion and anode slimes, Canada being the main foreign supplier. The increasing demand for the element for the thermoelectric and alloy uses has created a near critical shortage which is reflected in the price increase from $1.50 per pound in 1956 to $50.00 per pound in more recent years for commercial grade tellurium (99.7 per-

Larger quantities of tellurium would be consumed if they were available at a price competitive with that of substitute materials such as selenium. The more limited and somewhat inelastic supply is a deterrent on its use but the increasing interest in tellurium for thermoelectric and alloy purposes indicates the need for better recovery of the element from its main source, the copper and lead ores.

The tellurium-bearing slimes from electrolytic refining of copper and lead contain small amounts of copper, lead, selenium, tellurium, gold, and silver which require multiple processing before the tellurium is separated. Although some of the refining methods are closely guarded trade secrets, it is estimated that only about 50 percent of the tellurium in the refinery slimes is recovered.

Arizona is a major domestic source of byproduct tellurium but the actual output from individual mines or the State is unknown. The anode copper from Arizona smelters may contain as much as 0.01 percent tellurium which is concentrated to as much as 8.0 percent in the electrolytic refinery slimes. Based on 740,000 tons of recoverable copper produced in Arizona in 1966, an estimated average tellurium content of 0.005 percent in the copper anodes, and a recovery of 50 percent, the Arizona production of tellurium from copper ores for the year would be about 37,000 pounds.

The highest-grade tellurium-bearing ore known in Arizona occurred near the surface in the copper ore over an old fire zone in the United Verde mine in the Verde district (No. 9). This ore contained 0.01 to 0.1 percent tellurium. However, the content of the ore below the fire zone, such as on the 4,500-foot level, was less than 0.001 percent tellurium (Everett, 1964, p. 19).

Tellurium will continue to be recovered as a byproduct of Arizona copper ores but the amount will depend on the tonnage of copper produced, the tellurium content of the ore, and the percentage recovery of the contained tellurium. A rough estimate of the recoverable resources of tellurium in Arizona is about 800 short tons.

SELECTED REFERENCES


BERYLLIUM

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

INTRODUCTION

Beryllium is a dark gray metal belonging to the alkaline earth group of elements and thus, chemically, is closely related to magnesium and aluminum which, in some respects, it resembles. It has several physical properties which make it valuable in certain industrial applications, including its low specific gravity (1.84), comparatively high melting point (1,287°C), and its relative hardness (about 6).

Although beryllium was discovered in 1797 through the concerted efforts of the mineralogist Hauy and the chemist Vauquelin, it was not until 1828 that the element was successfully isolated from any of its compounds. Since that time research into the chemical behavior and metallurgy of beryllium has advanced considerably, and the list of its applications has grown steadily.

During the first half of the 20th century, beryllium found its most important use alloyed with copper and nickel. Alloys containing 98 percent copper and 2 percent beryllium, when quick-chilled, are easily worked and can be shaped into many forms. When objects made in this fashion are reheated to 725° F. (400° C.) and then cooled slowly, under closely controlled conditions, they attain considerable strength, hardness, and toughness, and are comparable to some steels. Such alloys have replaced steel in various applications, such as air-

craft-engine valve springs, nonsparking alloys, and in electrical switching devices. Since 1950 many uses have been developed for the unalloyed metal in nuclear engineering, high-speed flight equipment, inertial guidance gear, and space exploration vehicles. The oxide and various beryllium compounds find use in ceramics and in porcelain for electrical insulation and the element has been used in a phosphor compound for fluorescent lamps.

Beryllium does not occur as a native element, and of its many minerals, only beryl and bertrandite are presently considered as commercial sources. Other beryllium minerals of potential use are phenacite, chrysoberyl, barylite, gadolinite, and helvite. The beryllia (BeO) content of these minerals varies from 40–45 percent in the case of bertrandite and phenacite to 6–14 percent in beryl, gadolinite, and helvite. Large, low-grade deposits of bertrandite have been discovered in Utah and are under development but no commercial production thus far (early 1968) has been recorded from them.

During the period 1956–66, the United States consumed 72,915 short tons of beryl with an average BeO content of 11 percent. This represents nearly 73 percent of the total world production for that period, whereas domestic production was less than 3 percent of the world production. It is obvious that this country has been largely dependent upon imports for its supplies of beryllium ore and these imports have come mainly from Brazil, India, Argentina, and several countries in Africa. Domestic production has come mainly from Maine and New Hampshire in the northeast and South Dakota, Colorado, and New Mexico in the west. Only minor production has been reported from Arizona, Massachusetts, and Wyoming.

Occurrences of beryllium have been reported from more than 80 localities in Arizona, as shown in figure 16. A brief description of each occurrence is given in table 11. Only trace quantities of beryllium have been found at most of these localities, and beryl ore probably has not been produced at more than a fourth of them.

The first recorded commercial production from Arizona was in 1949 (Clark, 1951, p. 1294), when small shipments of beryl were made from the White Picacho district, Maricopa and Yavapai Counties (fig. 16), the Rare Metals mine, Mohave County (No. 27), and from near Crown King, Yavapai County (No. 62). It is estimated that since 1949 about 50 tons of beryllium ore valued at about $23,000 have been produced from the State.

Beryllium minerals have been found in three principal types of deposits in Arizona. These are, in order of decreasing present importance, pegmatite deposits, vein deposits, and disseminated deposits in tactites.

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EXPLANATION

- Mining district
- Pegmatites and aplites
- Veins

Tactites, replacements, and disseminations in granitic rocks

(Numbers refer to localities mentioned in text and in table 11)

FIGURE 16.—Beryllium in Arizona.
TABLE 11.—Beryllium occurrences in Arizona

<table>
<thead>
<tr>
<th>Locality No. in fig. 16</th>
<th>County and locality name</th>
<th>Number of occurrence</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>Gilles—Continued</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>Beryl and bertrandite(1) in quartz veins of Precambrian schist. Grade 0.005-0.15 percent BeO.</td>
<td>Meves, 1966, p. 56.</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Twilight and Grey claims</td>
<td>Beryl(1) in pegmatite dikes which intrude altered Precambrian schist. Grade 0.27 percent BeO.</td>
<td>Meves, 1966, p. 57.</td>
</tr>
<tr>
<td>19</td>
<td>Greensleeves</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Fourth of July mine</td>
<td>Beryl(1) in quartz-fluorite veins of volcanic rocks. Grade 0.01 percent BeO.</td>
<td>Meves, 1966, p. 58.</td>
</tr>
<tr>
<td>21</td>
<td>Maricopa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Morning Star mine</td>
<td>Beryl, associated with lithium and rare-earth minerals, in a 100-foot-thick, unmined pegmatite that cuts Precambrian granite and schist.</td>
<td>Meves and others, 1966, p. 20.</td>
</tr>
<tr>
<td>24</td>
<td>Holvies</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Beryl in unmined pegmatite of Precambrian granite.</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Beryl crystals in a 100-foot-thick, pod-like, unmined pegmatite that intrudes Precambrian granite. Grade 3.9 percent BeO.</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Beryl and rare-earth minerals in 2-foot-thick, unmined pegmatite dikes that cut granite.</td>
<td>Heinrich, 1960, p. 12; Heinrich, 1962, p. 21;</td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Rare Metals mine</td>
<td>Beryl and rare-earth minerals in pegmatite dikes, as much as 40 feet thick, that intrude Precambrian granite.</td>
<td>Heinrich, 1960, p. 18; Heinrich, 1962, p. 20.</td>
</tr>
<tr>
<td>29</td>
<td>Aquarius Cliffs</td>
<td>Beryl and rare-earth-borax minerals in both zoned and unmined pegmatite dikes that cut Precambrian granite. Grade 0.005 percent BeO.</td>
<td>Do.</td>
</tr>
<tr>
<td>30</td>
<td>Duncan mine</td>
<td>Cadmiumite in pipe-like pegmatite body that intrudes Precambrian granite.</td>
<td>Meves and others, 1966, p. 20.</td>
</tr>
<tr>
<td>31</td>
<td>Boriana mine</td>
<td>Beryl associated with scheelite and some fluorite in veins in quartz veins that cut Precambrian schist. Grade 0.005 percent BeO.</td>
<td>Meves, 1966, p. 58; Heinrich, 1962, p. 21.</td>
</tr>
<tr>
<td>32</td>
<td>Cottonwood Cliffs</td>
<td>Beryl(1) associated with gold, base-metal sulfides, and scheelite in quartz veins that intrude Precambrian schist.</td>
<td>McCurry and O'Haire, 1961.</td>
</tr>
<tr>
<td>33</td>
<td>Chloride district</td>
<td>Beryl in pegmatite.</td>
<td>Thomas, 1953, p. 401.</td>
</tr>
</tbody>
</table>

TABLE 11.—Beryllium occurrences in Arizona—Continued
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<tr>
<th>Locality No. in fig. 16</th>
<th>County and locality name</th>
<th>Manner of occurrence</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 Katherine mine</td>
<td>Beryl in pegmatite veins that cut Precambrian granite.</td>
<td>Warner and others, 1959, p. 102.</td>
<td></td>
</tr>
<tr>
<td>35 Katherine Wash area</td>
<td>Beryl in pegmatite veins that cut Precambrian crystalline rocks.</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>36 Arabian mine</td>
<td>Beryl in pegmatite veins that cut Precambrian crystalline rocks.</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>37 Oatman area</td>
<td>Beryl in pegmatite veins that cut Precambrian crystalline rocks.</td>
<td>Do.</td>
<td></td>
</tr>
<tr>
<td>38 White Hills</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>40 Virgin Mts.</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
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<tr>
<td>41 Lava fire claim</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>42 Converse Canyon</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>43 Windy claim</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
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</tr>
<tr>
<td>44 Consideht Mts. area</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>45 Sharon D mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>46 Rincon Mtns.</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>47 Helinea area</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>48 Santa Cruz</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>49 Newby mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
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</tr>
<tr>
<td>50 Lower Jumbo mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>51 Big Reef claim</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>52 Black Pearl mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
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</table>

Table 11.—Beryllium occurrences in Arizona—Continued

<table>
<thead>
<tr>
<th>Locality No. in fig. 16</th>
<th>County and locality name</th>
<th>Manner of occurrence</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>32 Outpost Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>33 Fi. &amp; O. Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>34 Midnight Owl mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>35 Independence Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>36 Tip Top Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
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</tr>
<tr>
<td>37 Lone Giant mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
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<tr>
<td>38 Berry's Wonder Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>39 B.0. Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>40 Juniper Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>41 Lake's Hole mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>42 Phoenecite Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>43 White Rock</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>44 (Unknown)</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>45 Dixie Queen Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>46 Jeep Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>47 Good Luck Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>48 Llaurre Peak Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>49 Aquamarine Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>50 Tungsten Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
</tr>
<tr>
<td>51 Black Pearl Mine</td>
<td>Beryl in veins that cut Precambrian crystalline rocks.</td>
<td>Grade 0.005 percent BeO.</td>
<td></td>
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</table>
TABLE 11.—Beryllium occurrences in Arizona—Continued

<table>
<thead>
<tr>
<th>No. in Fig. 16</th>
<th>County and locality name</th>
<th>Mineralization</th>
<th>References</th>
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<tbody>
<tr>
<td>72</td>
<td>Continental claim</td>
<td>Copper minerals in fracture zone between phyllite and andesite. Grade 0.02 percent BeO.</td>
<td>Neaves, 1966, p. 60.</td>
</tr>
<tr>
<td>73</td>
<td>White Christmas claim</td>
<td>Baryte and fluorite veins in fractures in andesite porphyry. Grade 0.04 percent BeO.</td>
<td>Neaves, 1966, p. 51.</td>
</tr>
<tr>
<td>74</td>
<td>Black Bird claim</td>
<td>Manganese in shear zone in andesite porphyry and tuff. Grade 0.1 percent BeO.</td>
<td>Neaves, 1966, p. 55.</td>
</tr>
<tr>
<td>75</td>
<td>Squaw T claim</td>
<td>Copper and tungsten minerals in contact metamorphosed quartzite. Grade 0.03 percent BeO.</td>
<td>Neaves, 1966, p. 61.</td>
</tr>
<tr>
<td>76</td>
<td>Red Chief claim</td>
<td>Manganese in trace zone in antigorite. Grade 0.03 percent BeO.</td>
<td>Neaves, 1966, p. 50.</td>
</tr>
<tr>
<td>77</td>
<td>National Debt claim</td>
<td>Manganese in fracture zone in schist.</td>
<td>Do.</td>
</tr>
<tr>
<td>78</td>
<td>Sheep Tanks claim</td>
<td>Gold, silver, and lead minerals in fault zone in folded and faulted volcanic rocks. Grade 0.02 percent BeO.</td>
<td>Neaves, 1966, p. 61.</td>
</tr>
<tr>
<td>79</td>
<td>Mina da Nana</td>
<td>Barite and base-metal sulfides in fault zone in andesite porphyry. Grade 0.03 percent BeO.</td>
<td>Neaves, 1966, p. 55.</td>
</tr>
<tr>
<td>80</td>
<td>Castle Dome district</td>
<td>Barite, fluorite, and lead and zinc sulfides in breccia zone in quartz monzonite. Grade 0.02 percent BeO.</td>
<td>Neaves, 1966, p. 61.</td>
</tr>
</tbody>
</table>

PEGMATITE DEPOSITS

Pegmatite dikes and pods are locally abundant in the Precambrian crystalline rocks exposed in the mountainous region of central and northwestern Arizona, and many of the pegmatites contain beryllium minerals.

In the Virgin Mountains (No. 40), pegmatite dikes occur in a Precambrian crystalline complex consisting predominantly of mica schist, granite-gneiss, and amphibolite. These dikes, which are essentially concordant with the foliation of the enclosing rocks, strike N. 40°–60° E., and dip between 65° SE. and vertical. They range from a few inches to 8 or 10 feet in thickness, have an average thickness of 4 to 5 feet, and are composed essentially of quartz, feldspar, and muscovite. Locally, as on the Hummingbird claims (Olson and Hinrichs, 1960, p. 189), they contain small quantities of beryl and chrysoberyl. Development work on the Hummingbird deposit and on claims to the west, in Nevada, has produced small quantities of beryllium ore. The Rare Metals mine in the Aquarius Range (No. 27), has yielded nearly 6 tons of beryl from a zoned pegmatite in Precambrian granite (Heinrich, 1960, p. 16). The main pegmatite mass, which strikes N. 85° E. and dips 30–40° NE., is over 600 feet long and about 40 feet wide at the mine workings. The beryl occurs in a muscovite-rich zone which is marginal to a conspicuous core of quartz, and is associated with several rare-earth minerals, including gadolinite, which also contains beryllium.

Undoubtedly, the pegmatite deposits in Arizona that are most productive of beryl are those in the White Picacho district in Maricopa and Yavapai Counties (Nos. 23 and 49–55). In this area complex pegmatites occur as dikes, pods, and irregular bodies in Precambrian metamorphic and igneous rocks throughout an area of about 150 square miles (Heinrich, 1960, p. 9). Beryl has been produced from several mines in the area, but the Midnight Owl, Outpost Lode, and Home-Stead Lode have been the most productive.

In this district, most of the pegmatite bodies productive of beryl are characterized by two or more rather distinct mineralogical zones. According to Jahns (1952, p. 22), these include an outer or border zone of fine- to medium-grained quartz and sodic plagioclase; a wall zone of fine- to coarse-grained quartz-perthite rock containing subordinate plagioclase and mica, with garnet, beryl, and spodumene as accessory minerals; one or more intermediate zones typically consisting of massive quartz and giant crystals of coarse-grained perthite; and a core pod of massive quartz or extremely coarse-grained quartz-perthite rock. Beryl has been produced commercially from deposits in both the wall zone and in one or more of the intermediate zones in pegmatites of this district.

Beryl-bearing pegmatites occur in southern Arizona at the Sharon D. mine, on the north pediment of the Sierrita Mountains (No. 45), from which a few hundred pounds of gem material has been produced.

VEIN DEPOSITS

Beryllyum has been detected in minor quantities in veins occurring in widely scattered parts of Arizona, but the greatest abundance of beryllium-bearing veins appears to be in the extreme western and southern parts of the State. The vein deposits can be subdivided into three general classes on the basis of mineral assemblage: (1) quartz-gold, (2) quartz-tungsten, and (3) quartz-fluorite veins.

The quartz-gold vein assemblage is best exemplified in the Oatman- Katherine district where at least five beryllium-bearing veins have been found (Nos. 34–38). Spectroscopic analyses of tailings from the gold mill at Katherine indicated as much as 0.03 percent BeO (Warner and others, 1959, p. 102), but no information on the nature of the minerals containing the beryllium was obtained. The quartz-gold veins in the Oatman-Katherine district occur in Precambrian granite, gneiss, and schist and in Tertiary volcanic rocks. The veins are considered to be epithermal by Lausen (1931, p. 90).

The principal quartz-tungsten veins carrying beryllium that thus far have been found in Arizona, are in Cochise County (No. 9), Gila County (No. 12), and Mohave County (No. 30). The Cline claims (No. 12), in Gila County, include four quartz veins, a few tens of feet apart, which strike N. 20°–25° E. and dip nearly vertically. They range from a few inches to 2 feet in width and cut a coarse-grained pinkish-gray granite. The veins contain scattered particles of wolframite, scheelite, beryl, and pyrite and appear to be associated with pegmatitic masses containing disseminated scheelite and some fluorite.

The Bluebird and Tungsten King properties in Cochise County (No. 9) have yielded high-grade scheelite and huebnerite concentrates from veins cutting quartz monzonite and schist. Beryl occurs sparingly in the veins as small, pale blue to colorless crystals and blebs. Spectro-
graphic analyses of channel samples from the veins (Warner and others, 1959, table 48) indicate that locally the veins contain more than 0.05 percent BeO. Generally, however, the grade is less.

The Boriana mine (No. 30), in Mohave County, has been an important producer of tungsten ore (see “Tungsten,” p. 276). Wolframite, scheelite, metallic sulfides, and beryl occur in a gangue of quartz with minor fluorite and calcite, filling veins in schist intruded by biotite granite. If new reserves of tungsten ore should be developed in the mine, the beryl possibly could be recovered as a byproduct.

Although many of the beryl-bearing veins cited principally for their gold or tungsten content contain fluorite as a minor gangue mineral, several veins containing fluorite as a major constituent also contain beryl. These veins occur principally in Greenlee and Yuma Counties (Nos. 19, 20, 73, 76, 80) (see “Fluorspar,” p. 348). Typically, they are of hydrothermal origin and contain fissures and brecciated zones. The most favorable host rock is schist but notable deposits in volcanic rocks are found in Greenlee County (Nos. 19, 20). Commonly, base-metal sulfides and barite accompany the fluorite and in some areas, as at Castle Dome (No. 80), make up appreciable parts of the vein material. The beryllia (BeO) content of some selected samples is as much as 0.05 percent. The beryl-bearing mineral, however, has not been identified in these veins, although it is assumed to be either beryl or helvite.

**Tactite Deposits**

In southeastern Arizona beryl is found in association with tactites developed through the pyrometasomatism of Paleozoic and Precambrian limestones. Representative of this type deposit are the replacement ore bodies at the Abril mine (No. 1) and at the Escondido property (No. 14).

At the Abril mine Carboniferous limestone and interbedded shale have been metamorphosed to marble, hornfels, and tactite by the intrusive Stronghold Granite. Lead-zinc-copper minerals replace part of the tactite from which several large ore bodies have been mined. The tactite consists of garnet, epidote, and specularite, and samples of the tactite contain as much as 0.02 percent BeO. The beryl-bearing mineral has not been identified, but is possibly beryl-bearing epidote.

At the Escondido property a garnet tactite occurs in the Mescal Limestone (Precambrian) adjacent to an intrusive mass of gabbro (Meeves, 1966, p. 57). This deposit contains silver and base-metal sulfides and some iron and manganese minerals. Analyses of selected samples indicate a content of 0.01 percent BeO (Meeves, 1966, p. 57), but, as with most deposits of this type, the beryllium-bearing mineral has not been identified.

W. R. Griffiths (written commun., 1968) has observed that non-pegmatitic beryl deposits in the Southwestern United States occur in two belts. One belt extends westerly along the boundary between Texas and Mexico and through southwestern New Mexico and southern Arizona. The general position of this broad belt in Arizona is evident from the distribution of the non-pegmatitic deposits in figure 16. The other belt is an arc around the southern two-thirds of the Colorado Plateau approximately from Mohave to Gila Counties. Beryl is not found in the Precambrian Shields, but, for the most part, in Precambrian and Paleozoic sediments associated with volcanic rocks.

Beryl-bearing deposits of the non-pegmatitic type have been reported in southeastern Arizona by Galbraith (1951), who described deposits in the Mogollon Mountains near San Carlos and the Escondido property near Globe. The Escondido property is an arc around the southern two-thirds of the Colorado Plateau approximately from Mohave to Gila Counties. Beryl is not found in the Precambrian Shields, but, for the most part, in Precambrian and Paleozoic sediments associated with volcanic rocks.

**Outlook**

The pegmatites of Arizona have provided income for several people through the sale of beryl and other minerals obtained from them. Pegmatites are expected to continue in this role in the foreseeable future, although the total production may be a small fraction of the national consumption.

The non-pegmatitic deposits of Arizona have yielded much less beryl than the pegmatites—probably a total of less than a ton. It seems possible, however, that such supplies might be increased substantially through new discoveries.

**Selected References**


Chromium

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

INTRODUCTION

Chromium, best known in chrome plating and as the chief alloying constituent of stainless steel, is vital to modern industrial nations. The only commercial chromium mineral is chromite, the name given to chromium-bearing spinel, a heavy black oxide with variable quantities of magnesium, iron, chromium, and aluminum. Besides being the source for chromium, chromite is an important refractory. Because of the paucity of domestic reserves of chromite and the resulting dependence on foreign sources of supply, it is classed as a strategic mineral, and stockpiled. Almost all of the foreign chromite production is in the eastern hemisphere. For the year 1967, U.S. imports came from South Africa (36 percent), U.S.S.R. (23 percent), Philippines (17 percent), Southern Rhodesia (14 percent), Turkey (7 percent), and other countries (3 percent). The highest-grade ores came from the U.S.S.R. (Morning, 1967).

ARIZONA OCCURRENCE

Large primary deposits of chromite are associated with ultramafic rocks such as peridotite, norite, and dunite. The notable scarcity of even minor occurrences of chromite in Arizona is attributed to the general lack of these and related rock types. Only two occurrences of such rocks occur in the State and both are older Precambrian in age. One occurrence crops out in T. 7 N., R. 9 W., in the central part of the Mazatzal Mountains astride the Maricopa-Gila County boundary, and the other crops out in extreme northern Maricopa County northeast of Cave Creek (Wilson and others, 1957). Chromite, however, has not been recognized in these rocks. At the only reported locality of chromite in Arizona, it occurs as disseminated grains and small masses in mica schist in the Trigo Mountains, Silver district, in southern Yuma County (Galbraith and Brennan, 1959, p. 39). This occurrence is only of academic interest.

Although it is likely that new occurrences will be found, especially in the ultramafic rocks associated with the older Precambrian of central Arizona, the possibilities for discovering commercial chromite deposits in Arizona appear remote.

SELECTED REFERENCES


The United States consumed nearly 30 percent of the world cobalt production in 1967, but contributed less than 10 percent. Imports came largely from the Congo (45 percent) and Belgium-Luxembourg (25 percent). Domestic mine production is derived almost entirely from cobalt-bearing iron deposits near Cornwall, Pa. (U.S. Bur. Mines, 1968, p. 38; Ware, 1965a, p. 247).

Neither cobalt nor nickel are found as native elements in commercial quantities and cobalt is produced only as a coproduct or byproduct in the mining of other metals, chiefly copper, silver, nickel, and iron. Important ore minerals of cobalt include carrollite, Co₃CuS₆; linnaeite, Co₄S₄; safflorite, (CoFe)₂As₂; cobaltite, CoAsS; and asbolite, CoO₂MnO₂·4H₂O. Important nickel minerals are pentlandite (NiFe)₉S₈, and garnierite, a hydrous nickel-magnesium silicate of variable composition. Smaltite (CoNi)₈As₄, and skutterudite (CoNi)₉As₄, are important for their content of both metals. Commercial deposits of cobalt and nickel are most generally associated with ultramafic rocks, either as magmatic differentiates or in hydrothermal deposits related to the ultramafic rocks.

**Arizona Occurrences**

No commercial production of either cobalt or nickel has been made from Arizona. However, minerals containing these metals have been reported from several localities (fig. 17). Pentlandite has been reported by Galbraith and Brennan (1959, p. 17) in association with pyrrhotite and chalcopyrite in mafic dikes in the Virgin Mountains, near Littlefield, Mohave County (No. 1, fig. 17). In this part of the Virgin Mountains a complex of Precambrian granite, gneiss, and schist has been intruded by amphibolite dikes which in turn have been intruded by pegmatite dikes. In general, the various dikes are nearly concordant with the foliation of the enclosing metamorphic rocks, which strikes N. 55°–70° E. and dips steeply. Exploratory work by the U.S. Bureau of Mines (Needham, Soule, and Trengove, 1950) on the Great Eastern group of claims, which are located on an extension of the Virgin Mountain deposit a short distance into Nevada, indicates a nickel content between 0.01 and 0.72 percent in small disconnected pods or lenses.

Spectrographic analyses of arsenopyrite samples from the Old Dick mine (No. 2, fig. 17) revealed a cobalt content of as much as 0.6 percent. The ore zone consists of separate lenses of massive sulfide, mainly chalcopyrite and sphalerite, that strike northeast, dip steeply westward to vertical, and are essentially parallel to the foliation of the enclosing rocks. Locally the cobalt-bearing arsenopyrite makes up as much as 30 percent of the sulfide masses (Anderson and others, 1955, p. 47, 89).

A small cobalt prospect is located in the Grapevine Gulch area of the Black Hills, Yavapai County (No. 3). Shallow workings in a small patch of gabbro have exposed a vein that strikes N. 30° E. and dips 60°–70° W. The vein ranges in width from a knife-edge to 14 inches, and is about 15 feet long. The vein material is partly oxidized and altered gabbro that contains relics of sulfide, possibly cobaltiferous.
arsenopyrite. The vein in part of the workings is covered with erythrite, a pink, hydrous cobalt arsenate (Anderson and Creasey, 1958, p. 177).

Nicolite, NiAs, and chloanthite, (NiCo)As₂, have been found in small quantities, associated with native silver and copper and silver sulfides, at the Monte Cristo mine (No. 4), near Constellation, Yavapai County (Galbraith and Brennan, 1959, p. 16, 22). The principal host rock is medium-grained granite, with some inclusions of schist. Ore bodies occur in fissure veins and breccia zones which trend northeast and consist of oxidized copper minerals, copper and silver sulfides, and auriferous limonite in a gangue of calcite and glassy quartz.

Reported occurrences of cobalt and nickel minerals, but for which little data are available, include erythrite, one-half mile northeast of Mule Shoe Bend of the Salt River (No. 5); smaltite in a silver-gold-bearing vein at the Blue Bird mine, Graham County (No. 6); and cobaltite at an unidentified locality in the Comobabi Mountains (No. 7), in Pima County (Galbraith and Brennan, 1959).

There is very little likelihood that cobalt or nickel will be produced commercially from Arizona in the immediate future. The most promising occurrence is the large tonnage of cobaltiferous arsenopyrite at the Old Dick mine (No. 2) but this deposit apparently could only be exploited for cobalt under economic conditions more favorable than at present.

Selected References

COPPER

(By C. A. Anderson, U.S. Geological Survey, Menlo Park, Calif.)

Introduction
Copper has been an important metal for all civilizations from prehistoric to the present, owing in large part to its versatility. Early uses were for tools, utensils, weapons, and objects of art, because of its malleability, resistance to corrosion, durability, and its attractive colors in alloyed or unalloyed forms. In the 19th century, copper became important for transmitting electrical energy, and this property is responsible for the spectacular growth of the electrical industry and associated industries relying on electricity for power, light, and heat. At present, more than half of all copper consumed in the United States is used for the transmission of electricity. About 40 percent is used for alloy manufacture, largely brass. The automobile industry uses 30 to 40 pounds per vehicle and accounts for 9 percent of U.S. copper consumption. In addition to its role in copper base alloys (brass and bronze), copper is an important constituent of a large number of alloys having a metal other than copper as the principal component (McMahon, 1965). Since 1965, there has been an increased use of copper in silverless dimes and quarters and as a replacement of some silver in 50 cent pieces.

History

Early Prospecting
Centuries ago, Indians mixed oxidized copper ore at the site of the United Verde mine at Jerome (fig. 18, No. 7, and table 12, No. 7) using the colored rock for personal adornment and as a dye for their blankets. Traces of old dumps, shafts, and tunnels were found at the beginning of active exploration in 1882. Stone hammers and other stone implements were uncovered in the old workings (Anderson and Creasey, 1958). Indians also mined turquoise at and near the present site of the Mineral Park mine (fig. 18, No. 11), with the greatest activity occurring from 1800 to early 1900 (Eidel and others, 1968). The copper deposits at Ajo were worked in a small way by Spaniards and Mexicans as early as 1750, but owing to the low tenor of precious metals, production prior to the American occupation was small (Gilluly, 1946).

A rich deposit of native silver, Planchas de Plata, was discovered in northern Sonora in 1736, which stimulated prospecting in Arizona, but no deposits were found that approached the "Planchas" in spectacular richness (Dunning and Peplow, 1959). The Gadsden Purchase in 1853 encouraged renewed prospecting in southern Arizona and in 1855, 10 tons of selected copper ore from Ajo were shipped to Swansea, Wales, for treatment; this ore sold for a little less than $400 per ton. Probably this marks the first modern mining of copper ore in Arizona. In the absence of railway transportation, however, subsequent prospecting emphasized gold and silver. In the early seventies, silver prices were high and a "silver boom" developed, accompanied by an intensive search for additional silver. Ore bodies were discovered containing the base metals, copper, lead, and zinc, but they were not of economic importance at that time. "Among these unappreciated discoveries were nearly all of our present great copper mines, including Clifton-Morenci, Globe, Ray, Bisbee, and the United Verde" (Dunning and Peplow, 1959).
In 1876, the Southern Pacific Railroad reached Gila Bend from California and in 1882, the Atlantic and Pacific Railroad (later the Atchison, Topeka and Santa Fe Railway) crossed northern Arizona. These railroads solved the transportation problem by appreciably reducing the costs of importing heavy machinery and costs of shipment of the mine products. In a relatively short time, Bisbee, Globe, Morenci, and Jerome became significant producers of copper. In 1880, the price of copper was 21 cents per pound, but in 1893, the price dropped, along with other commodity prices, to 10 cents per pound. However, by 1893, copper even at this low price was established as “King in Arizona” (Dunning and Peplow, 1959).

A prospecting party from Silver City, N. Mex., discovered copper ore at Morenci (fig. 18, No. 27) in 1872 and located a number of important mining claims. In 1873, an adobe furnace was in operation at the Longfellow mine with a capacity of 1 ton per day. During the following year, the first water-jacket furnaces were built. By 1879, the Longfellow mine was producing 40 tons per day of ore containing 20 percent copper; the cost of mining was $10 per ton, and the price of copper was 20 cents a pound. The ore minerals were largely malachite and azurite, the carbonates of copper, associated with limestone. In 1884, a narrow-gage railroad was completed connecting Lordsburg on the Southern Pacific Railroad to Clifton, a town on the San Francisco River, 4 miles southeast from Morenci.

The Detroit Copper Co. began operating at Morenci in 1886 and built the first concentrator in Arizona. The oxide ore, containing 6.5 percent copper, was concentrated to 23.8 percent copper, leaving 3.9 percent copper in the tailings. The Arizona Copper Co. followed with a concentrator having a capacity of 100 tons per day which enabled that company to operate with a profit (Dunning and Peplow, 1959). By 1901, the rich copper carbonate ores had been largely mined out, and the sulfide of copper, chalcocite, became the chief ore mineral, which was concentrated for reduction in the smelters. At that date, the Arizona Copper Co. was the largest producer in the district and one of the largest in Arizona (Lindgren, 1905).

An army scout from Fort Huachuca, in 1877, noted bright-colored croppings in the Mule Mountains, where the town of Bisbee was later established, but it was not until 1880 that a serious exploration effort revealed the rich copper carbonate ore body in the Copper Queen claim (fig. 18, No. 25). This famous ore body first was quarried from an opencut and later worked by an incline down to the 300-foot level. Two water-jacket furnaces were built in 1881, and using wood as fuel, 250 tons of copper per month were recovered from ore averaging 28 percent copper. The success of the Copper Queen brought James A. Douglas of Phelps Dodge Co. to Bisbee, but being unable to purchase the mine, he bought the adjacent Atlanta claim, and started development in 1881 (Ransome, 1904).

At first, Benson on the Southern Pacific Railroad was the nearest railway station, but after the completion of the Sonora Railroad between Benson and Nogales, the Copper Queen Co. built a toll road over Mule Pass to the railroad at Fairbanks. In 1884, freight was hauled over this road by 18-mule teams at a rate of $7.25 per ton. That
same year, the first ore body of the Copper Queen gave out but fortunately a second ore body was found simultaneously in the Copper Queen and Atlantic properties. Litigation was avoided by consolidation of the rival interests in the Copper Queen Consolidated Mining Co. Subsequently the holdings of the Copper Prince, northwest of the Copper Queen, were acquired by purchase as well as other mines under separate ownership (Ransome, 1904, p. 13–14).

The average grade of the ore in 1884 was about 12 percent copper, which sold for about 18 cents a pound. The original smelting plant became inadequate in 1886 and was replaced by four new furnaces. In the early nineties, copper sulfide minerals were becoming important in the newly developed ore, so Douglas introduced a modification of the Bessemer process, as used at Butte, Mont.; thus, began the reduction of mixed sulfide and oxide ores.

Up to 1900, the Copper Queen continued to be the only important mine at Bisbee, but in 1903, the Calumet and Arizona Co. made a fabulous strike on the Irish Mag claim which eventually paid $15

### Table 12—Copper deposits in Arizona—Continued

<table>
<thead>
<tr>
<th>Locality No.</th>
<th>District or area, mine or property</th>
<th>County</th>
<th>Type of deposit and mine</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>Silver Bell mine</td>
<td>Pima</td>
<td>Disseminated chalcocite blanket. Open pit.</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Mission mine</td>
<td>Pima</td>
<td>Disseminated ore bodies in altered limestone and sandstone. Open pit.</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>Twin Buttes property</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>Esperanza mine</td>
<td>Pima</td>
<td>Disseminated ore bodies in altered limestone and sandstone. Open pit.</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Helvetia mining district</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Johnson Camp area</td>
<td>Cochise</td>
<td>Lime stone replacement deposits of copper and zinc. Underground.</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Copper Queen mine</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>Lona Star mining district</td>
<td>Graham</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>Normci mine</td>
<td>Gila</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Jacoba Lake area</td>
<td>Cochise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>White Mesa district</td>
<td>Pima</td>
<td>Disseminated ore bodies in altered limestone and sandstone. Open pit.</td>
<td></td>
</tr>
</tbody>
</table>

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</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Copper Creek area</td>
<td>Pima</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Castle Dome mine</td>
<td>Gila</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Copper Cities mine</td>
<td>Gila</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Old Dominion mine</td>
<td>Gila</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Mina Inspiration properties</td>
<td>Gila</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Christmas mine</td>
<td>Gila</td>
<td></td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>New Cornella mine</td>
<td>Pima</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Lakeshore mine</td>
<td>Pima</td>
<td></td>
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</tbody>
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<th>Locality No.</th>
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<th>Type of deposit and mine</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Jerome area</td>
<td>United Verde</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Copper Creek area</td>
<td>do.</td>
<td>Breccia pipes containing copper and molybdenum. Underground.</td>
<td>Kuhlen, 1941; Simons, 1944.</td>
</tr>
<tr>
<td>15</td>
<td>Mina Inspiration properties</td>
<td>Gila</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Christmas mine</td>
<td>Gila</td>
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<tr>
<td>17</td>
<td>New Cornella mine</td>
<td>Pima</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Lakeshore mine</td>
<td>Pima</td>
<td></td>
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</tr>
</tbody>
</table>
million in dividends. Later, this same company found another ore body to the south that thickened appreciably in depth (Dunning and Peplow, 1959).

Phelps Dodge and Co., who controlled the Copper Queen Co., was dissatisfied with the existing railway transportation by way of Benson and the Southern Pacific Railroad, so in 1896 they completed the El Paso and Southwestern Railroad, connecting Bisbee directly with El Paso, Tex. The new town of Douglas was built along the railroad, 26 miles east of Bisbee, where the land was flat and an ample water supply was available. Phelps Dodge and Calumet and Arizona each built new smelters in Douglas. Thus, the vegetation began to grow again in Bisbee (Dunning and Peplow, 1959).

It is reported that in 1875, U.S. Army scouts from Fort Whipple at Prescott, discovered mineral showings in the Black Hills west of the Verde Valley (fig. 18, No. 7). Staking of claims occurred the following year, which covered the important mineralized outcrops. Shallow exploration revealed copper ore but the difficulties of transportation inhibited progress in mining. In 1882, the United Verde Copper Co. was organized to purchase 12 claims, and a wagon road was built from Jerome to Ash Fork, 60 miles away on the new Atlantic and Pacific Railroad. Two small water-jacket furnaces were transported to Jerome and production of matte and bullion started in August 1883. Surface oxide ores, rich in silver and gold as well as copper, were mined, averaging about $30 per ton.

In 1884, the United Verde Copper Co. paid a dividend of $60,000, but the rich surface ores were exhausted; copper prices dropped, and the mine operation ceased that year. W. A. Clark of Montana visited the property in March 1888 and immediately made the first payment on an option giving him 70 percent of the stock of the United Verde Copper Co. Under Clark's guidance, active mining operations started in 1889 and the first dividend was paid in 1892. A branch of the Santa Fe Railway was built from Ash Fork to Phoenix via Prescott in 1893, and Clark built a narrow-gage railroad to connect Jerome with the Santa Fe at Jerome Junction, north of Prescott. In 1894, a new smelter was built at Jerome replacing the small smelting plant. Clark started buying the remainder of the widely scattered stock of the company, and at the time of his death in March 1928, he and his family owned about 299,000 of 300,000 issued shares (Anderson and Creasey, 1958, p. 86).

The United Verde ore body was unique among the important copper deposits in Arizona in that the ore was in a pipelike mass of pyrite. Chalcocite, the chief ore mineral, was concentrated in ore shoots in the south side of the pyrite pipe and, remarkably, the larger the ore shoot, the higher-grade the copper. Many stops were in ore containing appreciably more than 5 percent copper; for several decades the ore went directly to the smelter for reduction. The management, however, was plagued by underground fires that were generated in the pyritic parts of the pipe, and subsequent ground movement required the construction of a new smelter away from the mine area. It was built at Clarkdale, east of Jerome by the Verde River, and placed in operation in 1915. As the mine was deepened to lower levels, the ore shoots extended into a fringe of black schist; in 1927 a concentrator was built at Clarkdale to handle that ore (Anderson and Creasey, 1958).

Under Clark's management, the production of the United Verde mine steadily increased. From 1888 to the end of 1922 it totaled about 556,000 tons of copper, 563,375 ounces of gold and 18,408,282 ounces of silver. Later production figures were withheld (Lindgren, 1926, p. 63).

The early history of the Globe-Miami district (fig. 18, No. 15) is largely involved in the discovery and development of the Old Dominion and United Globe mine deposits. In 1874, prospectors from Florence prospected the Globe area and located the Globe claim on the Old Dominion vein (fig. 18, No. 14) but their interest was in silver, and the Globe claim, which subsequently became one of the richest copper producers in the district, received little attention until later. In 1881, the Old Dominion Copper Co. was organized to develop a copper vein to the west of Globe, but the ore was only a small pocket, and the mine was abandoned and the smelter was moved to Globe. In 1883 the company purchased the Globe and other claims and the mine became known as the Old Dominion. The company was reorganized in 1888, and the 6th level was opened from a new shaft. Production continued at an average rate of 3,500 tons of copper per year until 1895, when the mine was sold to the Lewisohn-Bigelow interests and named the Old Dominion Copper Mining and Smelting Co. The mine was then closed and the plant enlarged, in anticipation of the extension of the railroad to Globe. In 1896, mining was resumed on a limited scale, after the railroad was completed to Geronimo, 50 miles from Globe.

In 1892, a company was organized to develop the Buffalo vein, a small smelter was built, and some copper was produced. In 1891, this and other properties were purchased by Phelps Dodge and Co. and consolidated under the name of United Globe Mines. In 1897, the mine was abandoned and the smelter was moved to Globe. In 1898, the plant was enlarged and in 1899, a new concentrator was completed in 1905 and, for the next 10 years, the mine produced an average of 18,690 tons of copper per year. A new concentrator, designed to use the flotation process, was completed in 1914. By this time, the mine was open to the 12th level but water became a problem and the mine was not drained until 1903. Late that year, the Old Dominion Copper Mining and Smelting Co. and the United Globe Mines Co. were acquired by the Old Dominion Co., organized as a holding company under control of Phelps Dodge and Co., and both properties were placed under the management of L. D. Ricketts. A new smelting plant was built, a new shaft was sunk, and a new concentrator was completed in 1905 and, for the next 10 years, the mine produced an average of 13,670 tons of copper per year. A new concentrator, designed to use the flotation process, was completed in 1914. By this time, the mine was open to the 18th level, and it was necessary to pump about 3.75 million gallons of water per day to keep the mine workings drained. The smelter was closed in 1924 and shipments of ore and concentrate were made to the International Smelter at Miami. The concentrator was remodeled and enlarged to a capacity of 1,400 tons per day. Lower-grade ore was being mined by cheaper mining methods permitted profitable operations. In 1931, the price of copper had fallen to less than 10 cents per pound, the 20th level had been developed with discouraging results, and reserves were almost depleted. The mine closed in October 1931, after 50 years of almost continuous operation.
During the period from 1882 to 1931, the Old Dominion and United Globe mines produced approximately 382,000 tons of copper, 89,000 ounces of gold, and 4.5 million ounces of silver, with a total value of about $125 million. The total dividends paid by the Old Dominion Co. from 1905 to 1931 amounted to more than $14 million (Peterson, 1962, p. 98–100).

By 1900, annual production of copper in Arizona averaged about 60,000 tons, and was derived in large part from Bisbee, Globe, Morenci, and Jerome. The dollar value of the mined copper was more than three times the dollar value of mined gold and silver (Dunning and Peplow, 1959). These four districts continued to be the leading producers in Arizona for another decade.

EARLY 20TH CENTURY

The next episode deals with the development of the large, low-grade, disseminated copper deposits at Ray and Miami. Claims were located in the Ray district (fig. 18, No. 9) in the seventies, and a little mining was done about 1880. A company was organized in 1883, obtained ownership of 17 claims, and built a 30-ton furnace, but little was accomplished for the next 15 years. An English corporation, Ray Copper Mines, Ltd., purchased claims in 1899 and developed the town of Kelvin, built a 250-ton mill, shops, office, and staff buildings, and connected the mine and mill by a narrow-gage railway 7 miles long. The mine was developed by a shaft and three levels of crosscuts and drifts. In 1900, a smelter was built at Kelvin and by December of that year, the company had treated 16,000 tons of ore which averaged less than 2 percent copper instead of an anticipated grade between 4 and 5 percent copper. Moreover, the mill proved to be defective in plan and equipment, so subsequently the property became idle (Ransome, 1919, p. 17–18).

The success of the large-scale mining of low-grade disseminated copper ore at Bingham Canyon, Utah, encouraged the inspiration deposit. The Inspiration Mining Co. was organized in 1904 to develop claims in the western part of the deposit, and low-grade chalcopyrite ore was found at a depth of 130 feet. A 50-ton concentrator was built in 1906, and although the venture was not financially successful, it confirmed the presence of large reserves of low-grade disseminated chalcopyrite ore.

In 1908, the General Development Co., controlled by the Lewisohn interests, became concerned with the district, and after sinking two exploratory shafts in the eastern part of the deposit, organized the Miami Copper Co. in 1907. An extensive program of churn drilling and underground development was initiated and, by 1908, 5 million tons of ore containing 3 percent copper were estimated. In 1909, the company prepared for production; the railroad was extended from Globe to Miami, and by the end of the year, reserves of 14 million tons containing 2.75 percent of copper had been blocked out. The first unit of the concentrator began operating in March 1911, and the final unit was completed in 1912, bringing the capacity to 3,000 tons of ore per day. Concentrates were shipped to the Cananea Consolidated Copper Co. for smelting (Peterson, 1962, p. 83).

The Live Oak Development Co. was organized in 1909 to option claims at the western margin of the deposit; the original shaft was deepened, to prospect below a copper silicate ore body, and passed through 150 feet of chalcopyrite ore. A drilling program was started in 1910 and by the end of 1911, 15 million tons of ore had been developed. The Inspiration Copper Co. was organized in 1908 and underground development started to the east of the Live Oak mine; by 1910, reserves of 18 million tons of ore, containing 2 percent copper, has been found. In January 1912, the Live Oak Development Co. and the Inspiration Copper Co. were consolidated, and the new company, Inspiration Consolidated Copper Co., was capitalized at $30 million. Reserves at that time were about 45 million tons, averaging about 2 percent copper (Peterson, 1962, p. 84).

Additional properties were acquired by Inspiration Consolidated Copper Co. to give the company a solid block of ground for efficient mine operations, additional drilling was done to delimit the ore bodies, and hoisting shafts were sunk to prepare the mine for production, which started in 1915. The original plans for the mill called for conventional gravity separation, but oil flotation was coming into vogue, and Louis D. Ricketts, the company's consulting engineer, stopped work on the Inspiration mill and started test work with flota-
tion. A higher percentage of copper was recovered by this process, so in 1915 Ricketts erected Arizona’s first large flotation mill; with a capacity of 14,000 tons per day. It was an immediate success and was put on full flow at the beginning of World War I when copper was in great demand and followed thereafter by high copper prices (Dunning and Peplow, 1959).

The completion of the two mills, Miami and Inspiration, required more smelter facilities so a new smelter was constructed at Miami by the International Smelting and Refining Co., and was “blown in” in May 1916. In 1916, production of copper from the Miami-Inspiration-Globe area surpassed that of the Bisbee area for the first time (Dunning and Peplow, 1959). Inspiration Copper developed their mine for block caving at the beginning of their underground preparation. Miami Copper introduced this method on some of its ore in 1914, and in 1919, discontinued all other methods (Parsons, 1933).

**WORLD WAR I**

After the start of World War I, three important new copper mines came into production, the United Verde Extension, New Cornelia (Ajo), and Magma. In many aspects, the discovery of the United Verde Extension deposit is one of the most glamorous in Arizona’s mining history.

The United Verde ore body at Jerome (fig. 18, No. 7) cropped out in country rock west of the important Verde fault; to the east of the fault, the ore-bearing host rocks were covered by a thick blanket of younger rocks, and the ore deposits were hidden, which resulted in costly exploration. The Daisy shaft was sunk to the east of the fault and some copper was found below the 800 level, but the experts reported adversely, and exploration was stopped. James S. Douglas, son of Dr. James A. Douglas of Phelps Dodge and Co., visited Jerome in 1911, examined the workings on the 800 level, then took an option on the property. In 1912, he organized the United Verde Extension Copper Co. and invited friends to provide $225,000 to explore the property.

A second shaft was sunk in 1913 farther to the east of the Verde fault than the Daisy shaft to avoid the heavy ground in the fault zone. This shaft entered the ore-bearing host rocks at a depth of 678 feet, then was deepened to 1,400 feet and considerable exploratory work was done without productive results. In December 1914, when the financial resources were near exhaustion, a drift on the 1,200 level encountered a chalcocite body 5 feet wide, containing 45 percent copper. About $600,000 worth of ore was mined from this body in 1915. A drift was started at the 1,400 level in January 1916 to intersect the downward continuation of the ore found in the 1,200 level, but the drift encountered no ore where expected. A crosscut was then driven to the east on the 1,400 level—cutting 100 feet of high-grade chalcocite ore. Additional exploration revealed a large mass of chalcocite ore with a maximum width of 260 feet and a length of 440, covering an area of 62,400 square feet on the 1,400 level. During 1916, the United Verde Extension mine produced 18,200 tons of copper from 77,000 tons of ore, which averaged 23.5 percent copper, and contained 2,570 ounces of gold and 128,468 ounces of silver, the total worth $9,949,918, of which $7,400,000 was profit. This was a bonanza discovery!

The peak annual copper production of the United Verde Extension mine was reached in 1917, when 32,000 tons of ore were obtained from 115,000 tons of ore, averaging 27.5 percent copper. Peak annual tonnage was reached in 1929 when 385,000 tons of ore were mined, yielding 29,500 tons of copper from ore averaging between 8 and 9 percent copper. Reserves became exhausted in depth and the mine closed in 1938 (Anderson and Creasy, 1958, p. 135).

The history of the New Cornelia mine (fig. 18, No. 17) started in 1911 when the Calumet and Arizona Copper Co., operating chiefly at Bisbee, took an option on 70 percent of the stock of the New Cornelia Copper Co., owners of mineralized ground at Ajo. After drilling established the worth of the property, experiments were directed to develop a leaching process for treating the carbonate ores that cropped out at the surface and covered the underlying disseminated sulfide ore. Also, a search was made for the large water supply required for the proposed leaching plant. Adequate water was found several miles to the north at Childs Siding.

By 1915, the experiments on leaching led to the construction of a 40-ton experimental plant and a railroad which was completed in 1916, connecting Ajo with the Southern Pacific at Gila Bend. That same year, work was started on a 5,000-ton leaching plant; by April 17, the plant was ready for operation, and the first shipment of electrolytic copper was made in June 1917. By the end of 1917, 8,760 tons of copper was produced. Steam shovels were used to excavate the ore and Arizona’s first large open-pit mine was in operation. The New Cornelia ore body consists of disseminated copper sulfide minerals, chalcopyrite and bornite, and, unlike the ore bodies at Ray and Miami-Inspiration, no chalcocite blanket was formed; instead the carbonate capping contained the same amount of copper as the underlying sulfide ore.

Looking ahead to the exhaustion of the carbonate ore at the New Cornelia, a test mill for treatment of the underlying sulfide ore was built in 1919. The postwar depression curtailed production, but in 1922, construction began on a 5,000-ton sulfide concentrator, and a second shaft was sunk at Childs Siding to develop additional water. The concentrator was put in operation in 1924, and both leaching and sulfide ore were treated until 1930 when the leaching plant closed. Meanwhile, the capacity of the concentrator was increased to 16,000 tons. In 1931, Calumet and Arizona Copper Co. merged with Phelps Dodge Corp., and since then, the New Cornelia mine has operated as a branch of Phelps Dodge (Gilluly, 1946, p. 100).

The Magma mine at Superior (fig. 18, No. 8) is in a vein deposit, which is similar in some respects to the Old Dominion vein at Globe. These are the only vein-type deposits in Arizona that have produced substantial amounts of copper. The early mining on the Magma vein was for high-grade silver ore. In 1908, chalcocite ore, left by the silver miners, was found in the old workings. In 1910, the Magma Copper Co. was organized and in 1912, work in depth on the Silver Queen vein resulted in the discovery of rich copper ore. An ore shipment of 114 tons assayed 48 percent copper and 68 ounces of silver per ton. A sec-
ond lot of 3,168 tons assayed 16 percent copper and 18 ounces of silver per ton. By 1914, the development had reached a stage where a railroad could be built to connect with the Arizona Eastern Railroad near Florence, and that same year electric power was brought in from Roosevelt Dam.

During 1916, development had progressed to the 1,500 level and a rich ore body was discovered, which was 34 feet thick and averaged 10.62 percent copper, and contained 0.128 ounces of gold, and 5.37 ounces of silver per ton. By 1918, the mining and milling costs were 18.425 cents and the selling price was 25 cents per pound of copper. The Magma ore bodies contain appreciable bornite, a copper sulfide which contains 63 percent copper, as well as chalcopyrite, which contains 34 percent copper; their combination can create rich copper ore. Development during 1921 revealed that the ore bodies increased in size with depth. Thus, the Magma mine has continued to be an important producer of copper, except during periods of low prices, and is the only important vein-type copper mine now operating in Arizona (Dunning and Peplow, 1959).

**POST-WORLD WAR I**

The decade after the end of World War I was not marked by discoveries of any large copper deposits. In the Morenci district, Phelps Dodge purchased the Shannon holdings in 1919 and the Arizona Copper Co. in 1921, which gave them ownership of nearly all of the district. Block caving was introduced in 1922 and by 1925, full-scale production was resumed at an annual rate of about 50 million tons of ore. This continued until the depression in the early thirties, when the type of ore that had sustained past production was virtually exhausted (Dunning and Peplow, 1959).

Sacramento Hill at Bisbee (fig. 18, No. 25) contains disseminated copper sulfides in a mass of silicified quartz porphyry. Phelps Dodge Corp. explored it by underground workings and surface churn drilling and in the early 1920's, decided that exploitation would be profitable, so the leached capping was stripped and a 4,000-ton-per-day concentrator built. In 1923, steam shovel operations began the removal of ore from an opencut. During a nine-year life, 10 million tons of ore was mined and 218,300 tons of copper produced (Parsons, 1957).

At the end of 1922, Miami Copper Co. had high-grade reserves for only 2 years of operation remaining. Adjacent to the old ore body, however, was a larger mass of lower-grade ore, which averaged less than 1 percent copper, whereas the original ore body averaged between 2 and 2.5 percent copper. In order to mine and treat the low-grade ore, it was necessary to increase the scale of operation and effect every possible economy. The management improved the block caving by installing conveyors and other mechanized equipment underground, improved the metallurgy, and increased the mill capacity to 12,000 tons per day. Development of the low-grade ore was started in 1924. The costs of production were even lower than anticipated and at the end of 1926, the reserves were recalculated in line with reduced costs. They were reported as 84.5 million tons of sulfide are averaging 0.93 percent copper and 7 million tons of mixed sulfide-oxide ore averaging 1.38 percent copper. Additional reductions in cost were made in 1927 and the concentrator capacity was increased to 18,000 tons per day. At the end of 1927, reserves of 99.6 million tons of sulfide ore averaging 0.88 percent copper were reported (Peterson, 1962, p. 85; Dunning and Peplow, 1959).

Inspiration Consolidated Copper Co. started experiments in 1922 in a leaching process to treat large reserves of mixed oxide and sulfide ore. The experiments were successful and a process of leaching with ferric sulfate solution and subsequent precipitation of copper by electrolysis was developed. Construction of a 9,000-ton leaching plant was completed in 1926, and the plant proved so successful that the concentrator was closed down permanently in 1930 (Peterson, 1962, p. 84).

**DEPRESSION AND WORLD WAR II**

The depression in the early thirties had a terrific impact on the copper mines in Arizona, but not one of the State's major mining corporations failed. Production in 1929 was 415,000 tons of copper; in 1933, it was 57,000 tons, just 13.5 percent of the 1929 production. Many mines were forced to close for various lengths of time, but by 1937, production of copper was up to 288,000 tons followed by a drop to 210,000 tons in 1938. But with the advent of World War II in 1939, copper increased in price and production rose to 262,000 tons, and during the peak war years it increased to 303,000 tons per year.

Bagdad (fig. 18, No. 3) became active in the mid-thirties, after a long largely dormant period following the initial discovery in 1882. In 1905, exploration adits were driven and in 1909, churn drilling was started and was carried on intermittently until 1928. A pilot mill was built in 1928, and in 1930, an experimental block-caving stopes was started. The success of the stoping method and satisfactory mill recovery encouraged the expansion of the pilot mill to a capacity of 300 tons per day, and two stopes were mined, and a small tonnage of copper was produced.

During World War II, the Bagdad Copper Corp. obtained a loan of $2.5 million from the Reconstruction Finance Corporation, to build a concentrator of 2,500 tons per day capacity, pay for a 70-mile power line from Parker Dam, build housing, and prepare the mine for underground caving. The road from Bagdad to Hillside on the Santa Fe Railway was shortened and improved by Yavapai County and the Federal Government. The new mill started operations in March 1943, but competent underground miners were scarce during the war period, and mining costs were high, so the mine never produced more than half the mill capacity. John C. Lincoln acquired control of the company in 1944, and mining methods were changed in 1945 to a combination of glory-hole and block-caving methods to increase production, and in 1947, open-pit mining was adopted. By 1950, all underground mining had stopped but the mill capacity was increased to 4,500 tons per day to treat the ores from open-pit operations. Ernest Dickie, the manager, used the Bagdad open pit as a laboratory for truck manufacturers. This resulted in improved design and performance in the trucks used to remove waste in stripping and to haul ore to the crushing plant. As a result, by 1952 the RFC loan was paid off (Anderson, Scholz, and Strobell, 1955, p. 43-46; Dunning and Peplow, 1959).
At present, the mill capacity is 6,000 tons per day, and a sulfuric acid plant provides acid for leaching copper from oxide dumps. In 1966, more than 13,000 tons of copper were produced from mill concentrates and 6,000 tons of copper were recovered by leaching. Bagdad Copper Co. recently joined Chemetals Corp. to build a copper powder refinery which has been in operation for two years. Part of the cement copper recovered from leaching operations is used as feed for the copper-powder refinery and the remainder is shipped to the smelter (G. W. Colville, written commun. 1968).

In 1931, the Morenci mine produced 1.3 million tons of ore, which had a gross value of $3.5 million, an average of only about $2.75 per ton, caused by the low price of copper. There is no record of production from July 1932 through 1936. Louis S. Cates, the new president of Phelps Dodge Corp. guided a long program of development drilling and experimental milling during 1937 and 1938, while 8,000 to 10,000 tons of copper were produced by leaching old stopes fills. By 1939, 230 million tons of ore had been developed, when Phelps Dodge decided to mine the ore by open pit. By the end of 1941, overburden stripping was advanced sufficiently to permit the mining of 28,000 tons of ore per day; the concentrator with that capacity was 90 percent complete, and the smelter to treat the concentrates was 75 percent complete. In the spring of 1942, these facilities were in full operation (Dunning and Peplow, 1959).

By this date, because of U.S. involvement in World War II, the U.S. Defense Plant Corporation requested that Phelps Dodge make an 80 percent increase in production at Morenci. Such a large increase required the enlargement of the refinery at El Paso and the enlargement of the concentrator and smelter. Mine production was increased so that by the end of 1943, the output was 45,000 tons of ore per day.

The Defense Plant Corporation financed this expansion to the extent of $26 million, and in turn, leased the facilities to Phelps Dodge Corp. After the war, Phelps Dodge Corp. purchased the additional facilities. This expanded production made Morenci the largest copper producer in Arizona, a position it has held to the present time (Dunning and Peplow, 1959).

The United Verde mine at Jerome closed and was idle during the early depression years. In 1935, it was purchased by Phelps Dodge Corp. from the heirs of Senator W. A. Clark. Mining was resumed underground as well as from a small open pit, at an average rate of 1 million tons of ore per year. This ore averaged between 5 and 7 percent copper. During the early forties, the grade of ore began to decline, but through the premium price plan, the United Verde was able to mine several million tons of marginal ore that otherwise would have been lost. By 1942, extensive exploration and deep drilling showed that the ore body was nearing exhaustion. Production gradually decreased, and the smelter was closed in 1950, but the mine continued operations on copper-zinc ore that was found at deep levels north of the main ore body. This ore was concentrated at Clarkdale until the mine was closed in 1953. Since that date, the Big Hole Mining Co., working under a lease from Phelps Dodge Corp., has been mining small ore shoots left in the southern and western margins of the open pit. The United Verde was one of the world's great copper mines; more than 1.375 million tons of copper was produced (Dunning and Peplow, 1959).

In 1941, the Federal Government combed the country for proven copper deposits to bring into immediate production. Porphyry Mountain, 6 miles west of the town of Miami, contained 33 million tons of ore, averaging 0.75 percent copper. The deposit, called Castle Dome (fig. 18, No. 12), was owned by Miami Copper Co., who regarded it as a potential source of copper. The Defense Plant Corporation supplied $13.5 million to finance initial stripping and to build a concentrator of 12,000 tons daily capacity, which it leased to Miami's subsidiary, Castle Dome Copper Co. By July 1943, the mine was being exploited as an open-pit operation and the facilities were producing concentrate. The mine closed in 1953 after producing 257,000 tons of copper and byproduct gold and silver valued at an additional $777,000 (Parsons, 1957).

KOREAN WAR TO THE PRESENT

The Copper Cities deposit (fig. 18, No. 13) (3 miles north of Miami), is similar to Castle Dome, and is mined by Copper Cities Mining Co., a subsidiary of Miami Copper Co. Exploitation was timed to start after the exhaustion of ore at Castle Dome. Stripping of overburden began in December 1953, and the Castle Dome concentrator was dismantled and moved to Copper Cities. The plant was in operation before the end of 1954. Through December 1962, the mine had produced more than 27 million tons of ore at a rate of 12,000 tons per day. More than 40 million tons of rock containing a little copper was placed on dumps where induced leaching operations started in December 1962 (Parsons, 1957; Simmons and Fowells, 1966).

The Korean War in 1950 caused concern as our production of copper was not meeting domestic needs. In 1950, Phelps Dodge Corp. installed a new smelter at Ajo, and in 1953 increased the concentrator capacity to 30,000 tons per day. Then company began developing the Bisbee East ore body as an open-pit (Lavender Pit), and in 1953 contracted with the Federal Government for a guaranteed floor price of 22 cents a pound for 225 million pounds of copper, although the market price was 24 cents a pound. By August 1954 the 12,000-ton mill was in operation (Dunning and Peplow, 1959).

The Ray mine from 1911 to the end of 1954 had produced 79 million tons of ore by underground block caving, but in 1947, the decision was made to mine part of the ore body by opencut methods. Shovel production started in 1950, which was so successful that underground mining was discontinued in 1954 and the entire mine converted to opencut operations. To handle the tonnage, the concentrator was improved and its capacity increased to 15,000 tons per day. By 1960, its capacity was increased further to 22,000 tons per day (Parsons, 1957; Dunning and Peplow, 1959).

At the end of 1951, Miami Copper Co. had only three years of ore reserves remaining in their Miami mine, but large tonnages of submarginal material, containing less than 0.5 percent copper were present along the southeastern edge of their ore body. Additional development, however, outlined a minable block of 35 million tons containing more than 0.5 percent copper. A contract was made with the Defense Mate-
rial Procurement Administration to purchase 115,000 tons of copper from this block of ground at a guaranteed price of 27.55 cents per pound of copper. Production started in 1954 and terminated in 1959. Leaching of copper from old stopes was started in 1941, and to the end of 1952, 44,000 tons of copper had been recovered by leaching. Leaching has continued and Miami is still producing a significant amount of copper (Peterson, 1962).

Some mining was done at Silver Bell (fig. 18, No. 19) between 1891 and 1911, with a total production of 20,000 tons of copper. By 1909, the possibilities of mining disseminated copper ore were recognized, so sufficient churn drilling was done to partly delineate two copper sulfide deposits, the Oxide and El Tiro. The submarginal character discouraged exploitation of the disseminated deposits, but selective mining of higher-grade ore bodies continued until 1930.

American Smelting and Refining Co. began exploratory and check drilling in 1948, and made plans to mine the Oxide and El Tiro ore bodies at a rate of 7,500 tons per day. The company, however, needed assurance of a continuing good market for copper before risking the $17 million required to put the mine in operation. In 1951, the company contracted with the Defense Minerals Procurement Administration to sell 177 million pounds of the first 197 million pounds of copper produced, at a guaranteed price of 24.5 cents per pound. By April 1954, a concentrator with a daily capacity of 7,500 tons was in operation; and in 1955, 21,000 tons of copper concentrates were produced (Dunning and Peplow, 1959). The contract ran for five years without the necessity of the company selling any copper to the government.

San Manuel (fig. 18, No. 10), the second largest copper mining operation in Arizona today, has had a long and complex history (Knoerr, 1958). The original locations were made in 1870 and a couple of unproductive holes were drilled in 1917. In 1942, H. W. Nichols, one of the partners owning the property, applied for a preliminary drilling program to mine the ore. By December 1944, and north of the Pima mine and were partly mined by underground mining and Peplow, 1959). The expansion indicates that the Pima district was the first major ore body to be discovered by geophysical methods in Arizona (Dunning and Peplow, 1959).

In 1959 the Pima Mining Co. made an agreement with the Banner Mining Co. to mine and concentrate the ore from along the common property boundary—the ore from Banner property to be treated for Banner account at cost of production (Arizona Star, 1959). Additional low-grade ore was developed on Pima property east of the original pit. By 1960, the Pima mine was expanded to treat 18,000 tons of ore per day and started further expansion to treat 30,000 tons daily and recover molybdenum as well as copper (Komadina, 1967). The expansion indicates that lower-grade materials can be mined.

In 1945, San Manuel Copper Corp. was organized as a subsidiary of Magma Copper Corp. to carry on the exploration (Schwartz, 1953). An extensive drilling program was carried on by the San Manuel Copper Corp. until 1947, and underground development and preparation continued until 1956. By 1951, the reserves were estimated to be 470,650,000 tons containing 0.77 percent copper. The shape and depth of the ore body prohibited open-pit mining, so plans were made to mine it by block caving. By the end of 1955, underground development was complete, a 30,000-ton flotation concentrator and a new town had been built. The total costs to this date were approximately $100 million—before a pound of copper was produced. In January 1956, San Manuel started production and, after overcoming additional difficulties, was in smooth production by late 1957 (Dunning and Peplow, 1959).

The latest exciting episode centers in the Pima district, south of Tucson, an area which has had a long history of sporadic mining. In the late forties, the United Geophysical Co. made a systematic study of some of the areas in Arizona that might contain hidden ore bodies, and selected the Pima district for detailed work where alluvium 200 feet in thickness covers the bedrock. Using a combination of geophysical methods, a drilling site was selected and the first drill hole encountered bedrock at 209 feet and copper sulfide ore at 255 feet (Thurmond and others, 1954). In November 1951, the Pima Mining Co. was incorporated and underground development started on the ore body, and in 1952 and 1953, 67,000 tons of ore containing 6 percent copper were shipped. In 1955, Cyprus Mines Corp. assumed management of the Company; Union Oil Co. retained a 25 percent interest, and a 25 percent interest was sold to Utah Construction Co. In late 1955, stripping operations were started to prepare for open-pit mining. In 1956, a concentrator of 3,500 tons daily capacity was built and production of copper concentrates started in 1957. The Pima mine is the first major ore body to be discovered by geophysical methods in Arizona (Dunning and Peplow, 1959).

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From 1961 to 1963, the Banner Mining Co. was notably active in exploring the district. Ore bodies were found beneath the alluvium west and north of the Pima mine and were partly mined by underground methods. About 61/2 miles south-southeast of the Pima mine, near Twin Buttes, under a large area, a low-grade deposit was found beneath alluvium as much as 500 feet thick (Bowman, 1963). In 1963 The Anaconda Co. obtained exploration rights and an option to lease the Banner property, and later took a long-term lease and began a vigorous drilling program (Tucson Daily Citizen, 1964). The following year an exploration shaft was started and large ore samples were taken for metallurgical testing. Stripping for the Twin Buttes open-
pit mine began in late 1965 (Eng. Mining Jour., 1965), reportedly the largest initial stripping operation ever undertaken on a copper deposit. The Twin Buttes mine and concentrator are scheduled to go into production in mid-1969 at a minimum rate of 30,000 tons of ore per day (Eng. Mining Jour., 1967, nos. 4 and 10).

The Mission deposit of the American Smelting and Refining Co. was discovered in 1954 northeast of the Pima mine. Following extensive diamond drilling and testing by an exploration shaft, stripping operations and construction of a 15,000 ton-per-day concentrator started in the fall of 1959, and the Mission open-pit mine went into full production in September 1961 (Argall, 1962). Since the latter part of 1964, molybdenum and zinc have been recovered as byproduct (ASARCO Annual Report, 1964). An expansion program to treat 27,000 tons of ore per day was started in 1966 and scheduled for completion in 1967 (Eng. Mining Jour., 1966, no. 1). When ore along Pima’s property line is mined, the Mission and Pima mines will join to form a single open pit.

After discovery of the Mission ore body, the American Smelting and Refining Co. obtained exclusive exploration rights on parts of the adjacent San Xavier Indian Reservation at a cost of more than $1 million (Eng. Mining Jour., 1957). Another low-grade disseminated copper deposit was discovered on the Reservation about 2 miles northwest of the Mission deposit beneath a shallow cover of alluvium. A little copper ore was mined in 1967 from an open pit on this deposit, and production is expected to increase significantly in the future (Eng. Mining Jour., 1967, no. 10).

The Esperanza ore body of the Duval Corp. was discovered in 1955 about 3 1/2 miles southwest of the Pima mine. Waste removal began November 1957 (Eng. Mining Jour., 1958) and the Esperanza open-pit mine went into production in March 1959. The concentrator then had a rated capacity of 10,000 tons of ore per day and recovered both copper and molybdenum (Eng. Mining Jour., 1959). Unlike the recent discoveries in the Pima district, the Esperanza area is a large area of exposed bedrock, in which there had been small-scale exploration and mining in the past. The Esperanza discovery was a direct result of geologic interpretation of the leached capping by Harrison Schmitt (Lynch, 1966).

Duval’s operations in the district have expanded since 1959. Recovery of copper by leaching from the Esperanza mine dumps began in May 1962, the West Esperanza open-pit mine was started in 1964, and the Esperanza concentrating facilities were increased to 15,000 tons per day in 1966 (Eng. Mining Jour., 1966, no. 12). Plans to develop the Sierra ore body, located still farther west, were announced in 1967; when the Duval Corp. received approval for an $83-million advance against future copper deliveries from the General Services Administration. The advance is to help finance the development of an open-pit mine and to construct a 60,000-tens-per-day concentrator. Under terms of the contract, the new mine and mill must be in production in November 1969, and the General Services Administration will buy 109,000 tons of copper for the government stockpile. Duval plans to produce 57,000 tons of copper per year during the first five years of operation and 68,000 tons per year for the following 15 years. In addition to the copper output, the mine is expected to yield 12 million pounds of molybdenum and 455,000 ounces of silver annually (Eng. Mining Jour., 1967, no. 12).

The Mineral Park mine, in northwestern Arizona (fig. 18, No. 1) and owned by Duval Corp. is the most recent open-pit mine to start operations. It is an old mining district, with early significant production from fissure veins of rich gold-bearing silver ores. During the first half of this century silver-bearing lead-zinc ores were mined from some of the larger veins. The total production from the district to 1950 totaled $25 million. In 1960, Duval Corp. started an exploration program at Ithaca Peak, culminating in 1963 in the development of the Mineral Park deposit and construction of a concentrator and auxiliary facilities. Production started in November 1964 with a capacity of 14,000 tons of ore per day; copper and molybdenite are recovered (Eidel and others, 1968).

In recent years, improved methods have been developed to recover copper from oxidized sulfide ore bodies which has stimulated the mining of several copper oxide deposits. The Emerald Isle mine, just west of Mineral Park, is operated by the El Paso Natural Gas Co., using a process that leaches copper from chrysocolla (copper silicate) precipitates the copper by sponge iron, and concentrates the resulting cement copper by flotation. Current mine production is 600 tons of ore per day (Eng. Mining Jour., 1967, no. 6).

The Zonia deposit (fig. 18, No. 5), owned by the McAlester Fuel Co., is largely chrysocolla with minor malachite, cuprite, and black copper oxide forming lenses in a shear zone in Precambrian schist. The ore is milled from an opencut, heap-leached with acid, and the cement copper is precipitated on scrap iron (D. F. Anderson, written commun., 1968).

The Bluebird mine, between the Inspiration and Castle Dome mines at Miami, is owned by the Ranchers Exploration and Development Co. It produced 4,100 tons of cement copper in fiscal year ending June 30, 1967. The company plans to install a new electrolytic copper facility in order to treat 1 million tons of ore per year (Eng. Mining Jour., 1967, no. 10).

Kennecott Copper Corp. is developing a modified vat leach process to recover copper from copper-bearing clay minerals at Ray (Stephens and Metz, 1967).

The Lakeshore mine (fig. 18, No. 18) originally owned by Transazriona Resources, Inc., started an open-pit operation in 1960 to mine chrysocolla ore containing 2 percent copper. Copper is recovered by the segregation process involving the heating of crushed ore to high temperatures with sodium chloride and coke in a reducing atmosphere and recovering the fine metallic copper by conventional flotation methods. The present owners, Narragansett Wire Co. and El Paso Natural Gas Co. are expanding the treatment plant from 400 to 800 tons per day, and have leased 2,677 acres of land on the adjoining Papago Indian Reservation in order to expand production (Eng. Mining Jour., 1960; 1966, no. 10).

Banner Mining Co. is working on a process to use a new alkali-leach method for the recovery of oxide copper from carbonate-rich ores, found in the Pima and other districts in Arizona. These ores are
not amenable to leaching by ordinary methods so this research could lead to increased copper resources in the future (Eng. Mining Jour., 1966, no. 7).

Current exploration activity is at a high level in southern Arizona. A program of the Quintana Minerals Corp. carried on to the west of the San Manuel mine, resulted in the discovery of the Kalamazoo ore body, a faulted segment of the San Manuel deposit (Lowell, 1967). Elsewhere in Pinal County, exploration is continuing at Owl Head, to the west of the Kalamazoo discovery, and in the Vekol district at the northern margin of the Papago Indian Reservation (southwestern corner of Pinal County), where Newmont Development Co. has been doing extensive drilling (Eng. Mining Jour., 1966, no. 10; 1967, no. 4).

In Pima County, active exploration is being carried on in the Helvetia district (fig. 18, No. 23) and in the Patagonia region to the south in Santa Cruz County. Other areas commanding current attention are near Johnson Camp in Cochise County (fig. 18, No. 24) and near Safford in Graham County (fig. 18, No. 26) (Eng. Mining Jour., 1967, no. 4; Robinson and Cook, 1966; Hansen and Rabb, 1968).

Production

In 1965, production of copper in the United States totaled 11.5 million short tons, having a cash value of $967 million, and the domestic consumption of new copper was 1.5 million short tons. In 1965, the annual production of copper in Arizona was 703,371 short tons, representing 52 percent of the domestic production and 18 percent of the free world output. The average domestic price for copper in 1965 was 35.4 cents per pound in contrast to the average price of 30 cents per pound in 1961; the cash value of Arizona's production in 1965 was $497,991,000 (Wideman, 1966; Larson and Henkes, 1967).

In 1965, 10 of the leading 25 copper mines in the United States were in Arizona. Listed in order of decreasing production these were: Morenci, San Manuel, Ray, New Cornelia (Ajo), Copper Queen-Lavender Pit (Bisbee), Mission, Inspiration, Esperanza, Silver Bell, Bagdad, Copper Cities, Magma, Mineral Park, Pima, Miami, and Christmas (Wideman, 1966).

These 16 mines consist of 12 large open-pit mines (including the Lavender Pit at Bisbee) and 5 underground mines (including the Copper Queen at Bisbee), and together account for 97 percent of the copper mining in Arizona but began to increase before 1933, culminating in a peak production during World War I. The recession in 1921 resulted in a drastic reduction, followed by increasing production to more than 400,000 tons in 1928. The depression in the early thirties caused a severe cutback until World War II. Military requirements were curtailed in 1945, and the following year, productivity was shortened by strikes and it was again shortened by strikes in 1954 and in 1959. In general, however, the production of copper since 1933 has steadily increased and, at the present time, Arizona leads the Nation in copper production.
Large low-grade copper deposits of the type commonly referred to as "disseminated" or "porphyry copper," are the major source of current copper production in Arizona. All of the large open-pit mines and two of the important underground mines are exploiting this type of ore. Most of the current exploration activity in Arizona is focused on finding additional large low-grade copper deposits.

The term "disseminated," although widely used, is a misnomer because many of these large low-grade deposits are found only in minor portions of the ore body. The term "porphyry" is also a misnomer because many are contained in schists, silicated limestone, volcanic rocks, or even-granular granitic rocks. However, with the above reservations in mind, the term "porphyry copper deposits" is hereby used interchangeably with "disseminated deposits." For a more detailed discussion of these deposits that follows, see Anderson (1965).

A feature common to all of the porphyry copper deposits in Arizona is that they are spatially related to stocks, plugs, sills, dikes of essentially quartz-bearing porphyritic to granular intrusive rocks, variously classified as quartz diorite, granodiorite, quartz monzonite, and granite, or their porphyritic equivalents. Many reports emphasize that these intrusive rocks are monzonitic because K-feldspar and plagioclase are common constituents.

Some of the porphyry copper deposits are in stocks of granodiorite or quartz monzonite that became mineralized following shattering of the intrusive body. The Bagdad, Castle Dome, Copper Cities, and Mineral Park deposits are examples. The Lavender Pit at Bisbee is in a shattered stock containing various masses of breccia, all of which are mineralized. At Morenci, the ore body makes up two-thirds of the exposed stock, and adjacent limestones are also mineralized.

Rhyolitic rocks intruded by stocks are sufficiently mineralized to be part of the ore body at Ajo and Esperanza. A more complicated geologic history has been unraveled at Silver Bell, in that the earliest stock, alaskitic in composition, was exposed by erosion and then buried by volcanic rocks that in turn were intruded by quartz monzonite. At Silver Bell, the El Tiro ore body consists of mineralized alaskite and quartz monzonite, whereas the Oxide ore body consists of mineralized alaskite, younger volcanics, and quartz monzonite.

Precambrian quartz monzonite is an important host rock for the San Manuel ore body along with younger quartz monzonite porphyry. The Mission-Inspiration ore body occurs in the Pinal Schist (Precambrian) and younger granite and granite porphyry, with about half of the ore body in the schist. Much of the past production at Ray has been in Pinal Schist but present production also comes from associated diabase.

The Mission, Pima, Banner-Anaconda, and Twin Buttes deposits are in silicated limestone, sandstone, and siltstone that are cut by sill-like bodies of intrusive quartz monzonite porphyry and rhyolite. The porphyry is mineralized but is rarely of ore grade.

It has been common practice in Arizona to relate the stocks and other intrusive rocks to the Laramide orogeny, which occurred during Late Cretaceous and early Tertiary time. The distribution of these intrusive rocks is shown in figure 18, based largely on a map by the Arizona Bureau of Mines (1962). Geologic evidence indicates that the mineralized stock in the Lavender Pit is older than the overlying Glance Conglomerate of Early Cretaceous age, and the conclusion is inescapable that this particular stock is Jurassic or older. A nearby granite rock has been dated radiometrically as Early Jurassic in age, and the presumption is that the Lavender Pit stock is of the same age or younger in the Jurassic Period.

Radiometric dates are available for intrusive rocks in 10 porphyry copper deposits in Arizona, that range from 60 to 72 million years (m.y.) in age. The concept that perhaps all of the deposits in Arizona, except Bisbee, are of Laramide age (Late Cretaceous to early Tertiary) should be noted, however, that the porphyry copper deposit at Elv, Nev., is 120 m.y. old and that the Bingham deposit in Utah is only 37 m.y. old. Radiometric dates of unaltered and mineralized stocks in three deposits indicate that the intrusion of the igneous rocks and their mineralization to form the ore deposits were essentially contemporaneous. On geologic grounds, Gilluly (1946) preferred a porphyrite age to the above reservations in mind, the term "porphyry copper deposits" is hereby used interchangeably with "disseminated deposits." For a more detailed discussion of these deposits that follows, see Anderson (1965).

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Precambrian quartz monzonite is an important host rock for the San Manuel ore body along with younger quartz monzonite porphyry. The Mission-Inspiration ore body occurs in the Pinal Schist (Precambrian) and younger granite and granite porphyry, with about half of the ore body in the schist. Much of the past production at Ray has been in Pinal Schist but present production also comes from associated diabase.

The Mission, Pima, Banner-Anaconda, and Twin Buttes deposits are in silicated limestone, sandstone, and siltstone that are cut by sill-like bodies of intrusive quartz monzonite porphyry and rhyolite. The porphyry is mineralized but is rarely of ore grade.

It has been common practice in Arizona to relate the stocks and other intrusive rocks to the Laramide orogeny, which occurred during Late Cretaceous and early Tertiary time. The distribution of these intrusive rocks is shown in figure 18, based largely on a map by the Arizona Bureau of Mines (1962). Geologic evidence indicates that the mineralized stock in the Lavender Pit is older than the overlying Glance Conglomerate of Early Cretaceous age, and the conclusion is inescapable that this particular stock is Jurassic or older. A nearby granite rock has been dated radiometrically as Early Jurassic in age, and the presumption is that the Lavender Pit stock is of the same age or younger in the Jurassic Period.

Radiometric dates are available for intrusive rocks in 10 porphyry copper deposits in Arizona, that range from 60 to 72 million years (m.y.) in age. The concept that perhaps all of the deposits in Arizona, except Bisbee, are of Laramide age (Late Cretaceous to early Tertiary) should be noted, however, that the porphyry copper deposit at Elv, Nev., is 120 m.y. old and that the Bingham deposit in Utah is only 37 m.y. old. Radiometric dates of unaltered and mineralized stocks in three deposits indicate that the intrusion of the igneous rocks and their mineralization to form the ore deposits were essentially contemporaneous. On geologic grounds, Gilluly (1946) preferred a porphyrite age to the simpler transition from late magmatic alteration to the final shattering allowing the mineralizing solutions to percolate through the stock.

The mineralogy of the porphyry copper deposits is rather simple. The primary or hypogene minerals are dominantly pyrite and chalcopyrite, but the ratios between these two minerals range widely between deposits and even in parts of an individual deposit. Molybdenite is a minor constituent in nearly all deposits. Bornite is an important ore mineral at Ajo, but this mineral is found only in minor quantities in other deposits. In some of the Arizona porphyry copper deposits, the content of copper in the primary or hypogene zone is sufficiently high for profitable mining, as at Ajo, Mission, and Pima. Other such deposits are minable because of supergene enrichment.

Supergene enrichment is the process by which the primary sulfides, pyrite, chalcopyrite, and bornite, are altered by percolating water and oxygen in the cracks and pore spaces of the rocks. The oxidation of the pyrite and copper sulfide minerals forms copper sulfate, iron sulfate, and sulfuric acid, which are commonly carried downward in solution. The sulfuric acid may eventually be neutralized by reaction with rock minerals, causing the iron to be precipitated as limonite, a hydrated iron oxide. In the absence of oxygen, the copper sulfate reacts with chalcopyrite and pyrite to form chalcocite (Cu$_2$S) or, less
commonly, covellite (CuS), thus increasing the copper content in the lower zone. The selective replacement of chalcopyrite in preference to pyrite has been widely noted in all of the disseminated ore bodies in the Western States. Pyrite is rarely replaced by chalcocite until most of the chalcopyrite is replaced.

The evidence of supergene enrichment is given by an uppermost low-grade leached zone generally containing only sparse oxidized copper minerals, such as chrysocolla and malachite, with varying amounts of azurite, cuprite, native copper, and black copper oxide. A narrow transition zone commonly separates the leached zone from the underlying higher-grade chalcocite zone or blanket, and the chalcocite zone in turn grades sharply into the underlying lower-grade chalcopyrite zone. The copper content in the chalcocite zone may be two to ten times the copper content in the chalcopyrite zone, and the thickness of the chalcocite blanket may range from a few feet to hundreds of feet. Figure 20 illustrates the ranges in copper content in two typical deposits that have undergone supergene enrichment, Bagdad and Ray (Anderson, Scholz, and Strobell, 1955; Ransome, 1919).

The Morenci ore body is an example of dominant supergene enrichment of a low-grade deposit formed by hypogene mineralization. The leached capping that covered the ore deposit, now largely removed by stripping operations, ranged from 50 to 600 feet in thickness, with the bottom conforming in general to the present topography. The chalcocite blanket ranges in thickness from 50 to 1,000 feet. The bulk of the leached capping and formation of the chalcocite blanket may have occurred during middle Tertiary time, about 20 million years ago. Exploratory drill holes beneath the chalcocite blanket reveal rock mineralized with chalcopyrite and pyrite and having a grade of 0.10 to 0.15 percent copper; the pyrite content ranges from 3.5 to 8 percent. South of the disseminated deposit, oxidized veins and replacement deposits of chalcopyrite and sphalerite in limestone were the principal sources of ore in the early mining activity (Moolick and Durek, 1966).

The eastern part of the Miami-Inspiration ore body has been mined by Miami Copper Co. and the western part by Inspiration Consolidated Copper Co. The ore body has a length of 12,000 feet, a maximum width of 3,600 feet and, in places, a thickness of as much as 900 feet, but the average is about 250 feet. The ore body is dominantly a product of supergene enrichment, with chalcocite and covellite the chief minerals (Peterson, 1962).

The leached capping over the Inspiration part of the ore body contains very little copper and ranges in thickness from 0 to 1,000 feet and averages about 400 feet. Later oxidation of the chalcocite blanket has produced a copper-oxide zone averaging about 200 feet in thickness that presently furnishes about half of the ore. Chrysocolla, malachite, azurite, and brochantite are the important copper oxide minerals. Primary minerals below the chalcocite blanket include pyrite, chalcopyrite, molybdenite, and some bornite (Olmstead and Johnson, 1966).

The Miami part of the Miami-Inspiration ore body is similar in most respects to the Inspiration part except that the oxidized portion of the chalcocite blanket lies at greater depth. It was not recovered by underground mining, but is now being recovered by leaching caved ground.

Ransome (1919) pointed out the lack of conformity of the top of the chalcocite blanket with the present topography and presented convincing evidence that the major part of the supergene enrichment of the Miami-Inspiration ore body took place when the mineralized schist and granite were exposed to weathering before the region was partly covered by a widespread blanket of volcanic rocks during middle Tertiary time. The ore body at Ray is an irregular chalcocite blanket several hundred feet thick; native copper and cuprite are present locally in the oxidized zone. Much of the chalcocite ore has been slightly oxidized on grain surfaces, and a leach-precipitate float process is used to improve copper recovery. Supergene enrichment is negligible in the intrusive masses of diabase that are present in the Pinal Schist, but the content of chalcopyrite is sufficiently high in the diabase to form an important part of the ore (Metz and Rose, 1966).

Supergene chalcocite ore is mined at Silver Bell from two pits, El Tiro and Oxide. The chalcocite blanket is 100 to 200 feet thick, lying beneath leached capping, which is 100 feet thick (Richard and Courtright, 1966). At Mineral Park, the leached capping averages about 120 feet in thickness, with turquoise the only copper mineral of importance. The chalcocite blanket consists of chalcocite coatings or replacements of pyrite and minor chalcopyrite. The base of the blanket is irregular because of differences in fracture density. The copper

![Figure 20](https://example.com/figure20.png)

**Figure 20**—Graphs of copper content obtained from churn-drill-hole samples, showing range in grade in leached capping, chalcocite blanket (CBL), and underlying primary ore (P) at Bagdad and Ray.
content in the primary mineralized zone ranges from 0.10 to 0.15 percent, reflecting the low content of chalcopyrite (Richard and Courtright, 1966).

Several porphyry copper deposits contain ore that is a mixture of supergene and hypogene sulfide minerals. In the Globe-Miami district, Copper Cities and Castle Dome ore bodies show incomplete supergene enrichment except near the top of the chalcocite zone, but this partial enrichment is of economic importance because of the resulting overall improvement in grade. At these deposits, supergene enrichment appears to be related to the present topography and is of recent formation (Peterson and others, 1951; Peterson, 1962). At Esperanza, chalcocite of superegene origin was the most important ore mineral in the upper part of the ore body, but in lower elevations, chalcopyrite now is becoming increasingly important, and below the 3,970 bench, chalcocite predominates (Lynch, 1966).

The Lavender Pit ore body at Bisbee contains a chalcocite blanket 50 to 400 feet thick, which dips easterly and is essentially conformable to the erosion surface on which the Glance Conglomerate (Lower Cretaceous) was deposited. The leached zone separating the conglomerate and ore body contains practically no copper; here is an example of supergene enrichment that occurred in Jurassic time. Intrusive breccias, concentrated more or less in the interior of the intrusive complex, contain chalcoite ore in the upper part, grading in depth to hypogene sulfides mixed with only a little chalcocite. The copper ore in the intrusive (?) breccia on the south margin of the pit, consists of sporadic irregular lenses of rich chalcopyrite and bornite ore which grades outward into disseminated ore with little supergene enrichment. Much of the ore in the eastern part of the pit consists of typical, supergene, sooty chalcocite that replaces shattered grains of pyrite (Bryant and Metz, 1966).

Underground mining at Bagdad started in a chalcocite blanket ranging from a few feet to 180 feet in thickness; the base of the blanket was irregular, owing to its greater thickness along fault zones. The leached capping ranged from 0 to 400 feet in thickness, and the base of this zone sloped gently northward beneath a cover of gravels and lava flows. The southern margin of the leached zone and chalcocite blanket are truncated by the present erosion surface proving that the enrichment took place during an earlier erosional period. Ore in the chalcocite zone ranged from 1 to 3 percent copper. At the present time lower-grade ore mined in the open pit was in a chalcocite blanket that is largely hypogene chalcocite (Anderson and others, 1955).

The San Manuel deposit is a mixture of supergene oxide and sulfide and hypogene sulfide. The mine is of great economic importance because of the large volume of hypogene ore, but supergene enrichment is important in the upper levels, diminishing downward and fading into the hypogene ore body. As of January 1, 1962, the sulfide ore reserves were 457,907,000 tons with a grade of 0.747 percent copper (Thomas, 1966).

The Mission deposit in the Pima district was covered by a pediment blanket of sand and gravel averaging about 200 feet in thickness. Hypogene sulfides generally appear within 50 feet of the bedrock surface and are overlain by a thin veneer of supergene chalcocite.

Chalcopyrite and pyrite are widely disseminated in the silicified limestone and altered sandstone and siltstone, but the Mission ore body represents only the part where copper concentration is sufficiently high and located so it can be mined by an open-pit operation. Locally, large pods of chalcopyrite-bearing ore contain 5 to 15 percent copper, but lower copper content is associated with a lower total sulfide content in the mineralized rocks, or by an increase in the pyrite-chalcopyrite ratio. The average grade is typical of other porphyry copper deposits in the Southwest (Kinnison, 1966).

The Mission, Pima, and adjacent Banner-Anaconda deposits are part of the same major ore zone and are similar to one another in all essential respects. The Twin Buttes deposit in the southeastern part of the district also appears to be similar to the Mission deposit. These deposits are all associated with weakly mineralized quartz monzonite porphyry and are regarded by some geologists as contact metamorphic deposits. The Esperanza deposit, on the other hand, is a more “typical” porphyry copper deposit in that quartz monzonite porphyry is the favored host rock for both hypogene and supergene metallization (Lynch, 1966).

The New Cornelia mine at Ajo is unique among the porphyry copper deposits in that most of the ore deposit consists of hypogene chalcocite and bornite. A little supergene chalcocite was formed during the middle Tertiary, and remnant of this type of ore are exposed in the southern part of the ore body. Because of the low content of pyrite in the major part of the deposit, oxidation of the chalcopyrite-bornite ore produced insufficient sulfuric acid to favor extensive migration of the copper. Instead, it was deposited in place as copper carbonate, forming a capping of carbonate ore above the hypogene sulfides (Dixon, 1966).

ALTERATION

A porphyry copper deposit is formed essentially by hydrothermal (hot water) solutions rising through shattered rocks. Dissolved copper, molybdenum, and sulfur were deposited as sulfide minerals in the porous fractured zones, in part as disseminated grains, and in part as fracture fillings. In most deposits, iron for the chalcopyrite and pyrite is derived from the host rock; in some exceptional cases, iron is brought in or redistributed by the hydrothermal solutions.

Alteration of the host rocks takes place at the time of deposition of the sulfide minerals. Studies of altered rocks in and near the porphyry copper deposits are helpful for exploration geologists to evaluate the economic potential of mineralized ground where the different types of alteration can be recognized at the outcrop or in drill cores. Creasey, (1966) has recognized five types of alteration: (1) propylitic, (2) argillic, (3) potassic, (4) quartz-sericite and, (5) lime silicate.

The propylitic type is characterized by abundant lime-bearing minerals such as calcite and epidote. These minerals, with chlorite, talc, and kaolinite, form various mineral assemblages at the fringes of the porphyry copper deposits.

Argillic alteration is characterized by clay minerals. Muscovite, quartz, and the sulfide minerals, pyrite and chalcopyrite, are commonly present. Argillic alteration can develop by supergene alteration...
that is characteristic in much of the leached capping and in the chalcopyrite band zone formed by supergene enrichment. If pyrite and chalcopyrite are absent in rocks showing argillic alteration, it may be difficult to distinguish hypogene from supergene argillic alteration.

Potassic alteration is characterized by the assemblage muscovite-biotite-K-feldspars. Muscovite also occurs in the propylitic and argillic alterations; thus it has no special significance, but it is always present with biotite and K-feldspar. The hydrothermal biotite occurs as rims around relict K-feldspar and albite and in veins with or without quartz. Chalcopyrite is widespread in the potassic alteration; at Ajo, Bagdad, and San Manuel, the copper content in the zones of potassic alteration is ore grade without benefit of supergene enrichment, but in the ore deposits where argillic alteration prevails, such as Morenci and Castle Dome, the primary mineralized rock is not ore grade, and supergene enrichment is necessary to make ore.

Quartz-sericite alteration is marked by a quartz-sericite-pyrite assemblage and an absence of clay and K-feldspar. This type of alteration is present at Castle Dome, Morenci, Ray, Silver Bell, and Bisbee (Lavender Pit), and copper is present with this alteration at Morenci and Bisbee.

The lime-silicate alteration is marked by an assemblage of lime-silicate minerals, such as garnet, epidote, diopside, tremolite, etc., in the contact zone of calcareous rocks and granitic porphyry.

The importance of lime-silicate alteration has been emphasized by the development of the ore bodies in the Pima district where much of the ore is associated with this type of alteration. The classic interpretation has been that silicated limestone was formed by contact metamorphism or pyrometasomatism related to the intrusive rocks, and that the silicates were introduced later in Stage 1 and 2 sericite stage. It is suggested that the lime-silicate alteration was produced by hydrothermal solutions at the same time as the argillic and potassic alteration occurred.

**Replacement Deposits in Limestone**

Important copper ore bodies in Arizona have been formed by the replacement of favorable limestone beds by copper sulfide minerals, chiefly chalcopyrite and bornite, accompanied by some pyrite. These deposits formed in favorable limestone beds at the margins of Laramide stocks or not far from such intrusive masses. The source of the copper, iron, and sulfur in these deposits is probably related to hydrothermal solutions given off from the adjacent or nearby crystallizing igneous intrusive masses, or from deeper chambers that supplied the molten material to form these igneous rocks. In other words, hydrothermal solutions of essentially the same kind that formed the porphyry copper deposits are considered to be the source of these replacement deposits.

The Christmas deposit, 22 miles south of Globe (fig. 18, No. 16) and the Copper Queen at Bisbee (fig. 18, No. 28), are examples of this important type of copper deposit. Similar replacement deposits occur near the Magma vein at Superior (fig. 18, No. 8).

**Copper Queen Mine Deposits**

The Sacramento Hill stock at Bisbee is the focus of an area of replacement deposits in the district. The east-trending Dividend fault splits the stock and the Paleozoic sedimentary rocks that are the hosts for the replacement deposits on the south side of the fault. A horizontal projection of the replacement ore bodies shows a semi-circular arrangement south of the Sacramento Hill stock, with the ore bodies radiating outward like spokes of a wheel as a result of concentration of ore along fracture and fault zones (Bryant and Metz, 1966).

Copper ore occurs in all of the Paleozoic limestones, but the most productive have been in the upper half of the Abrigo Limestone (Cambrian), all of the Martin Limestone (Devonian), and the lower half of the Escabrosa Limestone (Mississippian). The favorable formations are brittle and tend to shatter under stress.

The ore deposits in the Abrigo Limestone are cigar shaped and appear at the intersection of a favorable bed and some controlling fracture. The vertical dimensions are small in comparison with the horizontal dimensions. The Martin Limestone is uniformly friable, with composition ranging from shaly limestone to highly dolomitic limestone to pure limestone. The ore deposits in the Martin are more football shaped, with the vertical dimensions greater than the horizontal, and the long axis follows the intersection of a favorable limestone zone with a fracture. The productive zone of the Escabrosa is a massive crinoidal limestone containing chert beds at the top. The ore deposits are pipe-like with vertical dimensions greater than the horizontal. They are localized at intersecting fracture systems, in breccia zones that formed by igneous intrusion, and along strong fracture zones.

Much of the ore is closely associated with porphyry dikes and sills and intrusive breccias. In places, breccia forms the wall of the ore body; in other places it cuts through the ore as a barren dike or sill; and in some places, the breccia is completely replaced by copper ore. The sizes of the individual ore bodies are quite diverse, ranging from a few thousand to more than a million tons. Possibly two-thirds of the production has been from ore bodies of 25,000 tons or less.

The copper ore bodies, consisting largely of chalcopyrite and bornite, are associated with larger low-grade bodies of siliceous pyrite. In places, the copper ore is above and, in others, it is peripheral to the siliceous pyrite, but in some scattered places it is in the pyritic mass.

Oxide ore bodies were the chief source of copper in the early days of mining but production from them today is small. Typically, the oxide copper minerals were peripheral to masses of ferruginous silica; normally there was little migration of copper during oxidation. Upgrading was the result of leaching of soluble products. The ore minerals are largely malachite, azurite, delafossite, cuprite, chalcocite, and native copper (Bryant and Metz, 1966).

**Christmas Mine Deposits**

The Christmas mine was an intermittent producer of copper starting in 1905, and by the end of 1933, production totaled more than 24,000 tons. In 1939, the mine started operating under a lease to the Sam...
Knight Mining Lease, Inc. and by the end of 1943, an additional 2,200 tons of copper were produced (Peterson and Swanson, 1956). Inspiration Consolidated Copper Co. acquired the property in 1954 and after considerable exploration and development, started production in 1962.

The ore bodies are in a thick series of gently dipping Paleozoic limestone series in age from Devonian to Permian (?). Intrusion of a small quartz diorite stock into the limestones caused contact metamorphism at the margins. In the Naco and Escabrosa Limestones, garnet and calcite are the principal contact-metamorphic minerals, along with small amounts of epidote, wollastonite, idocrase, chlorite, and serpentine. In the Martin Limestone, the lower beds are highly altered to serpentine, diopside, tremolite, and a little garnet. The numerous steeply dipping stringers and seams of sulfide minerals that cut the lime-silicate minerals indicate that the copper sulfides were introduced after metamorphism. The mineralizing solutions moved upward along fracture zones near the quartz diorite contact and formed extensive replacement deposits at intersections with favorable beds in the metamorphosed limestones (Eastlick, 1968).

The principal hypogene minerals are chalcopyrite, bornite, magnetite, pyrite, sphalerite, and pyrrhotite. Oxidation is almost complete above the 300 level and extends locally below the 800 level. The supergene minerals include chalcocite, native copper, copper oxides, and copper carbonates (Eastlick, 1968).

Early production came largely from ore bodies in the Naco Limestone, and a few have been mined from the Escabrosa Limestone (Peterson and Swanson, 1956). Inspiration Consolidated Copper Co. has been mining extensive ore bodies in the lower part of the Martin Limestone (Devonian). These lower limestones are consistently mineralized along the intrusive contacts. Where the intensity of metamorphism and mineralization was greatest, ore bodies extend upward into the lower part of the massive limestones in the middle member of the Martin. Laterally, the ore bodies grade from a pyrite-chalcopyrite zone near the intrusive borders, to a chalcopyrite-bornite intermediate zone, and to a pyrrhotite-pyrite-sphalerite-chalcopyrite outer zone. Vertically, in thick ores bodies, pyrite-chalcopyrite and sphalerite border a chalcopyrite-bornite central zone (Eastlick, 1968).

Veins

Veins are tabular bodies of ore minerals and associated nonmetallic minerals (gangue) that generally dip steeply and are found in a variety of rocks. Most of the copper-bearing veins in Arizona are related in time and space to Laramide stocks and dikes, and many contain lead and zinc and other metals in addition to copper. These veins were formed by hydrothermal solutions that arose along faults and fissures, deposited gangue and ore minerals along the walls and between rock fragments in fault zones, and also replaced rock fragments and favorable rocks adjacent to the faults or fissures. Important copper production has come from two vein systems in Arizona, the Old Dominion, at Globe, and the Magma at Superior.

In the early history of the Globe-Miami district, copper-bearing veins yielded nearly 500,000 tons of copper and more than $9 million in gold and silver, largely from the Old Dominion vein system. This system is only one of several vein systems to the northeast of Globe, all striking essentially northeast and dipping, with few exceptions, to the southeast. The Old Dominion vein system can be traced for 8,000 feet on the surface, and it has been developed for an additional 4,200 feet at the western end under a cover of younger rocks. To the east, the Iron Cap vein faults may be an extension of the Old Dominion vein system; these two have been developed for 3 miles, and were highly productive for 2.5 miles (Peterson, 1969).

The Old Dominion vein system formed largely by replacement of rock fragments (breccia) in the fault zone as well as replacement of adjacent wall rocks along the faults and fissures. The wall rocks are Precambrian (Apache Group) and Paleozoic sedimentary rocks containing appreciable masses of diabase. The displacement of these rocks along the fault zone is generally several hundred feet, and the longest and most continuous ore bodies are along faults or segments of faults having relatively large displacement. The character and volume of vein material differs from place to place, according to the kind of rocks in the wall. The Paleozoic limestones along the intrusive borders are most readily replaced and commonly contain thick lenses of rich ore. Where diabase forms both walls of the vein faults, the vein generally is narrow (Peterson, 1962). The hypogene minerals in the vein system are largely chalcopyrite, bornite, pyrite, quartz, and specular hematite. Early mining was in oxidized ore and supergene chalcocite ore, which extended southwest under a volcanic cover. The supergene enrichment occurred about middle Tertiary time, prior to the formation of the volcanic cover, similar to the history of the supergene blanket in the Inspiration-Miami ore body. The enriched chalcocite ore in the western part of the mine grades downward into primary ore of good grade, and in places continues as much as 800 feet vertically before changing into low-grade pyritic material (Peterson, 1962).

The Magma mine has produced more than 750,000 tons of copper; the grade of the ore from 1915 to 1964 has averaged 5.69 percent copper, and 1.93 ounces of gold, and 0.031 ounces of silver. The bulk of the past production has come from the Magma vein but most of the recent production has come from replacement deposits in limestone near the veins (Hammer and Peterson, 1968).

The east-trending Magma vein, and its splits or branches, is the chief mineralized structure in the area east and northeast of the town of Superior. This vein has been opened for more than 10,000 feet along the strike. In the upper levels, it dips about 65° N., and on the lower levels about 80° S. The vein cuts Precambrian and Paleozoic rocks which include schist, diabase, quartzite and limestone. The vertical displacement along the mineralized fault ranges from 350 to 450 feet, and suggests some rotational movement. The ore-bearing hydrothermal solutions may have come from the same source as the stock of Schultze Granite, southwest of Miami, which is Laramide in age (60 m.y.) (Hammer and Peterson, 1968).

The vein consists of quartz and sulfide minerals that have replaced gouge and wall rock. The maximum length of continuously stoped ground is 2,200 feet, and the vein thickness ranges from less than 1 foot to more than 50 feet. Chalcopyrite, bornite, tennantite (Cu₆As₃S₈), chalcocite, digenite (Cu₆S₈) and sphalerite are the chief ore minerals.