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STRATIFORM COPPER DEPOSITS OF THE MIDCONTINENT REGION, A SYMPOSIUM

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Symposium Co-chairmen:

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CONTENTS

	<i>Page</i>
Introduction to the Symposium <i>Kenneth S. Johnson</i>	1
Permian Copper Shales of Southwestern Oklahoma <i>Kenneth S. Johnson</i>	3
Geology and Mining Operations at the Creta Copper Deposit of Eagle-Picher Industries, Inc. <i>Paul R. Dingess</i>	15
Sabkha and Tidal-Flat Facies Control of Stratiform Copper Deposits in North Texas <i>Gary E. Smith</i>	25
Microscopy of Copper Ore at the Creta Mine, Southwestern Oklahoma <i>Richard D. Hagni and Delbert E. Gann</i>	40
Mineralogy and Microtextures of Sulfides in the Flowerpot Shale of Oklahoma and Texas <i>Albert L. Kidwell and Richard R. Bower</i>	51
Geochemistry and Petrology of Some Oklahoma Red-Bed Copper Occurrences <i>Richard P. Lockwood</i>	61
Geochemical Exploration for Red-Bed Copper Deposits in North- Central Oklahoma <i>Zuhair Al-Shaieb and Richard R. Heine</i>	69
Copper Occurrences Associated with Permian Rocks in South- Central Kansas <i>Truman C. Waugh and Lawrence L. Brady</i>	76
A Comparison of Selected Sandstone Copper Deposits in New Mexico <i>Dennis J. LaPoint</i>	80
Red-Beds and Copper Deposits—Why the Association? (Abstract only) <i>James D. Vine and E. B. Tourtelot</i>	97
Central European Versus South-Central U.S.A. Geologic Settings of the Permian Basins and Associated Copper Mineralization (Abstract only) <i>Jan Krason</i>	98
The Geology, Exploration, and Development of the Stratiform Copper Deposit Located Northwest of Crowell, Texas (Abstract only) <i>Howard G. Schoenike and Raul A. Zeballos</i>	99

STRATIFORM COPPER DEPOSITS OF THE MIDCONTINENT REGION, A SYMPOSIUM

INTRODUCTION TO THE SYMPOSIUM

Kenneth S. Johnson¹

Copper is known to occur in sedimentary rocks at hundreds of localities in the Midcontinent region. Most of these occurrences are referred to as stratiform, because they are layered mineral deposits. The deposits are small, typically, and the copper content ranges from a few tenths of a percent to more than 10 percent in portions of some deposits. So far, we know of only a few places in the Midcontinent with sufficient tonnage of ore-grade material to warrant possible commercial production. But inasmuch as stratiform copper deposits contain about 30 percent of the world's copper resources, they represent an important class of ore deposits.

In order to promote understanding of the geology, distribution, and economic potential of deposits in this part of the country, the symposium "Stratiform-Copper Deposits of the Mid-Continent Region" was held March 8, 1974, as part of the South-Central Section meeting of The Geological Society of America. Sessions were held at Oklahoma State University, Stillwater, Oklahoma, and were attended by 125 persons. The Oklahoma Geological Survey has published this volume in order to bring the results of the symposium to the attention of those who can conduct or encourage further research and exploration on stratiform-copper deposits. Twelve papers were presented at the meeting: 9 of the papers are published here, along with abstracts of the 3 that are not available for publication.

A stratigraphic correlation chart has been prepared (fig. 1) to show the relationships of Permian units as discussed by the various authors of this symposium. The nomenclature as proposed by the authors has been incorporated into the generalized stratigraphic column for each state to enable correlation between study areas. No attempt has been made to resolve differences in nomenclature. The stratigraphic column for New Mexico (fig. 1) relates to the paper by La Point; the Texas column relates to the paper by Smith; the Oklahoma column relates to the papers by Al-Shaieb and Heine, Dingess, Hagni and Gann, Johnson, Kidwell and Bower, and Lockwood; and the Kansas column relates to the paper by Waugh and Brady.

A major change has occurred since the meeting. In 1975, Eagle-Picher Industries, Inc., closed its open-pit copper mine and mill at Creta in southwestern Oklahoma. The mine closing, according to company officials, resulted from lower copper prices and higher production costs. After reaching a record domestic price of about 87 cents a pound for electrolytic copper in June, July, and August 1974, the price of copper fell to about 63 cents a pound in March 1975 and remained at that level for about 1 year. The price reduction resulted from a copper surplus caused by the construction slump that began early in 1974 and accelerated during the second half of the year.

Rising production costs were standard for the mining industry during 1974-75; expenses for labor, materials, and mining operations were all higher at Creta. In ad-

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dition, increased costs for smelting the copper concentrate in El Paso reduced the return to Eagle-Picher. Higher wages, more expensive materials, and the addition of pollution-control devices to minimize adverse environmental effects from the smelting of copper-sulfide ores combined to increase smelter costs.

Mining at Creta ceased February 23, and the 1,000-ton-per-day mill closed March 28. The future of the mine is undecided, but,

inasmuch as there are still reserves on the property, it is possible for the mine to reopen if the demand for copper and the price of copper increase.

REFERENCE CITED

McKee, E. D., Oriel, S. S., and others, 1967, Paleotectonic maps of the Permian System: U. S. Geological Survey Miscellaneous Geologic Investigations Map I-450, 164 p.

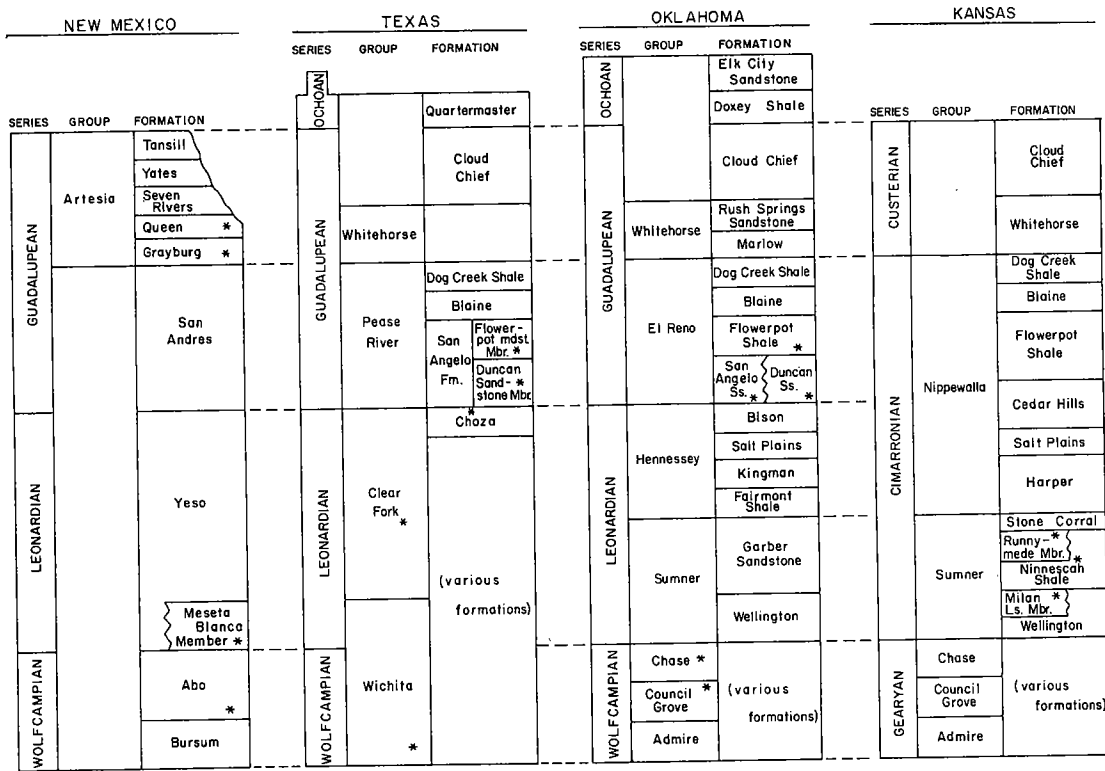


Figure 1. Generalized columnar sections showing stratigraphic relations of Permian strata discussed in various papers of this symposium. Modified from McKee and Oriel and others (1967, table 1) and the authors of this symposium. Asterisk (*) shows copper occurrence reported in symposium.

PERMIAN COPPER SHALES OF SOUTHWESTERN OKLAHOMA

Kenneth S. Johnson¹

Abstract—Many stratiform copper deposits are known in Permian shales and sandstones of western Oklahoma, but the most important ones are two copper-bearing shales in the Flowerpot Shale in exposures near Creta and Mangum in the southwestern part of the State. The two copper shales commonly range in thickness from 6 to 18 inches (15-46 cm), and their grade is 0.5 to 4.5 percent copper. The Creta deposit is being strip mined; it averages 7 inches (18 cm) thick, and the mined ore is about 2.3 percent copper. The Mangum deposit is currently under development; it averages about 14 inches (36 cm) thick and about 1 percent copper.

The flat-lying ore beds are medium-gray, laminated, silty shales containing chalcocite as the primary ore mineral and malachite at and near the outcrop. They are interbedded with red-bed clastics and evaporites deposited on the east side of the broad epicontinental Permian sea that covered much of the southwestern United States. The two copper shales extend 3 to 6 miles (5-10 km) along the outcrop. They are several feet apart, stratigraphically, and their exposures are about 15 miles (24 km) apart.

The host shales apparently were deposited in a brackish-water or shallow-marine environment, and syngenetic or early diagenetic copper mineralization may have occurred by replacement of pyrite.

INTRODUCTION

Permian strata crop out over an area of about 30,000 square miles (78,000 km²) in central and western Oklahoma and have an aggregate thickness of 5,000 feet (1,524 m). They consist mostly of gently dipping reddish-brown shales, siltstones, and sandstones, interbedded with gypsums and thin dolomites on the outcrop; thick sequences of salt (halite) are interbedded with red beds and gypsum in the subsurface. Copper minerals in these red beds were noted during exploratory expeditions around the middle of the 19th century (Marcy, 1854), and Bulletin 1 of the Oklahoma Geological Survey (Gould and others, 1908, p. 78), published one year after statehood, refers to widely scattered Permian copper occurrences.

Since then the publications of Fath (1915), Fischer (1937), Merritt (1940), and Stroud and others (1970), along with records of the Geological Survey, have pointed out more than 50 copper-bearing localities in the broad region of Permian outcrop. The pattern of occurrence is generally similar throughout the region. Chalcocite and malachite are the most common minerals, occurring in sandstone and shale as en-

crustations, impregnations, veinlets, and small nodules. Chalcocite also occurs in the form of chalcocitized wood. In spite of these widespread occurrences in central and western Oklahoma, the few early attempts at mining were financial failures, owing to the lean grade of the ore and small size of the deposits.

An entirely new concept was introduced in 1962 with discovery of malachite disseminated in a persistent 6-inch-thick (15 cm) shale bed in the Flowerpot Shale, along an outcrop distance of 3 miles (4.8 km), at Creta, in Jackson County, Oklahoma. Initially called the "lower copper bed," the deposit has a copper content ranging from 2.6 to 4.5 percent, and it was the first reported occurrence of a bedded copper shale in Permian strata of the United States. Credit for discovery of the Creta deposit goes to Kenneth E. Smith, formerly of Vinson, Oklahoma, who joined William E. Ham and me in field studies and preliminary evaluation of test results late in 1962 and early in 1963.

Results of the outcrop mapping, sampling, and analyses of the Creta deposit were first released by the Oklahoma Geological Survey as an open-file report on August 1, 1963, and the preliminary report on the deposit was published on February 18, 1964 (Ham and Johnson, 1964).

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Eagle-Picher Industries, Inc., which began field studies of the area in the summer of 1963, announced, on March 10, 1965, its intent to establish a copper mill at the Creta site and to mine a deposit of copper shale containing approximately 2 percent copper at the rate of 500 tons of copper ore per day. The company had determined by extensive drilling that chalcocite was the principal ore mineral under moderate overburden and that the ore bed could be mined by stripping. The mill was built for the production of copper sulfide concentrates by flotation. The first concentrates were shipped in October 1965, to American Smelting and Refining Company in El Paso, Texas. Present rated mill capacity is about 1,000 tons of copper shale per day. (See report by Dingess, elsewhere in this volume, for full discussion of Eagle-Picher mine.)

The discovery of Creta set off a wave of prospecting in Permian beds throughout Oklahoma and adjoining parts of Texas and Kansas. To date, the Creta deposit is the only copper shale being mined in the region, but a second discovery was made early in 1965 about 15 miles (24 km) north of Creta, near the town of Mangum, by Lobaris Copper Company. The Mangum deposit is a copper shale nearly identical to that at Creta, but it generally is more oxidized and occurs in a slightly higher bed of the Flowerpot Shale. Test pits have been dug and preliminary concentration tests made on the ore, and a mill is being built on the properties. Since 1965, several other significant discoveries in Texas, Oklahoma, and Kansas attest the possibility that other stratiform copper deposits of the region may be brought into production.

Acknowledgments

For release of information about the Creta deposit, I am grateful to past and present officials of the Chemicals and Metals Division of Eagle-Picher Industries, Inc., including C. O. Dale, D. C. Brockie, P. R. Dingess, P. Jones, and J. Thompson. Similar information about the Mangum deposit was kindly supplied by J. L. Hoard, R. H. Allen, and J. H. Warren, all of Lobaris Copper Company. Special acknowledgment is made to the late William E. Ham, with whom many of these data were collected.

REGIONAL SETTING FOR COPPER DEPOSITS

Paleogeography

Southwestern Oklahoma is on the east side of the Permian basin, a broad epicontinental sea that covered much of southwestern United States during the middle of Permian time (fig. 1). The sea was approximately 400 miles wide and 700 miles long (644 km by 1,127 km), and it was connected with the open ocean to the south via the Delaware and Midland basins of west Texas and adjacent New Mexico. Surrounding the sea were semiarid or arid lands of low relief from which clay, silt, and sand were eroded.

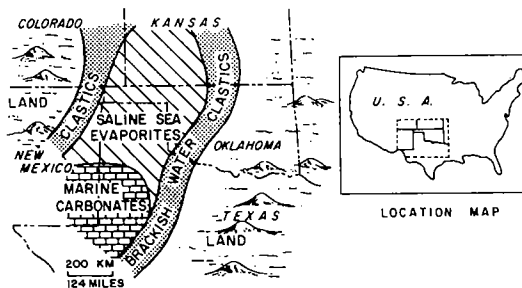


Figure 1. Paleogeography and principal facies in Permian basin of southwestern United States during evaporite deposition during the middle Permian.

Epirogenic movements caused slow but continual sinking of the crust beneath the inland sea and permitted accumulation of thick sequences of reddish-brown shales and interbedded evaporites. The Wichita uplift, part of which is now exposed as the Wichita Mountains, was a more stable crustal block extending westward beneath the sea (fig. 2). It subsided more slowly than nearby areas, and it partially separated the inland sea in Oklahoma into the Anadarko basin (north) and the Hollis basin (south). Both the Creta and Mangum copper districts are on the east side of the Hollis basin.

The copper-bearing Flowerpot Shale, as well as the underlying San Angelo (Duncan) Sandstone and overlying Blaine Formation, was deposited in southwestern Oklahoma in and adjacent to a transgressing sea whose shoreline retreated to the southeast. Lateral

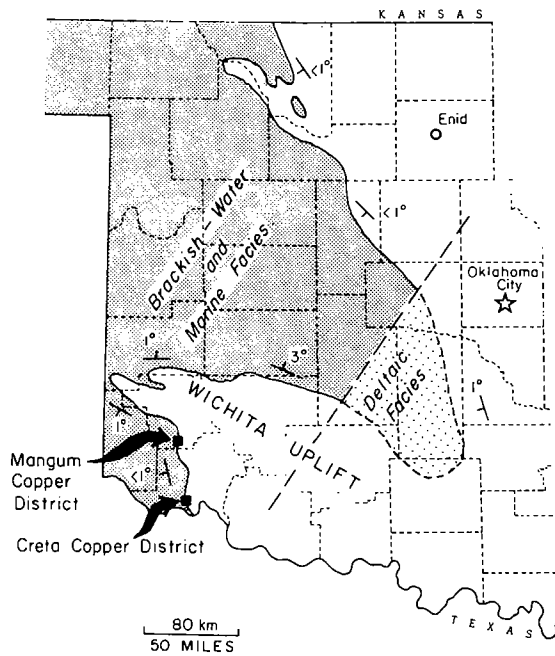


Figure 2. Map of western Oklahoma showing distribution and facies of upper Flowerpot strata. The two principal copper shales at Creta and Mangum are in brackish-water and marine facies.

facies changes from east to west (from land to sea) are: 1) deltaic and alluvial sandstones and mudstone conglomerates interbedded with shale; 2) brackish-water and marine reddish-brown shale with thin beds of gypsum and siltstone; and 3) an evaporite facies of interbedded gypsum, shale, salt, and dolomite. In the Hollis basin, the San Angelo (Duncan) Sandstone represents the deltaic-alluvial facies, the Flowerpot Shale is the brackish-water and marine facies, and the Blaine Formation represents the evaporite facies (fig. 3). Each of these formations is 50 to 200 feet (15-60 m) thick.

San Angelo deltaic beds underlie most of the study area, whereas the deltaic equivalents (Chickasha Formation) of the Flowerpot and Blaine formations were deposited 25 to 50 miles (40-80 km) farther southeast and are now preserved only in the eastern end of the Anadarko basin (fig. 2). Clays and sands of the Flowerpot and associated formations were derived from the largely concealed Ouachita System of Texas and southeastern Oklahoma: the nearby Wichita Mountains were sufficiently buried by earlier Hennessey time that they con-

tributed little or no detritus to the Flowerpot.

Structure

Outcropping rocks in the Hollis basin are essentially flat lying. They are underlain by 3,000 to 12,000 feet (900-3,600 m) of Paleozoic sedimentary rocks resting unconformably upon a basement complex of Cambrian and Precambrian igneous and meta-sedimentary rocks. The full section of Paleozoic strata has been penetrated in oil and gas tests in both copper districts, and evidence of post-Middle Cambrian magmatic or hydrothermal activity here or elsewhere in southwestern Oklahoma is lacking. The nearby Wichita Mountains comprise granites, rhyolites, and gabbros emplaced in Middle Cambrian time, 525 to 535 million years ago (Ham and others, 1964). Sediments in the Hollis basin have been deformed only by block faulting and gentle folding, mainly during the Pennsylvanian Period, and undisturbed outcropping Permian rocks in both copper districts dip only 5 to 40 feet per mile to the west and southwest. No evidence of copper mineralization has been found associated with faults or folds.

Topography

Topography in the Creta and Mangum districts is similar and reflects the present-day semiarid climate (average precipitation is 24 inches, about 60 cm, per year). The soft Flowerpot Shale forms a plain of low relief, sparsely covered with short grass suitable for grazing a few cattle. Where an alluvial or colluvial veneer is present, the plain is flat, and wheat, cotton, and sorghum are grown. The upper part of the formation is locally dissected into badlands and is well exposed in the face of the Blaine escarpment, which rises to the west and southwest 100 to 200 feet (30-60 m) above the Flowerpot plain. The Blaine escarpment also is dissected and notably benched, with individual benches supported by flat-lying beds of gypsum and dolomite.

STRATIGRAPHY

Outcropping sedimentary rocks of southwestern Oklahoma are Permian in age (fig. 4) and consist mainly of flat-lying reddish-

brown shales interbedded with evaporites and sandstones. Several of the evaporite units are excellent marker beds, traceable throughout southwest Oklahoma and adjacent north-central Texas.

The maximum thickness of Permian strata in the Hollis basin is more than 4,000 feet, but this report centers on the 450 feet (135 m) of rock comprising the San Angelo, Flowerpot, and Blaine formations. These three formations are part of the El Reno Group (Scott and Ham, 1957) and are of late Leonardian (McKee and Oriol, 1967) or early Guadalupian (Dunbar, 1960) age.

San Angelo Sandstone

The San Angelo Sandstone consists of light-gray and reddish-brown sandstones, siltstones, and mudstone conglomerates interbedded with reddish-brown and greenish-gray shales. It has an interfingering contact with the overlying Flowerpot Shale and is a deltaic and alluvial deposit that grades into shale northwestward in both the

Hollis and Anadarko basins (fig. 3). The name San Angelo is applied to the unit in northern Texas and in Oklahoma south of the Wichita Mountains, whereas equivalent and similar strata north of the Wichitas are called Duncan.

Exposures of San Angelo strata on the east side of the Hollis basin are sparse, for the formation is largely concealed by alluvium and terrace deposits of the Salt Fork of the Red River. The thickness of the San Angelo in boreholes in western Jackson County is generally 55 to 70 feet (17-21 m).

Copper mineralization had been noted in the formation locally, but not in the poor exposures of Jackson County. Fifty miles northeast of Creta, in highways cuts west of Gotebo in Kiowa County, nodules and fine disseminations of malachite are present in the basal sandstone. In north-central Texas, copper is reported in the San Angelo at many localities (Richard, 1915; Beede and Christner, 1926; Fischer, 1937; Stroud and others, 1970; and Smith, elsewhere in this volume), with a mineralized zone at the base being most conspicuous.

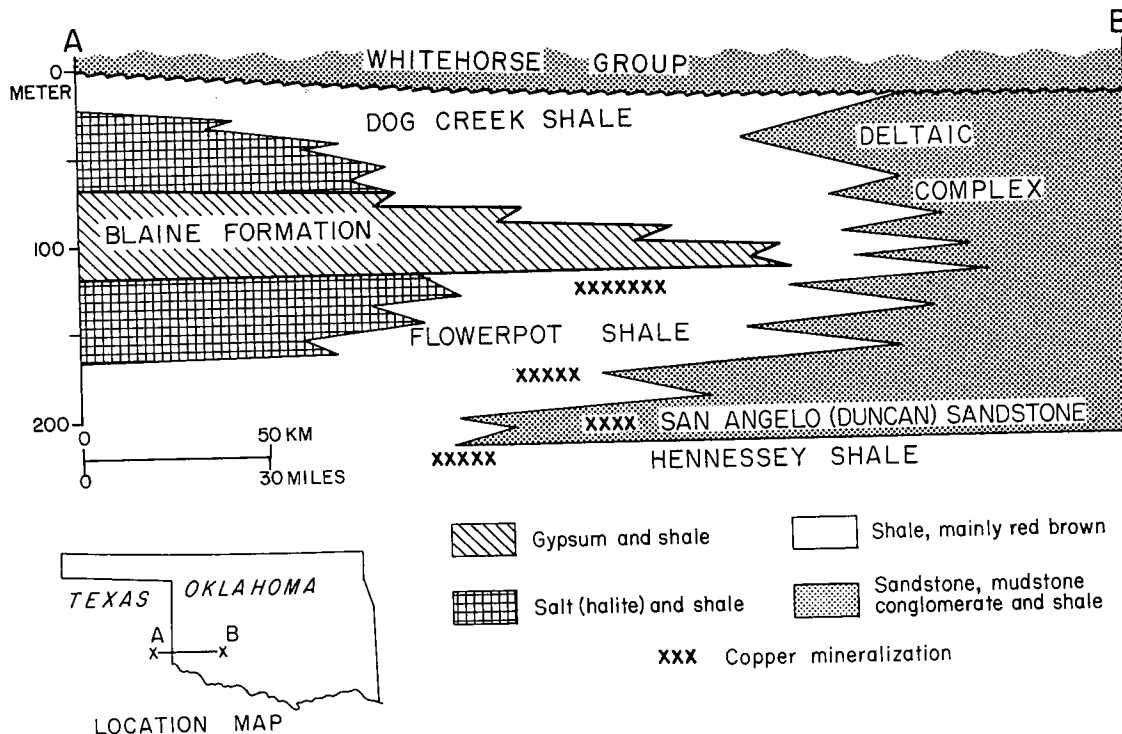


Figure 3. Stratigraphic cross section showing copper mineralization in Permian strata of southwestern Oklahoma and northern Texas.

Flowerpot Shale

The Flowerpot Shale, which contains the main copper shales, consists of reddish-brown shale with thin interbeds of gypsum, dolomite, siltstone, sandstone, and greenish-gray shale. It crops out in south-central Kansas, western Oklahoma, and north-central Texas (fig. 4). In subsurface to the west, the upper part of the formation contains several hundred feet of interbedded rock salt (halite) and salty shale. The formation's total thickness is about 185 feet (56 m) in the Creta and Mangum districts, and it ranges from 150 to 200 feet in nearby parts of the Hollis basin.

Most Flowerpot strata in western Oklahoma were deposited in marine or brackish water. Evaporite beds, each 0.1 to 4.0 feet (.03-1.2 m) thick, aggregate about 10 percent of the top half of the formation in both copper districts: gypsum makes up 80 to 90 percent of these thin evaporites, and the remainder is light-gray microgranular dolomite. Flowerpot strata in the Hollis basin undoubtedly graded southeastward into Chickasha-like deltaic and alluvial deposits that are now eroded.

Shales of the Flowerpot are typically reddish brown, blocky, slightly silty, gypsiferous, and lacking in megafossils. About 85 percent of the shale is reddish brown, and the remaining 15 percent is light gray, green gray, and medium gray. Reddish-brown beds are commonly 1 to 5 feet

thick, whereas gray beds are 0.1 to 2.0 feet thick and generally underlie thin evaporites.

Copper mineralization is chiefly in a copper-shale zone about 10 feet (3 m) thick and 30 to 40 feet below the top of the formation on the east side of the Hollis basin (fig. 5). This zone contains two ore beds, the Prewitt and Meadows copper shales, and several other lower-grade deposits. Mineralization in this zone extends discontinuously as far north and east as the Sentinel area, 25 miles (40 km) northeast of Mangum, and south into Texas (Stroud and others, 1970). Fay (1964) also reports malachite-stained dolomite about 10 feet below the top of the Flowerpot in northwestern Oklahoma. Three marker beds, the Chaney Gypsum Bed, the Kiser Gypsum Bed, and the Marty Dolomite Bed (ascending order), embrace 20 to 25 feet of upper Flowerpot strata, including the copper-shale zone.

Chaney Gypsum Bed.—The Chaney Bed is 1 to 4 feet of massive white gypsum that is 45 to 50 feet below the top of the Flowerpot in both copper districts. Strata between the Chaney Bed and the copper ores are mostly reddish-brown shales with thin crosscutting veins of satin spar gypsum.

Prewitt copper shale.—The Prewitt bed is a medium-gray gypsiferous and silty copper-bearing shale. It is 35 to 40 feet below the top of the Flowerpot and crops out southeast of Creta in southern Jackson County. Distinct laminations in the upper two-thirds of the bed set it apart from the blocky shales that characterize the Flowerpot. Its thickness ranges from 3 to 12 inches, averaging 8.5 inches (22 cm), and the grade is above 2 percent copper over most of its extent. It is now being strip mined by Eagle-Picher Industries, Inc. In earlier studies the bed was referred to as the "lower copper bed" (Ham and Johnson, 1964), but it is herein named informally for Ira C. Prewitt, the principal landowner of the deposit.

The Prewitt copper shale is 9 feet above the Chaney Gypsum Bed and 8 to 9 feet below the Marty Dolomite Bed (fig. 6). It is immediately below 0.5 to 0.8 foot of impure rock gypsum (caprock gypsum), and is 2 to 3 feet below a thin impure gypsum tentatively correlated with the base of the Kiser Gypsum Bed farther north (fig. 5). At the base of the Prewitt is 0.6 to 1.0 foot of blocky

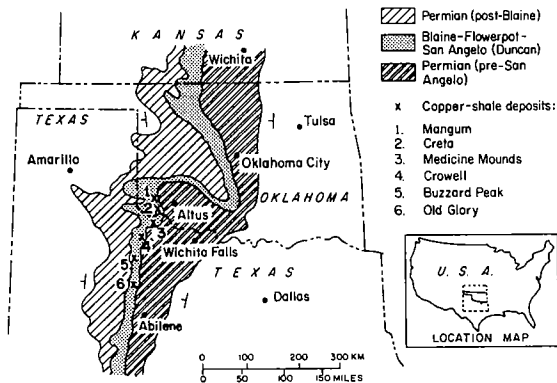


Figure 4. Map showing areal extent of Permian outcrops in western Oklahoma and adjacent parts of Kansas and Texas. The Flowerpot Shale and associated strata contain six significant copper-shale deposits in southwestern Oklahoma and north-central Texas.

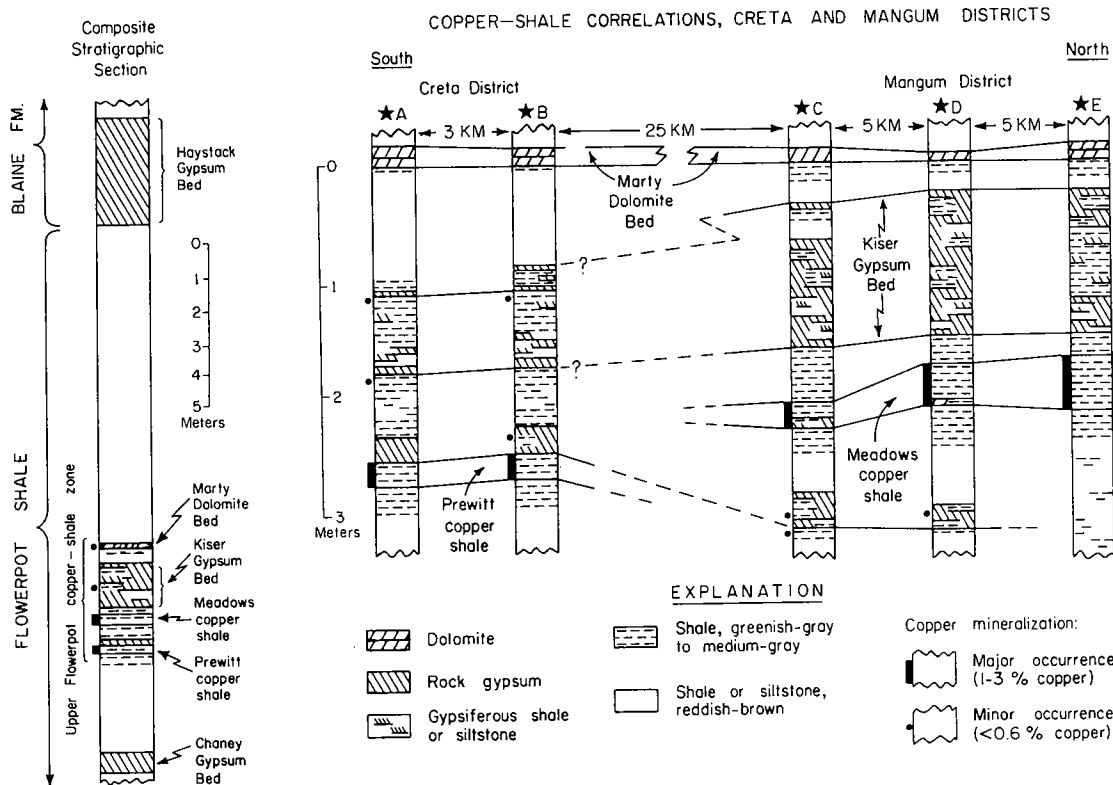


Figure 5. Stratigraphy of the upper Flowerpot copper shales in southwestern Oklahoma. Location of stratigraphic sections shown in figure 7 (A and B) and figure 9 (C, D, and E).

greenish-gray shale that, except for the low copper content, appears similar to the lower part of the ore bed. This shale grades down into reddish-brown silty shale with crosscutting satin spar veins.

Shales exposed at this stratigraphic position elsewhere in the Hollis basin show only slight mineralization or, most commonly, none at all. Strata closely related or equivalent to the Prewitt copper shale have malachite encrustations locally, in the area south of Mangum (fig. 5). These beds are a thin sequence of interbedded, impure gypsum and greenish-gray shale 2 to 3 feet below the Meadows copper shale.

Meadows copper shale.—The Meadows copper shale is a laminated, medium-gray, silty, copper-bearing shale herein named informally for J. N. Meadows, the principal landowner of the ore deposit. It is 30 to 35 feet below the top of the formation and crops out south of Mangum in southern Greer County. Elsewhere, shales at this stratigraphic level show little or no mineralization. The Meadows bed ranges

from 4 to 18 inches in thickness, averaging 14 inches (36 cm), and it is the middle part of a green-gray shale that is blocky and without significant copper at the top and bottom (fig. 5). The grade averages about 1 percent copper along the 6 miles (9.7 km) of outcrop. Lobaris Copper Company is currently working on milling techniques for developing the deposit.

The top of the Meadows bed is 0.5 to 1.5 feet below the Kiser Bed, and it is generally 5 to 7 feet below the Marty Dolomite Bed. The ore bed is commonly 10 to 12 feet above the Chaney Gypsum Bed.

The equivalent of the Meadows bed cannot be recognized at Creta, but most likely it is in the 2 feet of shale overlying the caprock gypsum. It is closely related, or in part equivalent, to a 6-inch-thick spore-bearing shale immediately below the Kiser Gypsum Bed west of Mangum (Wilson, 1962). Mineralization is lacking in shales equivalent to the Meadows or Prewitt beds at Wilson's locality (near the center of SE $\frac{1}{4}$ sec. 2, T. 4 N., R. 23 W.).

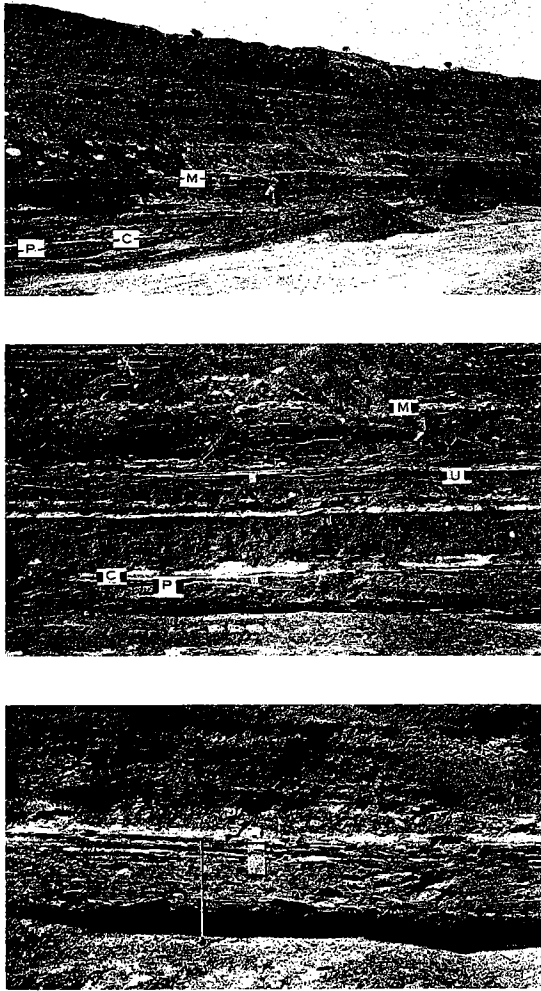


Figure 6. Photographs of copper shale and marker beds in upper part of Flowerpot Shale in highwall of Eagle-Picher Industries, Inc.'s mine at Creta.

Top: General view of 30-foot (9 m) face in NW¼ SW¼ sec. 3, T. 1 S., R. 22 W., showing Prewitt copper shale (P), and overlying caprock gypsum (C), in relation to Marty Dolomite Bed (M). Other rock exposed in face is mainly red-brown shale.

Middle: Close-up view in lower part of highwall (same locality as above) showing greater detail and stratigraphic relations of Prewitt bed, caprock gypsum, and Marty Dolomite Bed. Also shown is the noncommercial "upper copper shale" (U). Light-colored rock, except for the Marty Dolomite, is gypsum occurring either as beds of rock gypsum or as cross-cutting seams and veins of satin spar.

Bottom: View of Prewitt copper shale exposed in bulldozed face of strip pit in SW¼ sec. 15, T. 1 S., R. 22 W. Eight-inch-thick (20 cm) ore bed is covered by rectangular flag in center of photograph: upper part is dark-gray laminated shale cut by subhorizontal veins of satin spar; lower part is lighter greenish-gray blocky shale. Tape to left of flag is 2 feet (0.6 m) long.

Kiser Gypsum Bed.—In the Mangum district, the Kiser Gypsum Bed is 3 to 4 feet of interbedded impure gypsum, gypsiferous shale, and gypsiferous siltstone about 27 to 30 feet below the top of the Flowerpot. The bed caps a small bench at many places. The lower part of the bed is reddish-brown, whereas the upper part is gray. South of the Mangum district most of the gypsum grades into shale, and the Kiser is not easily recognized (fig. 5).

Marty Dolomite Bed.—A thin, persistent dolomite in the upper part of the Flowerpot is herein named the Marty Bed for exposures near the Marty siding on the railroad just east of Creta. The dolomite was earlier referred to as the "Kiser Bed" in the Creta area (Ham and Johnson, 1964), because it was considered equivalent or closely related to the Kiser Gypsum Bed, but stratigraphic relationships are better known (fig. 5) and this use of the term Kiser Bed is dropped. A type locality is designated as W½ sec. 3, T. 1 S., R. 22 W., where the bed is 0.5 foot of light-gray, microgranular, platy dolomite capping a conspicuous escarpment 10 to 15 feet high.

The Marty Dolomite Bed crops out on the east and north flanks of the Hollis basin and is typically 0.1 to 0.5 foot (0.03-15 m) of yellowish, tan, or light-gray, microgranular, platy dolomite. It is 25 to 30 feet below the top of the Flowerpot near Creta and is generally 26 to 28 feet below the top of the formation south of Mangum. In both districts, it is an excellent marker bed above the copper shales: it is 8 to 9 feet above the Prewitt bed and 5 to 7 feet above the Meadows bed. The Marty Dolomite Bed is considered the top of the upper Flowerpot copper-shale zone. Traces of copper are reported in the dolomite in several parts of the mine at Creta.

Blaine Formation

Overlying the Flowerpot is the Blaine Formation. It has been correlated in outcrops from south-central Kansas through western Oklahoma into north-central Texas. The Blaine consists chiefly of thick beds of pure gypsum interstratified with reddish-brown shale; thin beds of dolomite and greenish-gray shale typically underlie each of the gypsum beds. Evaporites in the Blaine were deposited during the maximum transgression of the sea, before its regression in

later Dog Creek time. The full thickness of the formation in the Hollis basin is 200 feet (61 m), and it comprises 9 persistent gypsum beds, each commonly 5 to 30 feet thick, separated by shales 1 to 30 feet thick. Dolomites underlying the gypsum beds are generally 1 to 2 feet (30-60 cm) thick.

In both copper districts the top half of the Blaine is eroded, leaving only the lower 75 to 115 feet. The normal thickness of individual gypsum beds is 5 to 15 feet, but locally they are partly or completely dissolved.

The Haystack Gypsum Bed at the base of the Blaine is massive white gypsum 10 to 15 feet thick. At its base, in the Creta area, is 0.1 to 0.8 foot of light-gray microgranular dolomite that has sparse bedding encrustations of malachite locally (just east of SW cor. sec. 23, T. 1 S., R. 22 W.). In northwestern Oklahoma, malachite encrustations are present in the basal Blaine dolomite and also in another thin dolomite higher in the formation (Fay, 1964).

COPPER-SHALE DEPOSITS

Copper is known in Permian shales and sandstones at more than 100 separate localities in Texas, Oklahoma, and Kansas. Although the number of occurrences of mineralization in sandstone is by far more abundant, the sites of shale mineralization are of greater economic significance (Ham and Johnson, 1964; Stroud and others, 1970; Johnson and Brockie, 1973; Dingess, this volume; and Smith, this volume). The first copper-shale discovery in the region was the Creta deposit in southwestern Oklahoma, and it is the only one now being mined (by Eagle-Picher Industries, Inc.). The Creta deposit has been investigated thoroughly. A find by Lobaris Copper Company, just south of Mangum, Oklahoma, is being investigated, and so are four significant copper shales in Texas (at sites near Medicine Mounds, Crowell, Buzzard Peak, and Old Glory; fig. 4).

Creta District—Prewitt Copper Shale

Preliminary outcrop study of the Creta deposit established that a 6-inch-thick (15-cm) copper-bearing shale in the upper part of the Flowerpot extended 3 miles (5 km) along

the outcrop, and that the grade ranged from 2.6 to 4.5 percent copper (Ham and Johnson, 1964). Subsequent core drilling and exploration by Eagle-Picher established that chalcocite is the primary ore mineral under moderate overburden (fig. 7) and that an ore body averaging 2.3 percent copper (undiluted) could be strip mined (Johnson and Brockie, 1973; Dingess, this volume).

The ore bed, called the Prewitt copper shale, is a medium-gray silty shale and mudstone containing chalcocite as the primary ore mineral and malachite and other oxidized copper minerals at and near the outcrop. It ranges in thickness from 3 to 12 inches and averages about 8.5 inches (22 cm). The Prewitt bed is about 40 feet below the top of the Flowerpot Shale and is about 8 feet below the thin but persistent Marty Dolomite Bed (figs. 5-6).

The ore bed consists of two basic lithologies: the upper 4- to 5-inch portion is laminated, thereby differing petrologically from other gray shales in the Flowerpot, whereas the lower 3 or 4 inches is blocky shale, generally resembling other shales in the Flowerpot. Silt laminae in the upper part of the bed commonly are 0.1 to 0.2 millimetres thick and constitute 10 to 20 percent of the unit. Thin-section study reveals that the ore bed consists mostly of microcrystalline clay minerals. Quartz grains, chiefly 10 to 40 microns in diameter, make up 10 to 20 percent of most of the samples. Much of the quartz floats in a clay matrix. According to Lockwood (1972, appendix 5), the laminated and blocky parts of the ore contain an average of the following mineral components: quartz (17 percent in laminated shale and 26 percent in blocky shale), gypsum (28 and 3 percent), illite (45 and 63 percent), chlorite (5 and 6 percent), and chalcocite (4 and 2 percent). Other analyses by the Oklahoma Geological Survey indicate that the ore bed also contains 0.1 to 3 percent carbonate minerals, chiefly dolomite and some calcite; the organic carbon content ranges from 0.09 to 0.56 percent and averages 0.3 percent, or about twice as much as in noncupriferous shales of the region.

Principal copper minerals in the Creta deposit are chalcocite (Cu_2S) and malachite ($\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$). Chalcocite, the primary ore mineral, occurs mainly as small grains (commonly 2 to 20 microns) disseminated in

the shale. Grains are also concentrated in some silt laminae in the upper part of the bed, and they also are concentrated in thin veins and fill small vugs in the blocky part of the bed. As seen in thin section, many of the grains have a cubiform outline and presumably are pseudomorphs after pyrite. Malachite and brochantite ($\text{CuSO}_4 \cdot 3 \text{Cu}(\text{OH})_2$) are oxidation products found on the outcrop and where the overburden is less than 10 to 15 feet. Malachite occurs as films and granules, and brochantite occurs with malachite in nodules locally present on the outcrop outcrop.

The Prewitt bed in the mined sulfide zone averages about 2.3 percent copper and ranges from about 0.5 percent to as much as

4.5 percent copper; the heads at the mill are about 2.0 percent copper. Metals present in low concentrations (Lockwood, 1972, appendix 6) include lead (10-50 ppm), silver (10-50 ppm), cobalt (10-50 ppm), nickel (30-60 ppm), uranium (50-100 ppm), vanadium (75-150 ppm), and zinc (150-400 ppm). Further examination of Lockwood's data indicates that lead values are a little higher in the ore bed than in the overlying and underlying barren shales, which contain only 0.1 to 0.3 percent copper, and, conversely, that the silver, zinc, cobalt, nickel, and vanadium concentrations are somewhat lower in the ore bed than in the adjacent barren shales. These observations apply in both the Creta and the Mangum deposits.

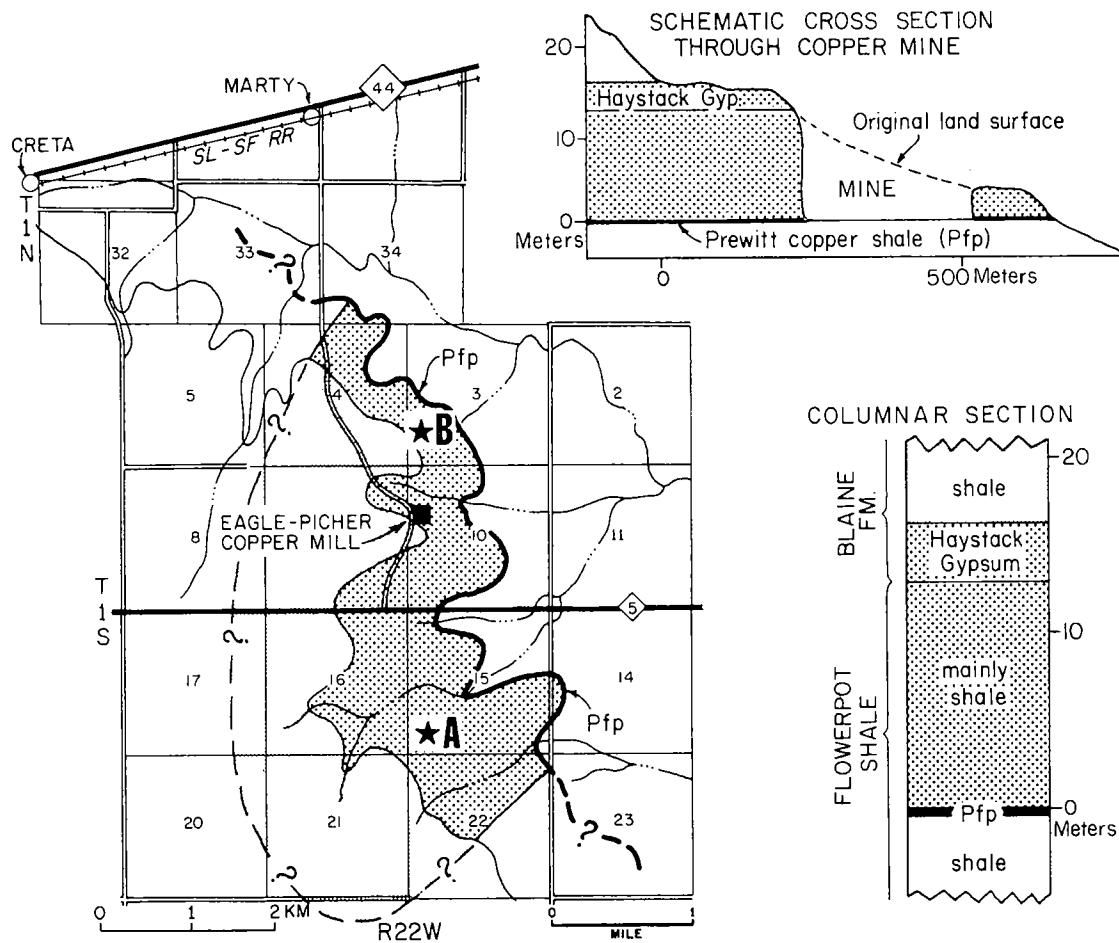


Figure 7. Schematic map, cross section, and columnar section showing principal features of Prewitt copper shale and overlying rock units at Eagle-Picher Industries, Inc.'s mine at Creta. Map shows areas where ore bed (6 to 12 inches, or 15-30 cm, thick and more than 0.5 percent copper) has shale and gypsum overburden of 0-50 feet (0-15 m) (dense stippling) and greater than 50 feet (15 m) (light stippling). Sites A and B show location (in mine highwall) of stratigraphic sections reported in figure 5.

Only copper is recovered in the mining and milling process, but a small amount of silver is recovered from the concentrates at the smelter. Another copper shale, just 5 feet above the Prewitt bed, is thinner (1 to 4 inches thick) and is lower in grade; it appears to be economically minable only in the extreme northern part of the reserve area.

Eagle-Picher began mining and milling operations in 1965. The present reserve area extends about 3 miles north-south and 1.5-2.0 miles east-west (fig. 7), although mineralized shale with some economic potential underlies a total area of some 12 square miles. Increasing depth of overburden becomes a limiting factor along the western edge of the reserve area. As much as 60 feet (18 m) of overburden has been removed in places. Strip mining is favored by the gentle westward dip of 10 to 20 feet per mile and the lack of faults or folds in the area (fig. 8). The company's 1,000-ton-per-day mill is designed to recover sulfide minerals and a portion of the nonsulfide minerals by flotation.

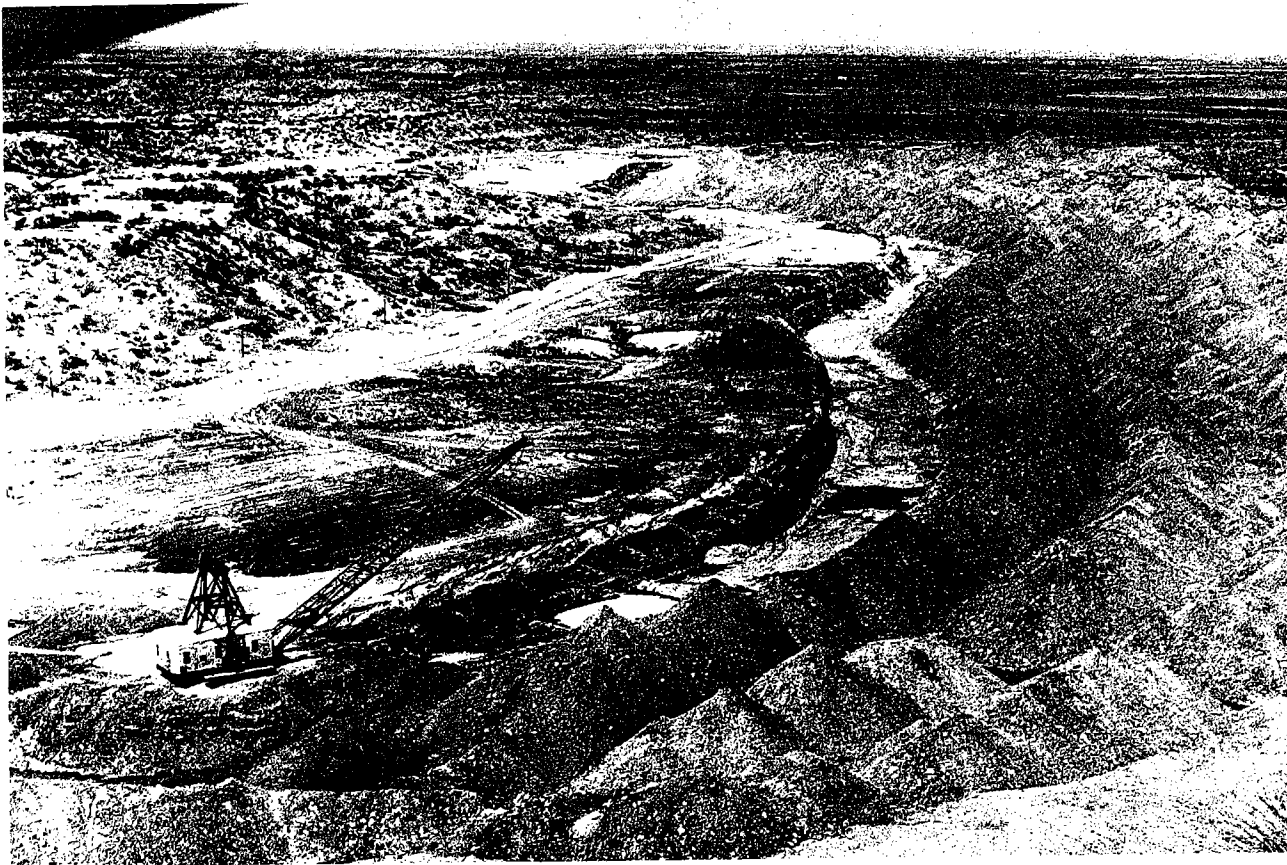
Mangum District—Meadows Copper Shale

The second major copper-shale discovery in Oklahoma was made in 1965 about 15 miles (24 km) north of Creta, near the town of Mangum, by Lobaris Copper Company. The Mangum deposit is similar to the Creta deposit, but it occurs in a slightly higher bed of the Flowerpot Shale.

The ore bed, the Meadows copper shale, is a medium-gray, laminated, silty, copper-bearing shale and mudstone. It is 30 to 35 feet below the top of the Flowerpot and about 6 feet below the thin Marty Dolomite Bed (fig. 5). The thickness of the Meadows bed ranges from 4 to 18 inches, averaging about 14 inches (36 cm), and it is the middle part of a green-gray shale that is blocky at the top and bottom and without significant copper. Mineralization in the Meadows bed extends about 6 miles north-south and as much as 3 miles east-west, and it probably underlies about 12 square miles (fig. 9).

Petrographically, the Meadows bed is somewhat similar to the Prewitt bed at

Figure 8. Oblique aerial photograph of Eagle-Picher copper-shale strip mine at Creta. Highwall shown is 40 feet (12 m) high. View looking northwest in SW¼ sec. 3, T. 15., R. 22 W.



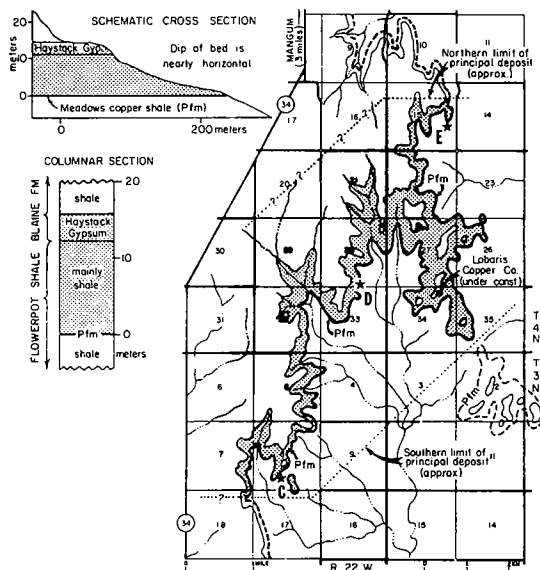


Figure 9. Schematic map, cross section, and columnar section showing principal features of Meadows copper shale and overlying rock units on Lobaris Copper Co. properties at Mangum. Map shows where copper shale (6 to 18 inches, or 15-45 cm, thick and more than 0.5 percent copper) has shale and gypsum overburden of 0-45 feet (0-14 m) (dense stippling) and greater than 45 feet (14 m) (light stippling). Sites C, D, and E show outcrop locations of stratigraphic sections reported in figure 5.

Creta. Lockwood (1972, Appendix 2) determined the following average mineral components: quartz (27 percent), gypsum (11 percent), illite (49 percent), chlorite (5 percent), and malachite (3 percent). More recent data show that organic carbon comprises an average 0.17 percent of the ore bed and that dolomite and calcite commonly make up about 5 to 10 percent of the bed (principally in a 1-inch-thick layer of crystalline dolomite near the base of the bed).

Malachite is the dominant copper mineral known so far, because nearly all the testing to date has been at the outcrop or in shallow test pits. Chalcocite has been identified at several test localities under 10 to 15 feet of overburden, and it seems likely that it is the dominant primary ore mineral throughout most of the deposit.

The grade of the Meadows bed at the outcrop and in shallow test pits averages about 1 percent copper and ranges from 0.5 to more than 2 percent copper. Copper

mineralization is not uniform throughout the bed's thickness: at many places where the bed is 12 to 15 inches thick, copper is concentrated in two or three zones 0.5 to 2.0 inches thick. Lockwood (1972, appendix 3) found other metals in the following low concentrations: lead (20-90 ppm), silver (24-45 ppm), cobalt (15-40 ppm), nickel (35-65 ppm), uranium (70-100 ppm), vanadium (100-140 ppm), and zinc (300-400 ppm).

The Mangum deposit was discovered early in 1965, during the first wave of prospecting after discovery of the Creta deposit, and shortly after that the Lobaris Copper Company was formed to develop the property. Lobaris obtained leases on the principal part of the deposit, and has been investigating the extent of reserves and the costs of beneficiation, including the construction of a pilot plant. Strata in the Mangum district dip westward gently at 5 to 15 feet per mile and are not disturbed by faults or folds. It is likely that the deposit could be strip mined in the same manner as the Creta deposit.

SUMMARY AND CONCLUSIONS

Two copper-shale ore bodies crop out 15 miles apart in the Permian rocks of southwest Oklahoma. Ore deposits are typically 6 to 15 inches (15 to 38 cm) thick, are elongated north-south or northeast-southwest (subparallel to the inferred Permian shoreline), have dimensions of about 6 miles (10 km) by 2 miles (3 km), and cover about 12 square miles (31 km²). Copper alone is present in significant quantities, with chalcocite being the primary ore mineral and malachite being the main oxidation product. Outcropping strata dip gently to the west into the Hollis basin, and there are no structural features believed to be related to the ore bodies. Furthermore, there is no evidence of hydrothermal activity anywhere in the region during or following deposition of the Permian sediments.

The higher concentration of sulfide minerals, the medium-gray color of the shales, and the preservation of laminations suggests that the copper shales were deposited in a reducing environment devoid of scavenging or burrowing animals: perhaps they were laid down in a lagoon or a shallow sea-floor depression where exchange

of water was restricted by subtle features on the sea floor.

Sulfur-isotope ratios reported by Lockwood (elsewhere in this volume) show a wide range in values of sulfides from the Creta deposit; he concluded that the sulfide ions were produced by bacterial reduction of sulfate ions in the sea water and surmised that the reduction could have been either syngenetic or diagenetic. The presence of chalcocite pseudomorphs after pyrite suggests that copper minerals might have replaced iron sulfide minerals that had been deposited earlier. The continuous lateral distribution of high concentrations of copper sulfide in thin beds with low permeability supports the idea that copper is emplaced in the host shales syngenetically or at an early stage of diagenesis.

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GEOLOGY AND MINING OPERATIONS AT THE CRETA COPPER DEPOSIT OF EAGLE-PICHER INDUSTRIES, INC.

Paul R. Dingess¹

Abstract—Copper mineralization is found in greenish-gray marine shales and mudstones of Permian age. Copper, in the form of chalcocite, presently is being exploited from the deposit, which occurs in a 3-inch to 1-foot zone at the top of a 2-foot shale/mudstone unit and which has an areal extent of more than 15 square miles. The chalcocite has been found to be the result of the replacement of pyrite and organic spores. In addition, chalcocite occurs as open-space filling in thin silt laminae, as veinlets lining compaction fractures, and as linings along bedding planes. Sulfur-isotope studies have indicated a biogenic origin for the sulfide ion.

The copper-bearing bed is in close stratigraphic proximity to beds containing flora that correlates closely with flora from the Zechstein (Upper Permian) of Germany, where the famous Kupferschiefer deposits are found.

INTRODUCTION

Copper mineralization is widespread in the Permian red beds of the United States, as has been known for many years. States having red-bed copper mineralization include Arizona, Colorado, Kansas, New Mexico, Oklahoma, and Texas. Numerous attempts have been made to exploit these deposits, but most have failed.

Among those deposits successfully mined are the Stauber mine in New Mexico and the Creta Copper Operations of Eagle-Picher Industries, Inc., in Jackson County, Oklahoma. The Stauber mine was discovered before 1918 (Soulé, 1956). Intermittent production has been recorded since 1925, and some recent reevaluations of the area have been conducted. Eagle-Picher began mining its Creta copper deposit in September 1965, with mining continuing at a rate of up to 1,000 tons per day. A red-bed deposit near Cuba, New Mexico, was recently brought into production by Earth Resources, and a deposit south of Mangum, Oklahoma, has been under investigation by Lobaris Copper Company for the past several years.

Many of the so-called red-bed copper deposits occur in light-gray sandstones, some of them in association with carbonized wood fragments. The Creta and Mangum deposits, in contrast, occur in dark shales

and mudstones that contain secondary selenite or satin-spar seams and veins. Providing a description of the Creta deposit is the purpose of this paper.

Acknowledgments

Thanks are due Eagle-Picher Industries, Inc., for permission to publish this paper. Special credit should be given to the personnel in the company's Metal Mining Department: Douglas C. Brockie, chief geologist, and William Arndt, assistant general manager, for their accurate and important first geologic appraisal of the deposit; and Claude O. Dale, vice-president and general manager, for his initial appraisal of the mining economics. Numerous other persons in the Eagle-Picher organization have contributed to the success of the operation and to the information contained in this paper.

A better understanding of the mineralogy can be attributed to Eva Kisvarsanyi of the Missouri Geological Survey and Richard Hagni of the University of Missouri at Rolla. Their aid is hereby acknowledged. In addition, discussions with Ken Johnson of the Oklahoma Geological Survey and Gary Smith of Amoco Production, Houston, Texas, have been stimulating and thought provoking.

Photomicrographs used were taken with the aid of the Eagle-Picher Research Laboratory at Miami, Oklahoma.

¹Cominco American, Inc., Burkesville, Kentucky.

Location

The Creta copper deposit is about 15 miles southwest of Altus, Jackson County, Oklahoma. The nearest landmark, Creta, a wheat-loading and shipping station on the St. Louis-San Francisco Railroad, is situated $3\frac{3}{4}$ miles northwest of the Eagle-Picher mill. Marty, a St. Louis-San Francisco Railroad siding that is $2\frac{1}{2}$ miles north of the Eagle-Picher mill, was constructed solely for loading copper concentrate.

Early History and Exploration

The existence of copper minerals in the region has been known since the Marcy expedition of 1852 (Marcy, 1854), but specific knowledge of the Creta deposit was unknown, or at least unrecorded, until the spring of 1962. At that time, Kenneth E. Smith of Vinson, Oklahoma, submitted a copper-bearing shale sample to the Oklahoma Geological Survey (Ham and Johnson, 1964). William E. Ham and Kenneth S. Johnson investigated the occurrence, released an open-file report in 1963, and published their findings in *Copper in the Flowerpot Shale (Permian) of the Creta Area, Jackson County, Oklahoma* (Ham and Johnson, 1964).

The geological staff of Eagle-Picher Industries, Inc., conducted their field work in 1963, at which time the copper-bearing outcrops were mapped and sampled. On the basis of this preliminary work, leases were obtained and six lines of east-west profile holes were drilled for further evaluation. Later, backhoe and dozer trenching was done in order to secure bulk samples for metallurgical testing. During this period, many additional core holes were drilled on 500-foot centers. Additional development drilling was conducted intermittently until commencement of actual mining operations.

Early exploratory drilling encountered problems of core recovery, due to the washing away of soft shales, core dinking, and some core expansion. Diamond Drilling utilized a Joy-22 core drill with water circulation. Later, experimentation with other drilling methods resulted in good core recovery by using an air-equipped Failing CHD-1 rotary drill. Sawtooth-type coring bits with carbide inserts were used successfully. With this equipment, rotary

drilling was completed through the overburden, and only the copper-bearing units of interest were cored.

Mining operations and mill production were begun in September 1965, with an initial daily capacity of 500 tons. The mill was expanded later to handle 1,000 tons per day. Production as of August 1973 amounted to over 1.5 million dry short tons of ore with an average grade of about 1.90 percent copper.

Mining Operations

Overburden removal at the Creta Copper Operations is accomplished by parallel stripping using 3 draglines, a 26-cubic-yard diesel electric Page, a 12-cubic-yard electric Marion, and a 12-cubic-yard diesel/electric Monighan. Drilling and blasting precede stripping. The overburden is stripped to the top of a gypsum unit that caps the mineralized Prewitt copper shale (previously known as the "lower copper bed").

After overburden removal is completed, a D-9 Caterpillar with a parallelogram ripper breaks the cap gypsum. This material is then flipped onto the top of the ripped area and pushed by 6-yard Caterpillar-988 rubber-tired front-end loaders lengthwise along the pit into areas where the ore has been mined.

As soon as this cap gypsum is removed, pit samples are taken along the highwall edge to determine the thickness of the mineralized zone. The ore itself is mined or broken by use of one RayGo and one Rex pulvimixer that have been specifically modified for this purpose. Generally, the upper 6 inches is broken, picked up, and stacked by the front-end loaders. The ore is then loaded into 30-ton Mack trucks and 22-ton Euclid trucks and hauled to the mill area where it is weighed, sampled, and then dumped on the stockpile pad for further drying or fed directly to the mill-crushing circuit.

After the initial 6 inches is mined and hauled to the mill, a second cut is made with the pulvimixer. The thickness of this additional cut is determined by the original pit samples and additional pit samples, and the material is loaded and hauled to the stockpile area. Following the second pass with the pulvimixer, the pit sampler returns to determine if any ore-grade material remains in the bottom of the pit. This sample in-

formation and visual inspection determines whether a third ore break is needed.

The ore is crushed and processed by normal milling and flotation methods. About 80-90 percent of the copper in the mill feed is in the form of sulfides. The mill recovers about 85 percent of the sulfide copper and about 30 percent of the nonsulfide copper. A copper concentrate of about 50 percent is produced. This is hauled to the Marty siding of the St. Louis-San Francisco Railroad and shipped to the ASARCO copper smelter in El Paso, Texas.

Reclamation of the spoil piles begins as soon as possible and in accordance with the reclamation laws of the State of Oklahoma.

PHYSICAL FEATURES AND GENERAL STRUCTURE

The Creta copper district is situated among the plains and escarpments of the Great Plains. The landscape is of the low-relief type and is occasionally dissected into badlands. Where escarpments have formed, sea-level elevations vary from about 1,500 feet on top of the mesas to about 1,300 feet in the low areas of the dissected badlands.

Flat areas are used extensively for growing wheat and cotton; dissected areas are used principally for grazing cattle. Vegetation consists of sparsely distributed short grass, mesquite trees, and cacti.

The regional structure is related to the large Permian basin of Texas, but the Creta area is within the smaller Hardeman basin of north-central Texas and southwestern Oklahoma. Dips are less than one degree, generally to the west. No apparent faulting has been recognized, although the beds are horizontal along the Red River and then rise fairly rapidly to the south in Texas.

GEOLOGIC HISTORY

Stratigraphy

The rocks of the region are assigned to the El Reno Group of Permian (Guadalupian) age (Dunbar and others, 1960). Formations exposed in the general area are the Dog Creek Shale (youngest), the Blaine Formation, the Flowerpot Shale, and the San Angelo Sandstone (oldest, and equivalent to the Duncan Sandstone north of the Wichita

Mountains). Figure 1 shows the stratigraphic section of the area and the relationship of the cupriferous shales of the Creta deposit. Note that only the Blaine Formation and the Flowerpot Shale are exposed in the area immediate to present mining.

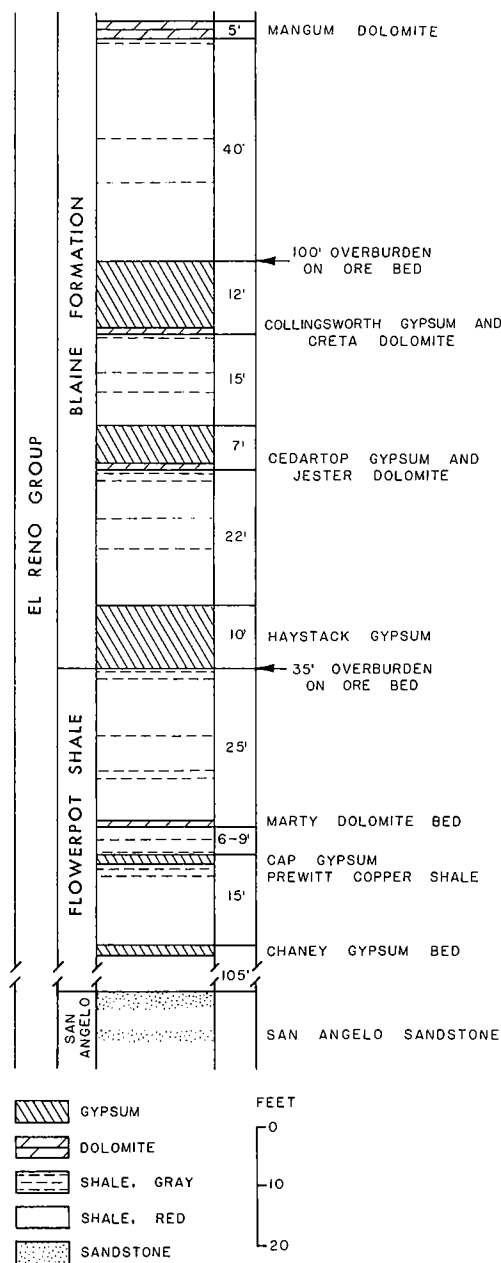


Figure 1. Stratigraphic section of Creta area (modified after Richter, 1960).

Blaine Formation

The Mangum Dolomite, the youngest bed of the Blaine Formation that is exposed in the Creta area, varies from 1 to 7 feet in thickness and is dominantly oolitic. The bed is escarpment-forming and caps the mesas and buttes of the area. The remainder of the underlying Blaine Formation consists of alternating beds of massive gypsum and green and red silty shales containing irregular thin seams and veinlets of selenite and satin spar. The Haystack Gypsum Bed is the lowermost unit of the Blaine Formation.

Flowerpot Shale

The Flowerpot Shale contains economic deposits of cupriferous shales. The uppermost 30 to 40 feet of the Flowerpot is extremely uniform, even in the subsurface, for some 10 to 15 square miles in the Creta area. The location of the Creta deposit in relation to the major facies of the Flowerpot Shale is depicted in figure 2.

Figure 3 shows the detailed stratigraphy for the interval between the Marty Dolomite and the copper-bearing beds.

Marty Dolomite Bed.—The Marty Dolomite is 25 to 30 feet below the base of the Haystack Gypsum. It is a platy, microgranular dolomite that has a distinctive ring when struck with rotary drill bits. This bed has been a valuable marker for

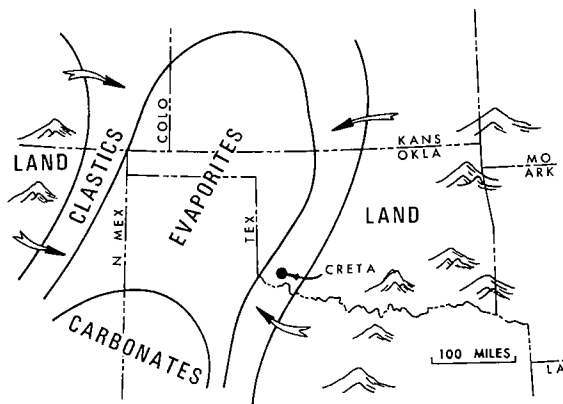


Figure 2. Major facies during deposition of Permian Flowerpot Formation in southwestern United States (modified from Johnson, figure 1, in this volume).

correlation purposes in the subsurface, but it eventually pinches out westwardly.

Cap Gypsum.—Perhaps of greatest importance is the persistent gypsum bed that caps the main copper shale. This bed has been termed the "cap gyp" and has been important in protecting the copper bed from alteration or weathering near the outcrop. It serves as an excellent horizon to which the draglines strip.

A thin gray shale lenses in and out of the middle of the cap gyp. The thickness of the cap varies from near zero to more than 12 inches in the general area.

Prewitt copper shale.—The Prewitt copper shale is greenish gray to dark gray and is composed principally of quartz, illite, and chlorite. It is divided into two separate parts—an upper laminated shale and a lower blocky mudstone. The laminated ore consists of interlaminated shale, silt, clay, and secondary satin-spar seams. Thicknesses vary from 0 to 12 inches within the ore body, but it does not appear to have extreme variances within short distances. Satin-spar seams are flat and discontinuous and constitute from 25-60 percent of this layered zone.

The underlying blocky mudstone, where mineralized, is massive, fairly well indurated, and breaks in a blocky conchoidal fashion. Thin discontinuous and undulating veins of satin spar form partings throughout the zone. Where unmineralized, the zone is flaky and softer, often containing irregular patches of gypsum. Thicknesses range from 1 to 1 $\frac{3}{4}$ feet, but the mineralized part is typically 3 to 5 inches thick.

ECONOMIC GEOLOGY

Stratigraphy of the Mineralized Zones

Two cupriferous shale zones, the upper and the lower, are present. The stratigraphic position of these zones is illustrated in figure 3. The grade of mineralization in the upper zone was quickly recognized as too low to be of widespread economic significance; therefore, discussion will be directed primarily to the lower zone.

Upper copper shale.—Mineralization in this zone is erratic and low grade, and only in

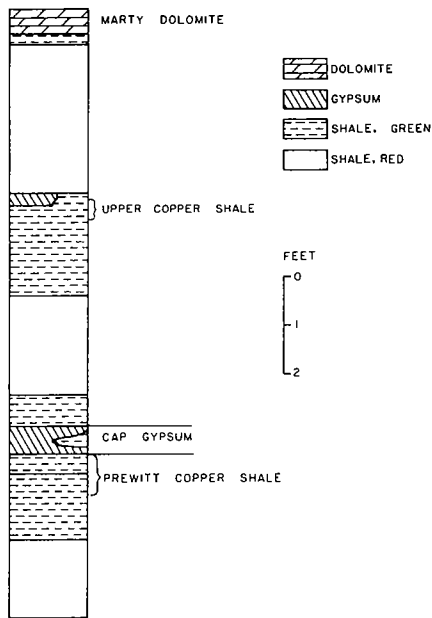


Figure 3. Detailed stratigraphy of the upper and lower copper zones.

a limited area at the extreme northern end of the operating properties is there sufficient mineralization to warrant mining.

This zone also has a gypsum cap; however, it is present intermittently and is punky or rotten in places. Zones of laminated and blocky rocks are present, as they are in the Prewitt copper shale.

Prewitt copper shale.—As noted earlier, the Prewitt copper shale is divided into two separate beds; the upper is laminated and the lower is blocky. Generally speaking, the contact between the two beds is horizontal and distinct. A satin-spar seam often constitutes the lowermost layer of the laminated zone.

The upper laminated portion constitutes a major portion of the ore body. In areas mined to date, a regional thinning of this unit has been noted from southeast to northwest. This "thinning," as it is called, appears to be due partially to facies change wherein the shale becomes extremely gypsiferous and eventually grades into the overlying cap gyp. Where this takes place, the cap gyp is wasted during mining, owing to a lack of ore-grade mineralization. In the southeastern end of the mined area, the upper 3-6 inches of

this laminated part is submarginal in grade, although good-grade mineralization occurs beneath. In general, the upper 3 inches is lower in grade than is average for the deposit. The thickness of this laminated portion varies from 0 to 12 inches.

The blocky portion of the Prewitt bed is consistently higher than the laminated in grade. Generally, the blocky-type mudstone is mineralized in the upper 3 to 5 inches, below which the copper content diminishes rapidly. From limited studies, it appears that the base of the mineralization is fairly flat and uniform. Local undulations occur but are probably not significant. The top one-quarter to one-half inch of this blocky mudstone is easily identified throughout the mined areas by a dark brown color that may be organic in nature.

In general, the mineralized blocky ore has a distinct bluish cast, due to disseminated chalcocite. It appears to be more dense, and it breaks with a conchoidal fracture. In contrast, the unmineralized blocky shale is flaky and has a light-green cast. This unmineralized portion has a leached appearance, and it contains numerous voids filled or partially filled with rotten crystalline gypsum. These special characteristics are valuable tools used in the mining operation to determine the base of the ore and thus to prevent excess dilution.

The total undiluted thickness of the ore body averages about 0.7 foot, which includes both the laminated and the blocky portions. Economic mineralization from 0.25 to 1.0 foot has been mined. Figure 4 shows the total thickness of the green shale (mineralized and non-mineralized shale) below the cap-rock gypsum. Figure 5 is an isopach of only the mineralized portion of that green shale and (or) mudstone. Figure 6 is an exaggerated, generalized cross section from southeast to northwest through the area being mined.

The ore body has a flat, tabular geometry conforming more or less to the rock units in which it occurs. The isopachs suggest a north-south orientation with the thickest mineralization occurring in the middle part of the long axis and thinning outwardly in all directions. The best mineralization is found to occur along the flanks of the thicker green-shale and mudstone unit. The cross section (fig. 6) suggests that the economic mineralization cuts across the bedding, in part.

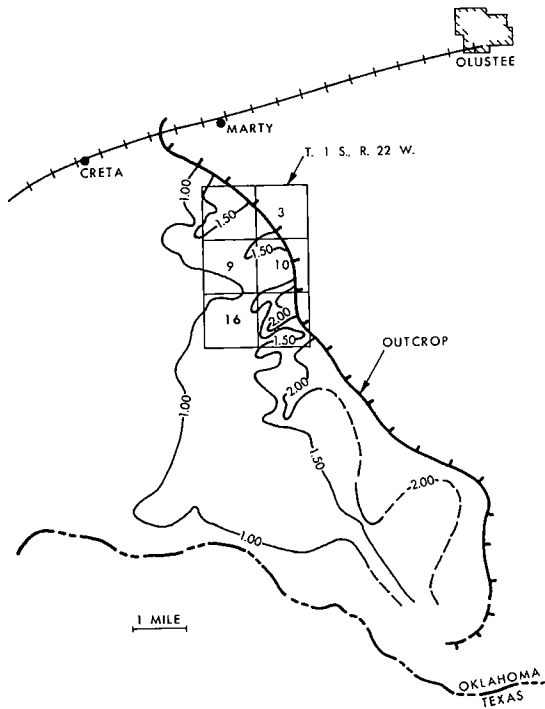


Figure 4. Isopach of green shale/mudstone of lower copper zone. (Contour interval, 0.5 foot.)

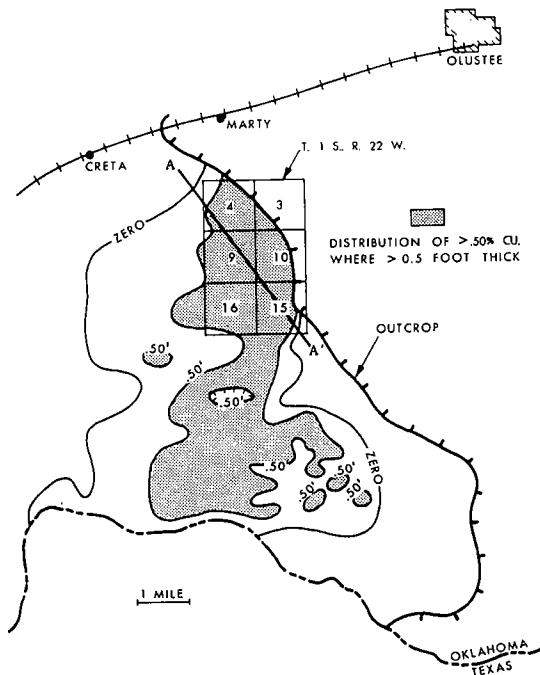


Figure 5. Isopach of greater than 0.50 percent copper in lower copper zone (Contour interval, 0.5 foot; see figure 6 for cross section.)

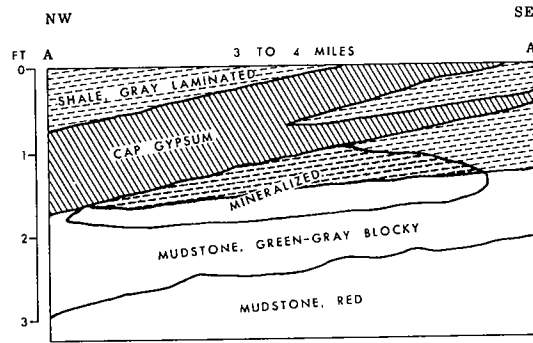


Figure 6. Idealized, exaggerated cross section through operating properties.

MINERALOGY AND GEOCHEMISTRY

The mineral composition of the ore body is simple. The principal economic mineral is low-temperature chalcocite. Silver occurs in the range of 3 to 5 ounces per ton of ± 50 -percent grade copper concentrate; native silver grains have been identified by Richard Hagni (personal communication, and article elsewhere in this volume), of the University of Missouri at Rolla.

Hagni has also reported the occurrence of pyrite locked with chalcocite in his studies of tailings from the Creta mill. Studies of thin sections by the writer and Eva Kisvarsanyi (personal communication) of the Missouri Geological Survey have revealed the fairly common occurrence of small (less than 10 to 100 microns) pyrite grains (figs. 7, 8).

Chalcocite can be seen intimately associated with pyrite, and possible pseudomorphs after pyrite have been observed.

Where exposed by weathering, the ore body has been oxidized and the minerals malachite and azurite have been produced. Very few iron oxidation products have been observed. Nonsulfide copper minerals in the mill feed vary from 10 to 20 percent. Ham and Johnson (1964) reported the presence of brochantite in nodules found near the outcrop below the lower copper zone. They also (questioningly) reported the occurrence of cuprite. An X-ray analysis of material from the deposit was run by Eagle-Picher's Joplin Research Department, which reported the occurrence of the botallackite $\text{CuCl}_2 \cdot 3\text{Cu}(\text{OH})_2 \cdot 3\text{H}_2\text{O}$ and callaghanite $\text{CaCu}_4\text{Mg}_4(\text{CO})_{14} \cdot 2\text{H}_2\text{O}$. These minerals are

extremely rare in this deposit and do not contribute to its economic potential.

A spectrographic analysis of a ± 50 -percent copper concentrate reported the following semi-quantitative estimations, in weight percent:

B	.0050	Bi	.0005	Ti	.0100
Mn	.1000	Al	.1000	Ni	.0005
Pb	.0500	Mo	.0020	Co	.0010
Mg	.1-1.0	Cu	40-60	Sr	Trace
Si	5-10	Ag	.0100	Ca	.0500
Fe	.5-1.0	Na	.1000		

Lockwood (1972), in comparing (unmineralized) gray shales with copper-bearing shales from the Creta deposit, concluded that the illite, gypsum, cobalt, nickel, organic material, zinc, and calcium are essentially the same in both types of shale. He concluded that there was more quartz, silver, vanadium, iron, uranium, and molybdenum in the gray shales and a higher chlorite, copper, and lead content in the copper-bearing shales.

Discussion with Ken Johnson of the Oklahoma Geological Survey, combined with an examination of Lockwood's raw data, suggest higher copper and lead concentrations and lower silver, uranium, vanadium, and nickel concentrations in the copper-bearing shales than in the adjacent noncupriferous shales.

In addition, Lockwood's study involved sulfur-isotope ratios, and he concluded that the sulfide ion was produced by the bacterial reduction of the sea-water sulfate ion, either syngenetically or diagenetically (Lockwood, elsewhere in this volume).

In the laminated zone, chalcocite occurs as: 1) thin layers or aggregates of grains concentrated along the contact between shale laminations; 2) concentrations in silt beds ($\frac{1}{2}$ mm thick), appearing sometimes to be open-space filling but also encroaching on the detrital silt; and 3) individual disseminated grains, some having a definite spherical shape. Grain size varies from less than 10 microns for the smaller disseminated grains to 50-150 microns for the larger, spherical grains.

Chalcocite in the dense blocky-type ore occurs in the following manner.

1. Fine disseminations, many of which are spherical in shape: individual grains and spheres vary from 10 to 150 microns, the

spheres generally being larger. The spherical chalcocite disseminations are common and of special interest. They leave casts when removed and appear to have replaced small individual soft orange to brown spheres that have been identified as spores by L. R. Wilson of the Oklahoma Geological Survey (personal communication). Near the top of the blocky ore, these spheres are solid chalcocite; lower, the outer part of the spheres is chalcocite, but the cores are composed of spore material or they are hollow. Still lower, the spores are unreplaced. Although more prominent as individual spores, occasional aggregates have been reported. It is interesting to note that Wilson (1962) has studied spores from an area near Mangum, Oklahoma, that is in close stratigraphic proximity to the Creta ore horizon. He stated that the closest floristic correlation appeared to be with the Zechstein flora of Germany. The Zechstein is the host for the famous Kupferschiefer deposits.

2. Loose grains and irregular veinlets in close association with soft satin spar and rotten, leached-appearing shale; these soft areas can be a few inches across and can generally be tied back to slickensided compaction fractures that are usually filled with satin-spar gypsum.

3. Thin, flaky, discontinuous veinlets that fill compaction fractures or coat the outside surface of satin-spar veinlets that fill the fractures: the horizontal and vertical extent of these fractures can be as much as a few inches, but the width of the filling is usually $\frac{1}{4}$ to 1 mm. In the lower, unmineralized portion of the blocky ore, the satin spar lining these small fractures is often orangish in color. A single spectrographic analysis of this material reported 40-60 percent calcium, 5-10 percent strontium (Sr), and 5-10 percent barium (Ba). Analyses of the white veinlets showed only calcium.

4. Aggregates of finely disseminated grains, sometimes appearing to be incipient nodules: these aggregates can be 10 mm or larger in length. In contrast to many red-bed occurrences, mineralization in this deposit is not associated with carbonized wood fragments. To the knowledge of the writer, only one small fragment of wood has been found, and no chalcocite was observed with it.

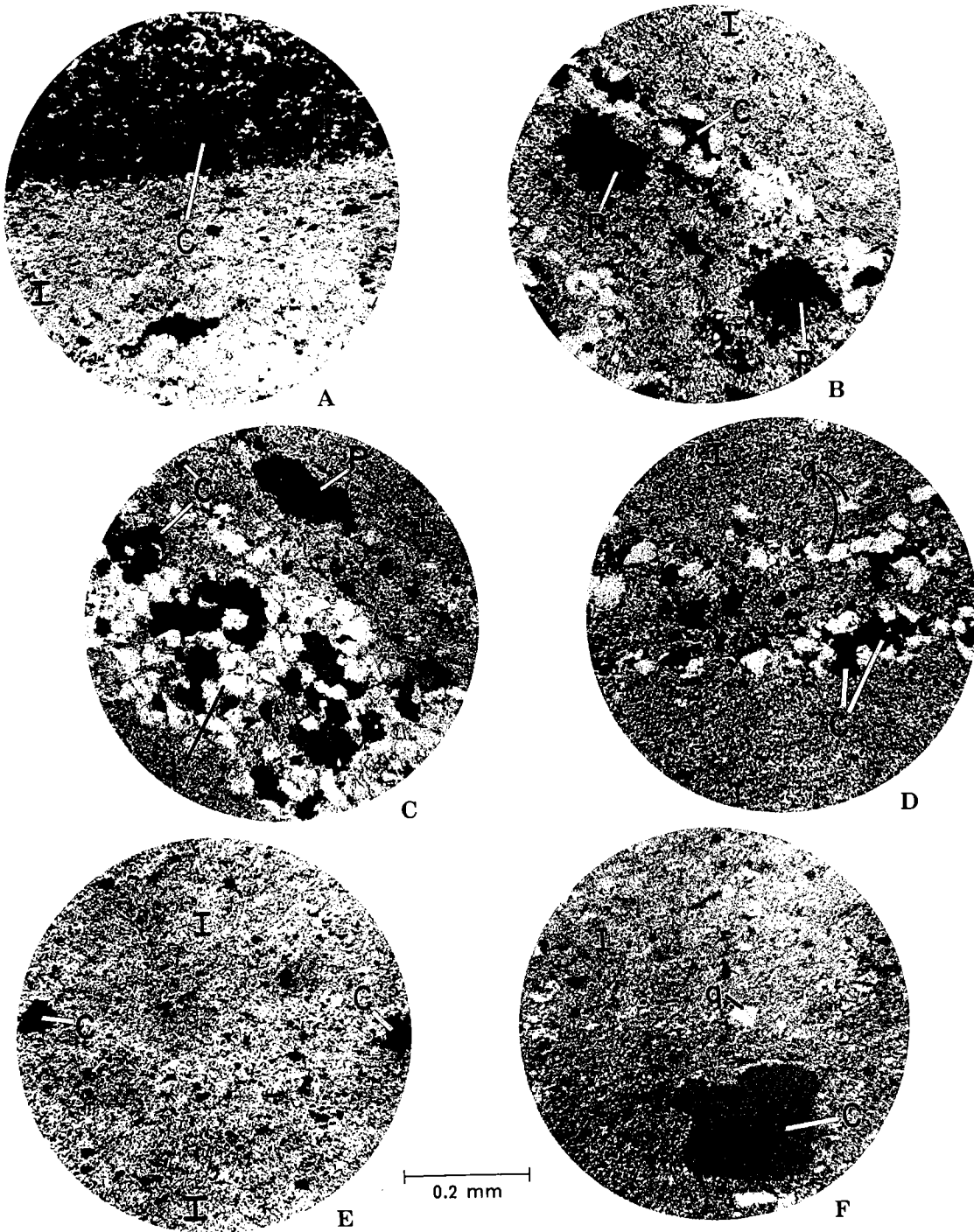


Figure 7. Photomicrographs of laminated ore: l, illite groundmass (gray); p, pyrite (black); c, chalcocite (black); q, quartz (white or light gray).

A — Layer of chalcocite grains along bedding plane.

B — Pyrite, some possible cubiform structure, some finely intermixed pyrite and chalcocite.

C, D, — Mostly chalcocite, some pyrite, concentrated in "silt" beds of quartz and (or) feldspar (light gray to white).

E — Chalcocite disseminated in illite/chlorite groundmass, some possibly replacing shreds of spore material.

F — Chalcocite, possibly pseudomorph after pyrite; scattered silt disseminated in clay.

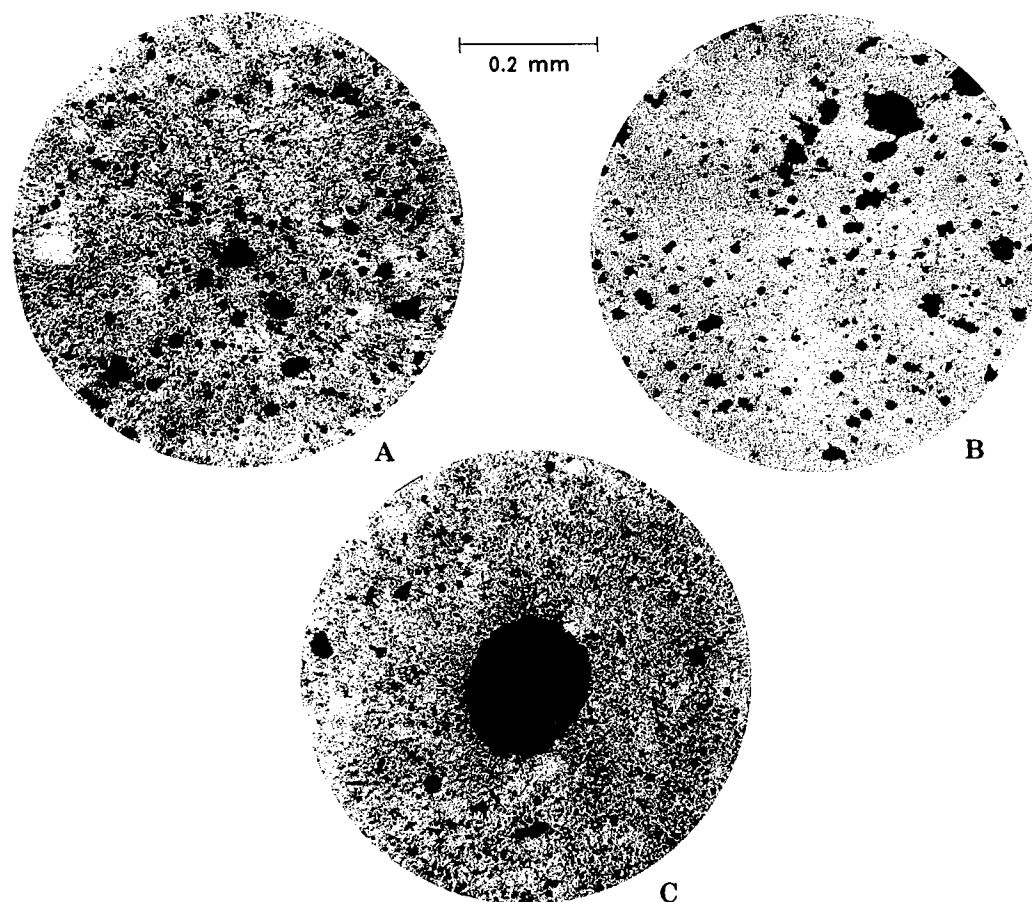


Figure 8. Photomicrographs of blocky ore.

- A, B** — Disseminated chalcocite (black) in illite groundmass (gray) with scattered detrital quartz and (or) feldspar (light gray); chalcocite possibly replacing spores or spore shreds and pyrite.
- C** — Spore replaced by chalcocite (black); vague, lighter central core is unreplaced spore material.

The Creta deposit is of singular interest, due to its similarity to the Kupferschiefer of Germany. Mineralogically, however, they are different, because the Kupferschiefer also contains chalcopyrite, bornite, sphalerite, and galena. No significant amounts of lead or zinc mineralization are found in the Creta ore.

ORIGIN OF MINERALIZATION

Widespread copper occurrences are known in Kansas, Oklahoma, and Texas and

involve several Permian horizons, especially the stratigraphic horizons of the San Angelo (Duncan) Sandstone, the Flowerpot Shale, and the Blaine Formation. The copper occurs in a variety of ways, including the obvious replacement of carbonized wood in channel deposits in sandstone in addition to the thin-bedded stratiform type in shale such as that found at Creta.

At Creta, ore minerals occur as replacement of organic spores and pyrite, as linings along bedding planes, as open-space fillings in the silt beds that sometimes en-

croach on quartz grains, and as veinlets filling compaction fractures. In a broad way, mineralization crosses the bedding. Sulfur-isotope studies indicate that the sulfur was biogenically produced, probably syngenetically or diagenetically. The secondary nature of the chalcocite occurrences and a regional distribution through a vertical stratigraphic range suggests to me that the copper concentration occurred after deposition and lithification of the host rocks—that is to say, epigenetically. The need for additional study throughout the Texas-Oklahoma red-bed copper belt is evident if we are to understand the mechanisms for precipitation and the origin of the copper.

SUMMARY

Eagle-Picher Industries, Inc., is mining a 6-inch to 1-foot seam of chalcocite-enriched shale in southwestern Oklahoma. The mining is done by open-cut methods where stripping up to 100 feet of overburden is indicated to be economic. The ore is processed by normal flotation methods and a ± 50 -percent grade copper concentrate is produced, containing 3-5 ounces of silver per ton of concentrate.

Ore-reserve estimates vary with operational costs, the market price of copper, and net smelter returns; but production as of August 1973 amounted to well over 1.5

million tons of about 1.90 percent total copper heads.

In the Creta area, copper could have been emplaced epigenetically, and the sulfur was probably generated diagenetically or syngenetically by biogenic action with available sulfate ions.

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SABKHA AND TIDAL-FLAT FACIES CONTROL OF STRATIFORM COPPER DEPOSITS IN NORTH TEXAS

Gary E. Smith¹

Abstract—A sabkha-diagenetic model is presented for the origin of stratiform copper deposits in the Permian San Angelo Formation. Copper mineralization is present primarily as widespread deposits in algal-mat facies shale and lenticular deposits in tidal channel-fill facies sandstone. Evaporative discharge from a sabkha creates an upward decrease in hydrodynamic potential with the result that primarily terrestrial ground water moves upward through the sabkha. Hydrogen sulfide, formed by bacteria, precipitates copper as ground water passes through chemically favorable facies. Some copper replaces pyrite formed as an early diagenetic mineral. Calculations indicate that 100,000 to 200,000 years may be necessary to form an economic deposit; alternate, epigenetic models involving diffusion over long distances or movement of solutions along faults and fractures were evaluated. Copper minerals include chalcocite, covellite, and malachite.

A depositional study of the San Angelo Formation (Duncan Sandstone Member and superposed Flowerpot mudstone member) serves as a framework for determining the origin of the mineralization. The Copper Breaks deltaic system and Old Glory fluvial-deltaic system flank the intermediate Buzzard Peak sand-rich, tidal-flat system; together they comprise the Duncan. Above the Duncan and coincident with the Flowerpot is the Cedar Mountain mud-rich, tidal-flat system in which most of the copper occurs. The Blaine sabkha and tidal-flat system, which is coincident with the lower Blaine Formation, overlies the Cedar Mountain system and is composed of nodular gypsum, mudstone, and dolomite deposited in sabkha and tidal-flat facies.

INTRODUCTION

Stratiform copper mineralization occurs in three general stratigraphic zones in the Permian of North Texas (fig. 1). Mineralization in the middle Permian is restricted to the Duncan and Flowerpot Members of the San Angelo Formation and the basal part of the Blaine Formation (fig. 2). Copper occurs principally in localized channel-fill sandstone lenses associated with masses of woody material, and in laterally persistent shale beds.

The contents of this paper dwell on the mode of occurrence and origin of copper mineralization in, and associated with, the San Angelo Formation. The study included an integration of surface observations, measured sections, subsurface information from oil-well electric logs, and petrologic data from thin and polished sections (Smith, 1974). The San Angelo outcrop area that I investigated extends over a linear distance of

135 km (84 miles) in north Texas (fig. 3) and was chosen to include all known San Angelo copper occurrences in Texas.

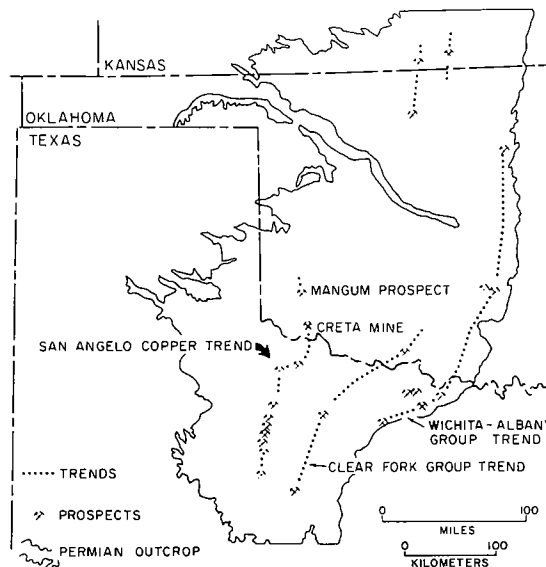


Figure 1. Permian copper prospects in Texas, Oklahoma, and Kansas.

¹Amoco Production Company, Houston, Texas (now with The Anaconda Company).

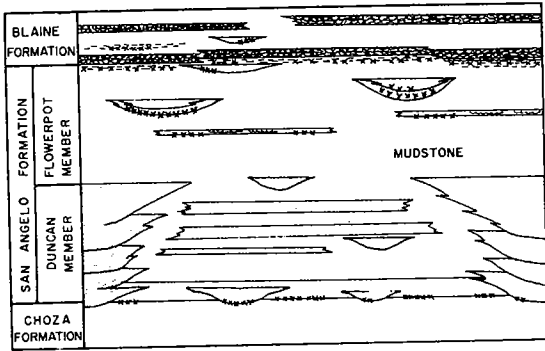


Figure 2. Distribution of copper minerals, San Angelo Formation, North Texas (x = copper-mineral zones).

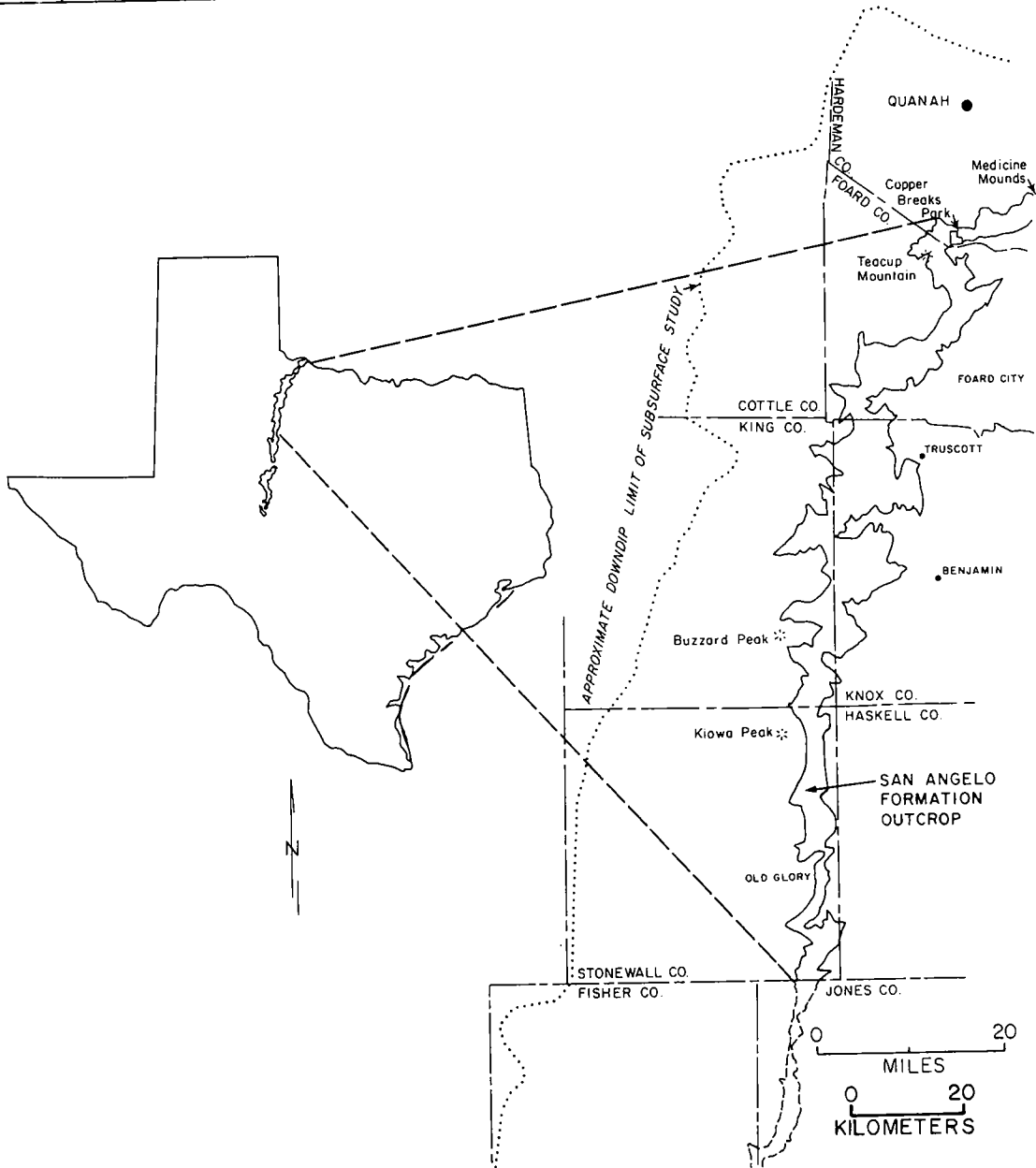


Figure 3. Location of study area, North Texas.

STRATIGRAPHY

In this study the San Angelo has been divided into 2 informal members: (1) the basal Duncan Sandstone Member, which is from 14 to 21 m (47 to 70 feet) thick, and (2) the upper Flowerpot Mudstone Member, which is from 8.4 to 19 m (28 to 63 feet) thick (fig. 4). The Duncan Member of the San Angelo Formation lies conformably on the underlying Choza Formation, although in places channeling during deposition of the Duncan Member resulted in local unconformities. The contact with the overlying Flowerpot Member is transitional and is characterized by an upward decrease in sandstone content and a concurrent increase in mudstone. The contact between the Flowerpot Member and the overlying Blaine Formation is gradational, both upward and downdip. For mapping purposes the base of the first regionally widespread gypsum bed (approximately 30.5 cm or 1 foot thick) was defined as the base of the Blaine Formation. Descriptions of lithologies present in these stratigraphic units are included in table 1.

DEPOSITIONAL SYSTEMS

The San Angelo Formation is comprised of the following depositional systems (1)

Copper Breaks deltaic system; (2) Old Glory fluvial-deltaic system; (3) Buzzard Peak sand-rich tidal-flat system; and (4) Cedar Mountain mud-rich tidal-flat system (fig. 5). The upper 9.2 m (30.5 feet) of the underlying Choza Formation examined in this study is interpreted to represent a depositional system composed of subtidal shelf, mud-rich tidal-flat, and sabkha facies that existed in the area prior to initiation of San Angelo deposition. The lower 30.8 m (101 feet) of the overlying Blaine Formation is likewise interpreted to represent a system of sabkha and mud-rich tidal-flat facies in the area covered by this study.

Copper Breaks Deltaic System

The Copper Breaks deltaic system crops out from Medicine Mounds southwestward into the Teacup Mountain area where the deltaic sediments disappear into the subsurface (fig. 3). The Copper Breaks system displays in outcrop a spectrum of facies from upslope upper delta plain to downslope deltaic. Deltaic facies, in addition, fit well into a tract from delta plain through delta front to distal prodelta facies, which because of the progradational nature of the deltaic system, has resulted in a vertical sequence of superposed deltaic facies.

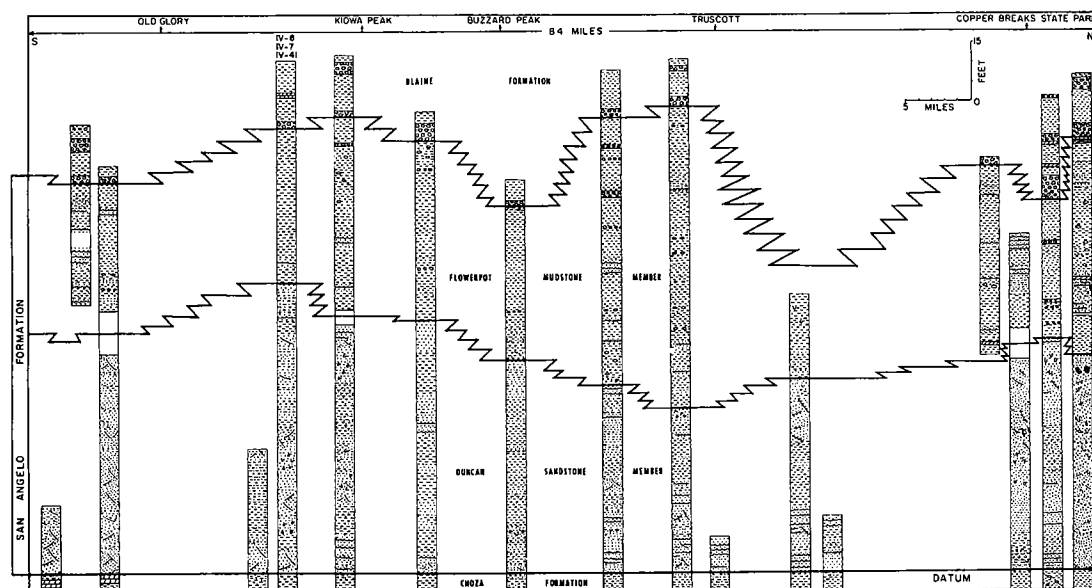


Figure 4. Strike section of the Duncan Sandstone Member and the Flowerpot Mudstone Member, San Angelo Formation (middle Permian), North Texas.

Table 1.—Summary of Stratigraphic and Facies Characteristics

FORMATIONS AND MEMBERS	DEPOSITIONAL SYSTEM	FACIES	LITHOLOGIC DESCRIPTION	SEDIMENTARY STRUCTURES AND BEDDING TYPES	BIOGENIC FEATURES	
SAN ANGELO FORMATION	Choza Formation (upper 9.2 m)	Subtidal, tidal-flat and sabkha (undiff. in study)	Red and gray mudstone (d); siltstone, very fine grained sandstone, gypsum beds and nodules, and dolomitic mudstone (m).	Massive to horizontal bedded mudstone and siltstone (d); lenticular, flaser bedded sandstone bodies (m); mud-cracks present.	No burrowing	
		Prodelta	Reddish brown mudstone and sandy mudstone.	Thin to medium, parallel laminated beds.		
	Duncan Sandstone Member	Delta front	Delta front	White, fine grained, well to moderately sorted quartz-arenite and sub-litharenite; CO ₃ cement (d).	Horizontal bedding with thin clay laminae separating thicker sand laminae.	No burrowing
		Distributary bar	Distributary Mouth bar	White, fine grained, well sorted quartzarenite. Carbonate cementation is dominant with minor silica.	Horizontal bedding (d); medium-scale trough cross bedding and climbing ripple cross-stratification (m).	No burrowing
		Distributary channels	Distributary channels	Reddish brown to tan, fine grained, well to moderately well sorted sub-litharenite and quartz-arenite. Cementation: carbonate and silica.	Medium to large scale trough cross bedding (d); small scale ripple cross-stratification, horizontal bedding and climbing ripples (m).	Burrowing is common
		Delta plain and associated facies	Delta plain and associated facies	Reddish brown siltstone, mudstone, and thin sandstone units.	Horizontal and trough cross bedding are dominant and are facies and process dependant.	Vertebrate bones present
	Flowerpot Mudstone Member	Duncan Sandstone Member	Characteristic facies are similar to those in the Copper Breaks system except for the introduction of pebbles of metamorphic quartz and rock fragments and a scarcity of quartz-arenites in the distributary channel facies. There is also a general increase in the size of trough cross-stratification.	Characteristic facies are similar to those in the Copper Breaks system except for the introduction of pebbles of metamorphic quartz and rock fragments and a scarcity of quartz-arenites in the distributary channel facies. There is also a general increase in the size of trough cross-stratification.		
			Tidal sand-flat	Very fine to fine grained, well sorted, white to tan quartz-arenite with weak silica cement.	Ripple cross-stratification, flaser and horizontal bedding (d); current lineations and clay laminae (m)	Minor burrowing
			Tidal channels	Similar to tidal channels described in Cedar Mountain mud-rich tidal-flat system (see below) except for a predominance of trough cross-stratification and the presence of calcite and silica cementation.		Minor burrowing
			Tidal mud-flat	Reddish brown mudstone (d); variable silt and sand content (m). Gray sandy mudstone and discoidal gypsum and barite nodules (m).		Vertebrate bones present
Lower segment			Very fine grained, gray, muddy sandstone to sandy mudstone.		Beds break into small (1/2 to 1-inch) blocks.	Carbonaceous material
Middle segment			Very fine grained, gray quartz-arenite; well cemented by gypsum.		Indistinct, small-scale ripple cross-stratification.	Minor carbon material
Blaine Formation	Blaine and Tidal-flat System	Upper segment	Very fine grained, gray quartz-arenite; well cemented by gypsum.	Sequence (bottom to top - idealized): bimodal bedding (r), low angle trough cross-stratification (m), horizontal bedding (m) and flaser bedding (d).	Vertebrate bones (?)	
		Swash-zone	Light gray, well sorted, very fine quartz-arenite with gypsum cement.	Small scale ripple cross-stratification.	None	
		Algal mat	Dolomite (dolomiticrite, oolitic dolomite, and intra-clastic dolomite), dolomitic shale, and well laminated gray shale.	Dolomite is thin bedded and exhibits mud cracks, syneresis cracks (r), mud clasts, and crenulations. Graded laminae are present in the dolomitic shale.	Cephalopod shells (trace-storm derived)	
		Sabkha	Nodular gypsum in discrete beds.	Nodular texture with thin red or gray clay coatings separating the nodules (d); enterolithic bedding (m).	None	
Blaine Formation	Blaine and Tidal-flat System	Tidal-flat (some undiff. sabkha sediments present)	Pale reddish brown and gray mudstone, claystone and gray dolomite (d); fine grained, gray, well sorted quartz-arenite present as lenticular channel-fill (m)	Salt hopper casts (m).		

Old Glory Fluvial-Deltaic System

The Old Glory fluvial-deltaic system crops out in the southern third of the area. Subsurface study indicates four areas of east-west trending, high net sand values (fig. 6) that are interpreted to represent individual fluvial-deltaic lobes. South of the town of Old Glory (fig. 3), the fluvial-deltaic sandstone becomes slightly conglomeratic, indicating a closer source area, different source rocks, and (or) a steeper paleostream gradient. The appearance of pebble-sized material in the Old Glory system corresponds with a local increase in dip of the strata from a regional dip of approximately 15 feet per mile to a dip of 30 feet per mile, possibly supporting a hypothesis that a steeper paleogradient aided in bringing coarser material into the coastal area. Characteristics of individual facies in the Old Glory and Copper Breaks systems are described in table 1.

Buzzard Peak Sand-Rich Tidal-Flat System

The Buzzard Peak sand-rich tidal-flat system (fig. 5) is present as a thin veneer

beneath the San Angelo fluvial-deltaic systems and is coincident with the Duncan Member through the middle third of the study area. The Buzzard Peak system developed as a result of intermittent long-shore transport of sand, silt, and mud from adjacent fluvial-deltaic systems in a manner analogous to the modern formation of mud flats and cheniers along the southwestern Louisiana coast (Gould and McFarlan, 1959, p. 268-269). Tidal flats that develop under conditions of relatively low sediment influx and weak to moderate tidal energy tend to be dominated by tidal processes that result in a winnowing of tidal-flat sediments and separation of sand-sized grains from clay-sized particles. In the Buzzard Peak system this resulted in the formation of chenier-like lenses of sand oriented parallel with the coastline. During periods of high sediment influx, mud flats formed in front of and over the sand lenses that underwent subsidence into subjacent muds. The Buzzard Peak system averages about 16 m (53 ft) thick and is composed of 1- to 3-m thick sandstone layers of the sand-flat facies interbedded with sandy mudstone. Sandstone extends 6.5 km downdip into the subsurface, where it pinches out into mudstone (fig. 6).

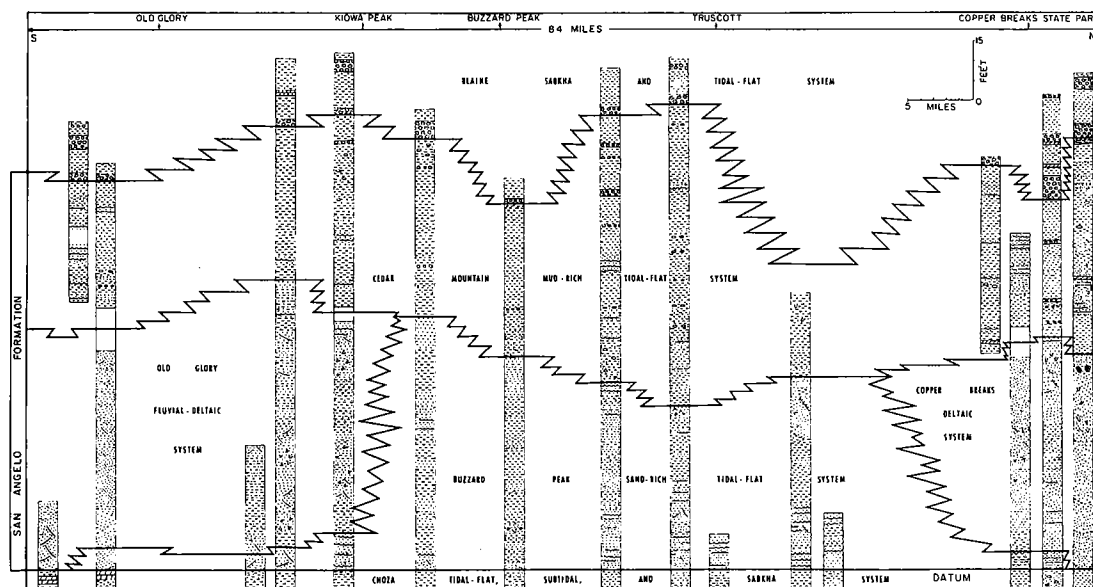


Figure 5. Strike section of the uppermost Choza, San Angelo, and basal Blaine Formation (middle Permian) with inferred depositional environments.

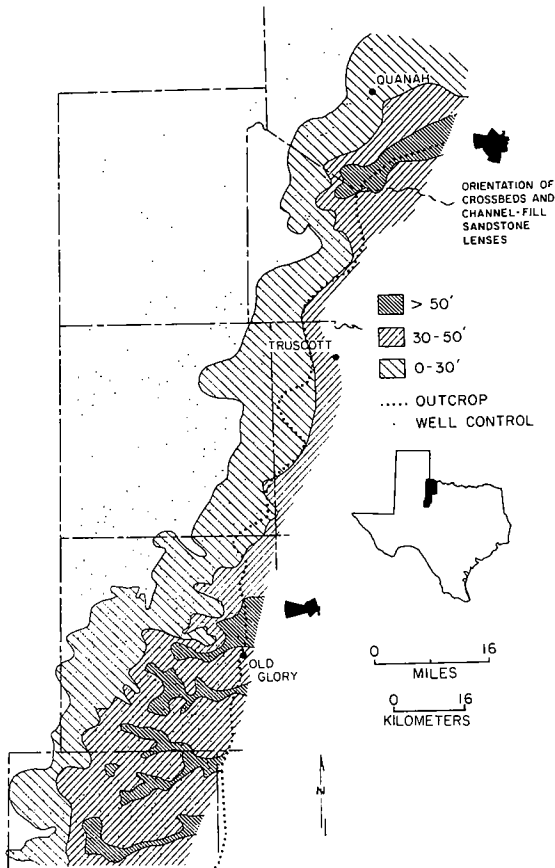


Figure 6. Net sandstone isolith map, San Angelo Formation. Rose diagrams, based on measurements of cross-bedding and channel-fill directions, indicate paleocurrent directions.

Cedar Mountain Mud-Rich Tidal-Flat System

The Cedar Mountain mud-rich tidal-flat system is gradational with the subjacent Buzzard Peak system (fig. 5) and is formed as a regressive unit by accretion and vertical aggradation of mud supplied by active deltaic systems centered possibly 130 km to the south.

Facies present in the Cedar Mountain system are summarized in table 1 and include tidal mud-flat, tidal channel-fill, swash-zone, and algal-mat facies. Deposits of the tidal-channel facies exhibit a facies tract that is divided in this study into lower, middle, and upper channel-fill segments in reference to relative position on the tidal flat (fig. 7). Lower tidal channel-fill sandy mudstone and

muddy sandstone deposits are 1.8 to 2.5 m thick and occupy channels eroded into red mudstone. Middle tidal channel-fill sandstone deposits average 1.2 m thick and commonly are present in a superposed position on top of the lower tidal channel segment. Both the lower and middle segments are lenticular shaped and average 30.8 m wide. Upper tidal channel-fill deposits are lenticular-shaped sandstone bodies 0.3-1.0 m thick and 9.2 m wide. Modern erosion of tidal-flat mudstone surrounding upper tidal channel-fill sandstone has locally exhumed the channel-fill bodies, which exhibit a meandering pattern.

Sandstone of the swash-zone facies forms 0.5- to 15.2-cm-thick tabular bodies that were formed by reworking of tidal-zone sediments.

Dolomite, dolomitic shale, and well laminated gray shale in the Cedar Mountain system grade laterally and vertically into each other and are inferred to have formed in association with algal-mat zones on the mud-rich tidal flats. Discontinuous brown laminae in thin sections of the dolomite are indicative of an organic, algal-mat origin. Beds of the algal-mat facies are 7.6 to 35 cm thick and usually underlie the first nodular gypsum of the Blaine sabkha and tidal-flat system, although algal-mat facies shale is sometimes present up to 6 m below the base of the Blaine system.

Blaine Sabkha and Tidal-Flat System

The Blaine Formation in the area of this study is interpreted to be a complex, repetitive sequence of regressive, offlapping, sabkha facies and transgressive tidal-flat facies at least 30.8 m thick. Each regressive and transgressive process caused aggradation of a thin sabkha and tidal-flat sequence. Transgression of tidal-flat facies landward over the sabkha was the result of compaction and subsidence of the subjacent facies. This may have occurred when a critical weight of offlapping sabkha sediments had accumulated.

Laterally continuous nodular gypsum beds of the sabkha facies are from 20 cm to 1.8 m thick, with a median thickness of 0.46 m; they form the framework elements of the Blaine system. Individual gypsum beds thicken and thin along outcrop and pinch out regionally to be replaced at slightly different

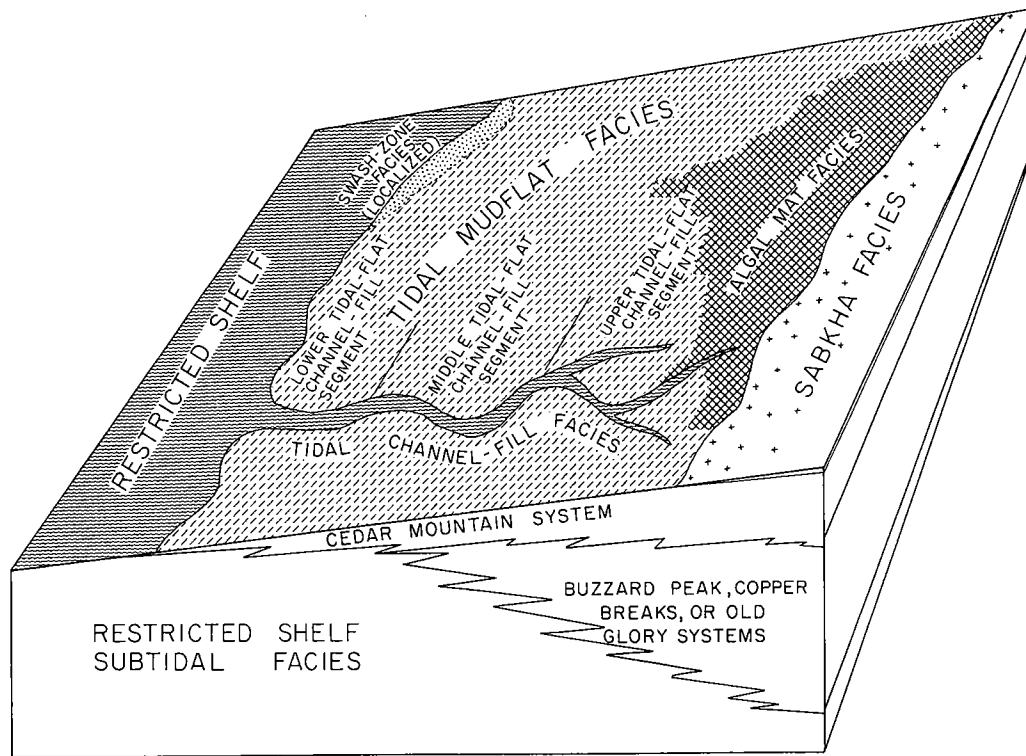


Figure 7. Depositional model of Cedar Mountain mud-rich, tidal-flat system. This system is coincident with the Flowerpot Mudstone Member.

stratigraphic levels. Nodular gypsum beds, in general, appear to lack bedding. On cut surfaces, the beds exhibit an intergrowth of 0.6-cm to 3.8-cm-diameter gypsum nodules that have coalesced to differing degrees and are set in a mudstone matrix. Gypsum beds may exhibit sequences of enterolithic layers as much as 1.2 m thick that are analogous to beds of gypsum up to 2.6 m thick (and containing enterolithic bedding) that are forming on the landward margin of modern Persian Gulf sabkhas (Butler, 1969, p. 74).

DEPOSITIONAL HISTORY

Mid-Permian depositional conditions in North Texas consisted of a broad, low, almost featureless coastal zone characterized by a hot and arid climate. West of this coastal zone was the broad, restricted, shallow shelf of the Midland basin, which served to dampen incoming waves; to the east was a broad alluvial plain of low relief. Bordering the alluvial plain on the east were the mountains of the Ouachita foldbelt

(Flawn and others, 1961, p. 186-190); to the northeast and southeast, respectively, were the Arbuckle Mountains and the Llano Highlands (fig. 8). These mountains and exposed Pennsylvanian and older Paleozoic rocks provided sediment to mid-Permian fluvial systems.

During late Choza time, the area of this study was a low coastal zone in which subtidal, tidal-flat, and sabkha facies were being deposited.

Initiation of nearby fluvial-deltaic activity increased the input of sand into the coastal zone, causing development of a thin veneer of offlapping, sand-rich tidal flats of the Buzzard Peak system that marked the beginning of San Angelo deposition. The increase of terrigenous clastics was soon followed by progradation of thin, but aerially widespread, deltas of the Copper Breaks deltaic system and the Old Glory fluvial-deltaic system (fig. 9) over deposits of the lowermost part of the Buzzard Peak system, which had undergone compaction and subsidence.

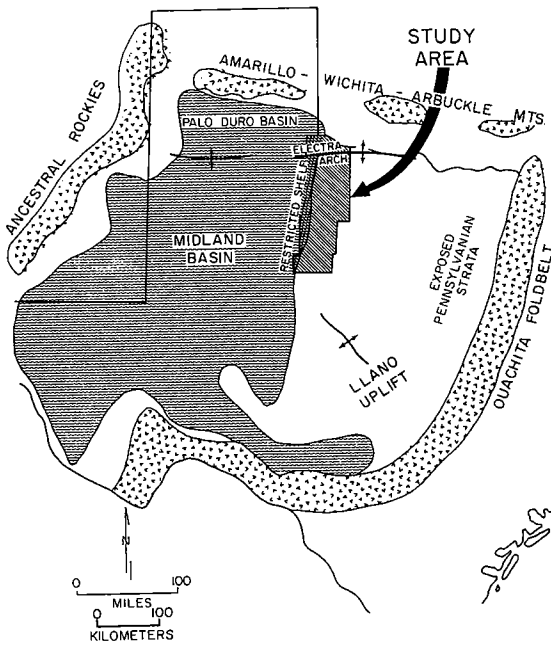


Figure 8. Regional geologic setting during middle Permian, North Texas and southwestern Oklahoma.

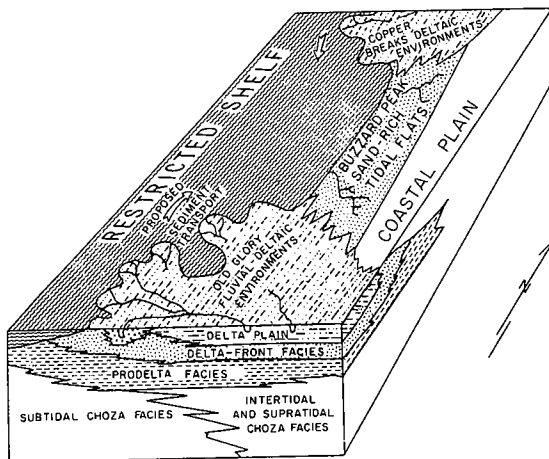


Figure 9. Depositional model of Old Glory, Copper Breaks, and Buzzard Peak systems. These systems compose the Duncan Sandstone Member.

Sand and mud were transported laterally by longshore drift from the fluvial-deltaic systems into the intermediate Buzzard Peak tidal system (fig. 9). Tidal processes generated by astronomic and wind tidal action resulted in regression of the Buzzard Peak sand-rich tidal-flat system. Compaction and subsidence contemporaneous with progra-

gradation created a relatively thick sequence of facies.

Upstream avulsion of rivers supplying sediment to the fluvial-deltaic systems ended deposition by the Old Glory and Copper Breaks systems; the fluvial-deltaic deposits slowly compacted and subsided into underlying muds. Sand supply for the San Angelo depositional systems was drastically reduced when fluvial-deltaic progradation ended, but it was replaced eventually by mud-rich sediment transported by longshore drift from a fluvial-deltaic complex active south of the area. Influx of mud initiated accretion of mud-rich tidal flats of the Cedar Mountain system (fig. 7) that eventually covered the previously deposited depositional systems. The Cedar Mountain tidal-flat system prograded over the restricted shelf deposits; contemporaneous compaction and subsidence created a relatively thick sequence of mud-rich tidal-flat facies. The tidal flats were drained by tidal channels that became progressively smaller up the tidal flat; portions of the middle and upper tidal flats were covered by algal-mat facies.

As coastal tidal-flat progradation continued, the inner, landward portion of the Cedar Mountain tidal-flat system was gradually raised above mean high tide, and a thin supratidal sabkha facies began to offlap the intertidal deposits (fig. 7). The end of extensive tidal-flat deposition concluded deposition of the Cedar Mountain system and led to development of the Blaine sabkha and tidal-flat system. Termination of Cedar Mountain deposition marked the close of San Angelo-Formation deposition in the area of this study.

Continued offlap of the initial Blaine sabkha facies covered the Cedar Mountain system (fig. 5). Each regressive episode of thin sabkha facies was followed by compaction, subsidence of the sabkha deposits, and onlap of thin tidal-flat facies. Continued repetition of these processes created a relatively thick sequence of Blaine facies.

COPPER MINERALIZATION

Stratiform copper mineralization has been recognized in the Permian rocks of North Texas for over 120 years. Many mining ventures were attempted, but

because of poor mining practices, primitive technology, erratic fluctuations in the price of copper, limited ore-grade reserves in individual mines, and a lack of understanding of the geologic relations between mineralization and the host rocks, attempts at exploitation have been unsuccessful.

Mineral Assemblage

Malachite, azurite, covellite and chalcocite were the only copper minerals found during this study. Malachite is the most common mineral at outcrop, whereas in unweathered samples, chalcocite predominates. Pyrite is present in minor quantities as an accessory mineral.

Distribution of Copper Mineralization

The lowermost sandstone bed of the Buzzard Peak, Old Glory, and Copper Breaks systems is commonly bounded at its base by a zone of light-gray, sandy mudstone averaging 5 to 30.5 cm thick. Copper mineralization in the Duncan Sandstone Member is restricted to this gray layer and the bottom 15 cm of the overlying sandstone (fig. 2). The copper occurs as widely disseminated blebs of sulfide and malachite and as localized interstitial malachite cement. Some possible charcoal and tar-like organic material occurs in the copper-bearing layer.

The bulk of the copper occurs in the Cedar Mountain mud-rich tidal-flat system of the San Angelo Formation (Flowerpot Member), and in the basal 3.1 m of the overlying sabkha and tidal-flat system of the Blaine Formation (fig. 2).

Copper occurs in the following four facies of the Cedar Mountain and Blaine systems: (1) swash-zone facies, (2) algal-mat facies, (3) sabkha facies, and (4) tidal channel-fill facies (figs. 2, 9).

Ripple cross-stratified sandstone beds of the swash-zone facies are distributed randomly through the Cedar Mountain system. Copper in the form of malachite can be found weathering out of the base of the sandstone beds and as coatings on weathered fragments of the sandstone.

Mineralization in the gray, well laminated shale, dolomitic shale, and dolomite of the algal-mat facies at the top of the Cedar Mountain system exhibits the best

lateral continuity. The copper-bearing gray shale beds range from 7.6 to 35.6 cm thick, with copper values as high as 4.4 percent through 5-cm intervals and 2.2 percent from 17.8-cm intervals. Copper is present in these extensive algal-mat shale beds as malachite and chalcocite; these minerals are present as platelets of malachite on shale laminae and as blebs of chalcocite. In outcrop, only malachite is observable unless the shale is artificially exposed. Black specks of what may be bituminous matter are present in the shale. No recognizable organic matter was actually noted in the algal-mat facies, but their origin as algally bound sediment and their dark color suggest that a significant amount of organic matter was present in these sediments at the time of burial.

Dolomite layers in the algal-mat facies contain chalcocite and malachite as scattered blebs, partial fillings in small vugs, and small fracture fillings. The dolomite is thin bedded and ranges from less than 2.5 cm up to 30.5 cm thick. Thin sections show that copper was deposited in pore spaces and as a replacement for organic matter.

Copper may also occur in trace amounts at the base of the first nodular gypsum bed of the sabkha facies in the Blaine system, immediately above the algal mat facies of the Cedar Mountain system.

The thickest ore, and the ore with the highest copper concentration, occurs in tidal channel-fill facies in the Cedar Mountain mud-rich tidal-flat system and in the basal portion of the Blaine system. Copper in these channel-fill deposits has been mined intermittently since 1877. The bulk of the copper comes from lower tidal channel-fill sandy mudstone and muddy sandstone. Phillips (1917) noted that mineralized zones in the lower tidal channel-fill facies range from 0.6 to 3.4 m thick, 5 to 14 m wide, and about 46 m in length. Copper minerals present in the tidal-channel deposits include malachite, azurite, covellite, and chalcocite. The ore in the tidal channel-fill facies occurs as copper nodules, replacements of wood fragments, disseminated blebs of copper, and interstitial cement.

Paragenesis

The paragenetic sequence has apparently been a four-step process, outlined as follows: (1) pyrite replaces organic material; (2)

chalcocite replaces pyrite; (3) covellite replaces chalcocite; and (4) malachite and azurite are formed. The precise time relationship between the first two steps depends on the origin of mineralization, which has not been definitely established. The position that covellite occupies in this sequence is equivocal, because the textures may have formed under a variety of conditions.

The essential parts of this sequence are shown in polished thin sections of copper nodules (see Smith, 1975). Pyrite has replaced woody material and preserved the outline of the cellular structure of the woody host material. Chalcocite exhibits evidence of having replaced pyrite, sometimes preferentially along relict cell walls. Replacement of chalcocite by covellite has occurred along the outer margin of chalcocite blebs and from numerous cracks that are present in chalcocite blebs.

Thin sections of mineralized gray shale and mudstone from the Creta copper mine in Southwest Oklahoma and from an area near Medicine Mounds (figs. 1, 3) contain scattered circular blebs of chalcocite, 0.10-0.15 mm in diameter, and numerous smaller blebs of chalcocite from 4-10 microns in diameter. The size and shape of the 4- to 10-micron blebs suggest that they are fram-boids (Rust, 1935, p. 407-408) of chalcocite pseudomorphic after pyrite. The 0.10-0.15 mm chalcocite spheres from the copper-bearing shale at the Creta mine are interpreted as mineralized spores. The gray, relatively unmineralized mudstone under the copper-bearing shale at Creta contains orange spheres 0.08 to 0.15 mm in diameter that have been identified as spores (Clair R. Ossian, personal communication, 1973). As the strongly mineralized shale is approached, the spores are mineralized from the inside to the outside in a progressive manner until, in the ore zone, only spheres of chalcocite can be observed.

Replacement of organics by pyrite may be an early diagenetic phenomenon that occurs soon after burial; pyrite is currently forming under reducing conditions at a depth of 40 to 70 cm in tidal-marsh sediments on the west coast of Florida because of anaerobic bacterial processes related to decomposing organic matter (Swanson and others, 1972, p. 58-61).

The age of the chalcocite, which is now

the dominant sulfide present, is less definite. Depending on the origin of the mineralization, it may have formed diagenetically before lithification of the sediment (but after pyrite replaced organic material) or after lithification of the enclosing sediments. Covellite may be formed a little later as an early replacement mineral or during the Holocene as an oxidation product of chalcocite. If covellite formed as an early replacement of chalcocite, its formation may have been caused by a relative decrease in reducing conditions in the concentrating environment as H_2S and HS^- were consumed in precipitation of copper sulfide. There is also a possibility that some of the covellite formed at the same time as the chalcocite. A polished section of a copper nodule contains small, apparently isolated, masses of covellite within chalcocite, which may indicate segregation of cupric and cuprous ions during formation of the copper sulfide.

Malachite and azurite formed during the Holocene as a result of oxidation of sulfides by surface and ground water, followed by reprecipitation in the presence of carbonate ions.

Origin of Copper Mineralization

The depositional history of the host rocks, the facies control of the mineralization, the importance of organic matter, a lack of mineral zonation, and absence of known igneous activity support a diagenetic theory and suggest that evaporative discharge through the sabkha surface may have been active in forming the copper mineralization in the San Angelo Formation. Alternate epigenetic theories involve movement of a solution containing copper chloride complexes along basin-rim-ming faults or metasomatic diffusion of copper over relatively long distances. Copper mineralization appears to be unrelated to any structural influence, and there is no apparent faulting in or near the area.

Sabkha-diagenetic Model.—Diagenetic processes associated with the sabkha environment can concentrate copper into economic deposits, provided that there is (1) adequate copper in the ground water; (2) a high evaporation rate; (3) sufficient reductant present; and (4) persistence of sabkha and intertidal sedimentation.

In the sabkha-diagenetic model (fig. 10), evaporative discharge at the sabkha surface, induced by evaporation, may create an upward decrease in hydrodynamic potential with the result that ground water of primarily terrestrial origin would be induced to flow upward through the sabkha. Hydrogen sulfide formed as a metabolic by-product of sulfate-reducing bacteria in decomposing algal mats, and in decomposing organic matter in tidal channels and ripple-bedded sands, should be capable of stripping out the copper by causing it to precipitate as copper sulfide. Hydrogen sulfide associated with decomposing organic matter at the base of the Duncan Member would likewise precipitate some copper. Later, small-scale diffusion and diagenesis could further concentrate available copper. Pyrite, which forms by early diagenesis prior to any significant concentration of copper, is partially replaced by copper sulfide during concentration of the copper. The copper content of the ground water, which is elaborated on later, need only be of approximately average value. A condition of depositional equilibrium, allowing sabkha processes to exist in the same area for a relatively long time, would allow the diagenetic copper-concentrating process to continue long enough to allow a potentially economic deposit to accumulate.

Evaporation rates in the Persian Gulf area are as high as 128 cm per year, and rainfall averages only 3.8 cm per year (Butler, 1969, p. 74). Hsü and Schneider (1974, p. 418-422) showed that this high

rate of evaporation causes a vertical hydraulic gradient to form in the sabkha. In response to the upward decrease in hydrodynamic potential caused by the interstitial water loss, evaporative pumping, or discharge, takes place (Hsü and Seigenthaler, 1969, p. 14-17). Saline lagoon water and terrestrial water are pumped laterally, and then vertically, to be discharged at the sabkha surface. The relative amount of terrestrial ground water and saline lagoon water that evaporates depends on the dynamic equilibrium that exists between the two. The writer proposes that most of the water evaporated in the model was terrestrial in origin (fig. 10). This would occur if the slope of the water table in the coastal zone created a hydraulic head sufficient to push the salt water wedge of the Midland basin away from the area immediately under the sabkha. Along the arid Trucial Coast today, terrestrial ground water has been found in the "high supratidal zone" of the sabkha (Butler, 1969, p. 79). During concentration of the San Angelo copper deposits, subdued highlands in the Ouachita foldbelt may have provided the elevation necessary to produce a sufficient hydraulic head. Hydrogen sulfide gas, sulfate ions, gypsum, and anhydrite are common features found in sabkha and intertidal sediments of the Trucial Coast (Butler, 1969, p. 75-79). Anaerobic, sulfate-reducing bacteria utilize organic material present in algal mats to provide energy with which to reduce sulfate, which is in the form of sulfate ions. The presence of these gases, and a lack of

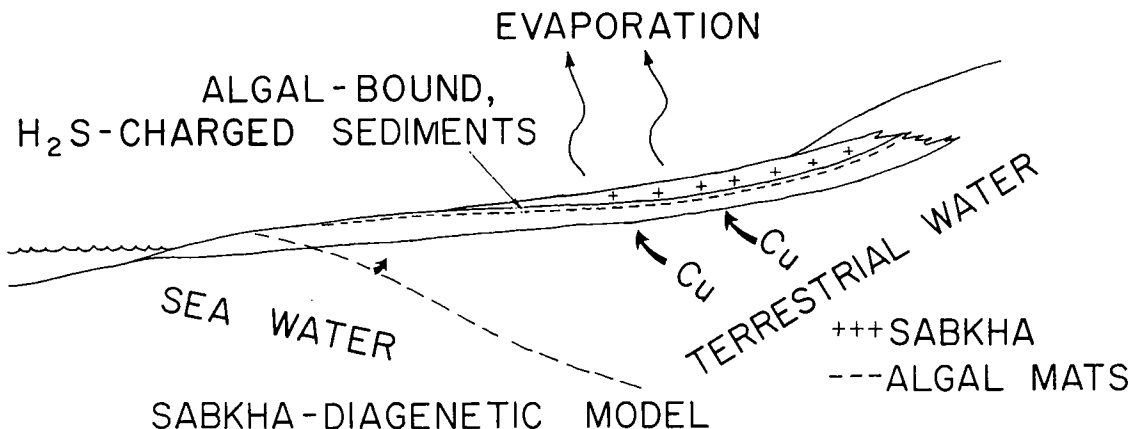


Figure 10. Sabkha-diagenetic model for copper mineralization (modified from Renfro, 1974).

oxygen, results in a low pH and a negative redox potential in the sediments.

Copper is contained in the ground water as dissolved copper in ionic form, copper adsorbed on clay-sized particles, and as colloidal and soluble organo-copper complexes which are pumped through the sabkha. As water passes through the zone of H_2S and HS^- , copper is extracted and precipitated as chalcocite. Breakdown of the various organic complexes and desorption of the copper may be facilitated by the strongly ionic (Na^+ and Cl^-) conditions under the sabkha facies, and the low Eh and slightly acidic pH in the organic-rich facies (Butler, 1969, p. 75). Studies by Temple and LeRoux (1964, p. 276) show that metal toxicity would limit the continued action of sulfate-reducing bacteria only if the rate of introduction of metals to the environment exceeds the rate of H_2S production. The gypsum layer above the algal-mat zone may have acted as a partial seal to upward dispersal of H_2S . The presence of some copper mineralization in the gypsum indicates that some H_2S did seep into the base of the gypsum layer. The gypsum layer of the sabkha would also serve as a seal to oxygen, thus preventing oxidation of the algal mats.

The amount of copper present in the ground water and the length of time in which the concentration process is active are critical factors in the sabkha-diagenetic theory. Hem (1970) reported that sea water contains 0.003 ppm copper. The mean copper content of fresh water streams is 0.010 ppm (Livingstone, 1963, p. G47). The fresh-water figure is undoubtedly too low, because most analyses do not consider copper that has been complexed by chelators such as humic acids, copper in metallo-organic compounds, or copper in suspension adsorbed on inorganic and organic detrital particles. From data by Kharkar and others (1968, p. 294) it can be seen that adsorption of cobalt by particles in streams causes a four-fold increase (average) in total cobalt content. Collins (1973, p. 74-75) suggested that similar figures may be obtained from a study of copper because of their similarities in behavior. Rashid and Leonard (1973) have demonstrated the importance of organic compounds (e.g., humic and amino acids) in dissolving insoluble metallic salts and in keeping them in solution by preventing their

precipitation under conditions that would otherwise lead to immobilization.

Unfortunately, few quantitative data are available on copper adsorbed on particles or as organo-copper complexes in ground water. White and others (1963, p. F20) reported as much as 0.12 ppm copper in ground water from a shale and siltstone terrane. Most values of copper in ground water from all terranes composed of unmineralized rocks are apparently under 0.010 ppm (based on charts in White and others, 1963). No mention is made by White and his co-workers of copper present as part of soluble or colloidal organic compounds or copper adsorbed on particles that may travel in ground water.

The amount of time that a sabkha environment can exist depends on the stability of depositional conditions. On the Trucial Coast, an average of 0.70 m of upper intertidal (algal-mat) and sabkha sediments has accumulated in about 3,500 years (Evans and others, 1969, p. 148-149). Depositional processes on the sabkha are such that the sabkha is slowly prograding across intertidal algal flats and into a lagoon connected to the Persian Gulf. Under alternate conditions suggested for the Blaine sabkha and tidal-flat system, a sabkha could prograde over an intertidal flat, subsidence could then occur—forming a wide intertidal algal flat over the sabkha, and a new sabkha could again prograde over the intertidal zone. This process could be repeated many times. Bosellini and Hardie (1973, p. 22-23) proposed a similar process for thick, ancient sabkha sediments in Italy. Near Old Glory, 30.8 m of the Blaine appears to be sabkha-intertidal in origin. At a deposition rate of .70 m per 3,500 years, it would take 154,000 years of sabkha deposition to accumulate 30.8 m of the Blaine Formation.

Calculations were made to determine the feasibility of concentrating economic copper deposits by the diagenetic process just described (table 2). Using the 154,000 years estimated to deposit the Blaine sabkha and tidal-flat deposits, it can be seen that the sabkha-diagenetic theory can be valid provided there is approximately 0.06 ppm copper in the ground water, the rate of evaporation from the sabkha is between 50 and 100 cm per year, and ground water is almost totally terrestrial in origin.

Table 2.—Number of Years Required to Concentrate a 25-cm Column of Copper over 1 square cm of Surface¹

Sabkha evaporation rates (cm per year)	ppm copper in ground water ⁴	Number of years required
100 ²	.06	100,000
100	.01	600,000
100	.003	2,000,000
50 ³	.06	200,000
50	.01	1,200,000
50	.003	4,000,000

¹ 1 percent copper and 25 cm thickness are personal estimates of the average thickness and tenor of copper bearing shale in the study area.

² From Hsu and Siegenthaler (1969), evaporation from standing surface of water.

³ From Hsu and Siegenthaler (1969), evaporative loss of interstitial water for sediments of 40 percent porosity.

⁴ Previously explained in text.

An important aspect of the sabkha-diagenetic theory is the necessity for having most of the ground water pulled through the lowermost sabkha, even when sabkha-intertidal sediments are 30.8 m thick. This requirement may be acceptable, inasmuch as sabkha sediments form a wedge of low permeability sediments with a slight seaward tilt that have prograded over intertidal sediments (Evans, 1969, p. 147-158). In general, the sediments seaward of the sabkha have low permeability, whereas sediments under and landward of the sabkha have relatively high permeability; this generalization holds true for the San Angelo Formation, even though there is a higher mud content in the San Angelo than in Trucial-Coast sediments.

Epigenetic Models.—The discovery of mineralized brines in the Red Sea (Bischoff, 1969, p. 368-401) and in the Salton-Sea sediments (White, 1968, p. 312-318) has recently focused attention on the importance of saline solutions as a transporting medium for a variety of elements. The importance of chloride complexes in the transportation and deposition of ore-forming metals has been pointed out by Helgeson (1964), and the formation of complex ions has been shown to increase the solubility of some metals by several orders of magnitude (Barton, 1959).

Transport of copper in chloride complexes vertically along faults or fractures

and then laterally along permeable horizons, with deposition taking place in favorable chemical zones, is proposed by the writer as an alternate, epigenetic origin for the copper in the San Angelo Formation (fig. 11A). Faulting or fracturing may have occurred in or near the area of this study, in response to sedimentary loading in the Midland basin or as a result of separation of the North and South American plates during the Late Paleozoic and Early Mesozoic (see Walper and Rowett, 1972, p. 111-115). Apparent alignment of copper deposits along the Midland basin and other basins in Oklahoma

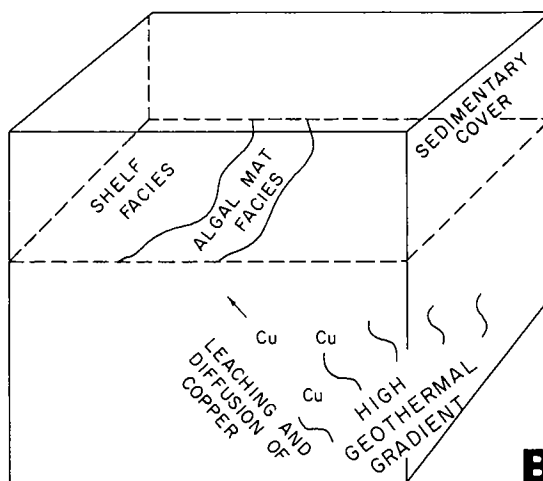
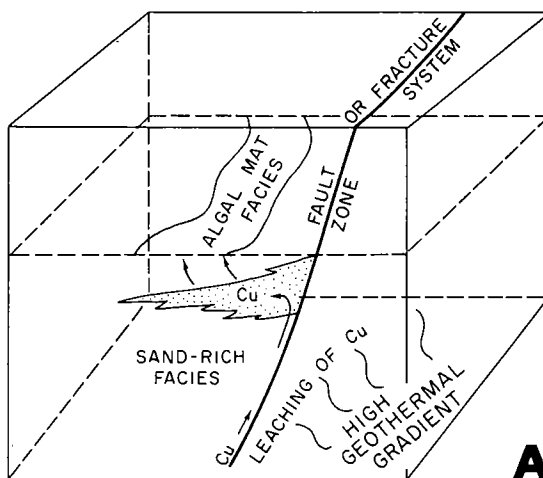


Figure 11. **A**, epigenetic model, fault- or fracture-controlled mineralization; **B**, epigenetic model, diffusion-controlled mineralization.

and Kansas (fig. 1) may possibly result from growth faulting along the margin of these basins. Deposition could have occurred when the mineralizing solutions came in contact with hydrogen sulfide in organic-rich zones such as tidal channel-fill facies and algal-mat facies. The copper could have been derived from the leaching of deeply buried copper-rich detrital minerals (e.g., biotite), connate water in older Paleozoic rocks, and possibly some copper ions from deep-seated, unidentified magmatic sources. A high geothermal gradient along the eastern side of the Midland basin, perhaps related to the separation of lithospheric plates, may have provided additional heat for leaching copper and increasing its solubility.

An epigenetic theory involving thermal diffusion and metasomatic processes (fig. 11B) may obviate the necessity of a fluid moving upward along a fault or fracture. Garrels and others (1949) stressed the possible importance of diffusion in transferring significant quantities of materials over relatively long distances. Ramberg (1952, p. 204-211) proposed that intergranular diffusion of atomic, ionic, or molecular-sized particles over relatively long distances may give rise to a low-temperature metasomatic type of ore deposit. Microporosity may be developed in lithified and perhaps semilithified, deeply buried rocks as a result of intragranular microfissuration (Dandurand and others, 1972). This porosity would be intermittently formed and destroyed as a result of uneven lithostatic stresses. The multitude of healed fractures noted in quartz grains (Sipple, 1968) may be partly caused by these processes. During the microfissuration process, fluids are released and the solubility of many minerals is increased (Dandurand and others, 1972).

Copper may be able to move out of its position in the lattice of minerals bearing trace amounts of copper and into an intergranular position or, if microfractures in the grains develop, into an intragranular position. The copper ion may then go into solution as a chloride complex, perhaps, and be transported a short distance by fluid movement; or the ion may diffuse a short distance through the solution and, perhaps, along grain boundaries. Over a sufficiently long period of time, an integration of this process throughout a large area and a

general upward movement of copper in the direction of the inferred concentration gradient may lead to the formation of an economic copper deposit when an H_2S -bearing strata is reached, and the microfissuration process ceases.

The emplacement of ore bodies by either epigenetic theory could take place after deposition of the host rocks and after an unspecified thickness of sediments has been deposited over the host rocks. The length of time in which H_2S could remain in association with organic-rich zones may be a limiting factor in regard to when concentration of copper could take place. A mechanism that would diffuse copper ions through the sedimentary column would take a considerable period of time (see Smith, 1974, p. 105).

Facies control of the copper mineralization observed on outcrop, the vertical succession of facies, the inferred paleogeographic history, and an absence of igneous or metamorphic activity in the region of this study, suggest that a diagenetic process, such as that outlined in the sabkha-diagenetic model, was active in concentrating the copper.

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MICROSCOPY OF COPPER ORE AT THE CRETA MINE SOUTHWESTERN OKLAHOMA

Richard D. Hagni¹ and Delbert E. Gann¹

Abstract—The primary copper in the Prewitt shale at the Creta mine in southwestern Oklahoma occurs as very fine grains of copper sulfides. The grains exhibit a variety of sizes and shapes, which are determined largely by the character of the organic matter and the grains of iron sulfide that they replace. Chalcocite replacements of numerous spores of the genus *Triletes* form elliptical to nearly spherical grains, which commonly are 100 to 200 μ in diameter and usually have smooth exterior surfaces. Smaller, nearly spherical grains, which commonly are 20 to 40 μ in diameter, have rough exterior surfaces, and consist mainly of grains of digenite and of lesser amounts of finely interspersed grains of chalcocite. Digenite grains and chalcocite grains of a similar size that possess six sides are less common; they are pseudomorphic after pyritohedral pyrite. This replacement of pyrite in the shape of an atoll and "sea island" textures attests to a replacement origin of iron sulfide by copper sulfide. Larger, irregularly shaped clumps of iron sulfide, up to 500 μ across, are partly replaced by digenite and chalcocite. Very tiny, disseminated pyrite crystals of octahedral and cubic habit, mostly less than 10 μ across, also appear to be partly replaced by copper sulfide.

Other grains of copper sulfide, which are irregularly shaped, and tabular, pseudo-hexagonal crystals of chalcocite appear to have crystallized directly from solution. The grains and the crystals are mostly less than 10 μ in size and are abundantly disseminated throughout the host shale and mudstone. Discontinuous, thin, chalcocite veinlets and interstitial chalcocite fillings of silty lamellae account for lesser quantities of copper. Bornite and native silver are very minor constituents in some specimens of the primary ore.

The textures of the Creta ore samples indicate that the copper sulfides were deposited subsequent to the early diagenetic development of iron sulfide. The organic content is an important feature, one that led to the concentration of both iron sulfide and copper sulfides. The copper ore is a result of processes that affected the host sediment during late diagenesis and is not a product of magmatic processes.

INTRODUCTION

Copper was first discovered at Creta in southwestern Oklahoma in 1962 (Ham and Johnson, 1964, p. 6). Mining began in 1965, and current production is about 1,000 tons of ore per day (see Dingess article, this volume, 1976).

The copper at Creta is in 2 or 3 thin stratigraphic horizons within a 7-foot-thick stratigraphic interval consisting principally of greenish-gray, nonlaminated claystone and mudstone. This interval is a part of the Permian Flowerpot Shale and lies about 25 to 30 feet below its top. The interval's gray color contrasts with that of the red shale that makes up most of the Flowerpot.

Within the 7-foot interval, 3 cycles of sedimentation are recorded. Each cycle begins with a greenish-gray mudstone. This is followed by a gray shale that is capped by a thinly laminated gypsum bed. The best copper mineralization is present at the same stratigraphic position within each sedimentary cycle. That position is the upper few inches of the gray shale and mudstone that is immediately beneath the thin gypsum unit. The lowest zone of mineralization, named the Prewitt copper shale by Johnson (elsewhere in this volume), is the main productive ore horizon at Creta. It includes the top 4 to 5 inches of a 2-foot, greenish-gray mudstone and the overlying thin, gray, laminated shale (see Dingess, this volume, fig. 3).

The Prewitt copper shale is similar in many respects to productive copper shales elsewhere. Especially well-known are the stratiform ore deposits of Poland and

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England, the Kupferschiefer of Germany, the Nonesuch Shale in northern Michigan, and the lower Roan in Zambia. The manner in which the copper was deposited in the shale at Creta may well be closely related to that of copper shales elsewhere.

The main ore horizon at Creta is stratiform and is 8 to 8½ inches thick. The copper grade averages close to 2 percent and ranges up to about 4½ percent. Most of the copper grains in the ore are invisible to the unaided eye and require microscopic examination to determine their presence.

Acknowledgments

This paper, which presents the preliminary results of ore microscopy and petrography, is part of a continuing study of the Creta deposit. The writers acknowledge the cooperation of Eagle-Picher Industries, Inc., in providing access to the Creta mine. The McNutt Foundation at the University of Missouri at Rolla has provided financial aid for field-sample collection. Discussions with Paul R. Dingess, A. C. Spreng, Douglas C. Brockie, Paul C. Jones, and John B. Thompson, have been particularly helpful. John W. Koenig has kindly reviewed the manuscript.

FORMS OF CHALCOCITE OCCURRENCE

Much of the copper ore at the Creta mine is present in the form of very small grains that exhibit a variety of shapes and are composed of copper sulfides. Most of the grains are so fine that they can be observed only with the aid of a microscope. The copper sulfides occur most abundantly as the replacements of spores and iron sulfide and as tiny grains and crystals of chalcocite. Lesser amounts of the copper sulfides form thin veinlets that traverse the shale and are concentrated in silty lamellae or replace other materials.

Spore Replacement

The most important type of copper occurrence in the Creta ore is the chalcocitic replacement of spores. Some of this replacement can be detected macroscopically

in the form of tiny specks of chalcocite that are disseminated throughout the host shale. The character of the smaller grains can best be studied with the aid of a microscope.

Polished sections of the ore grains show that they most commonly have ellipsoidal shapes as shown in figure 1, but spherical shapes as well are very common (fig. 2). The grains range in size from 50 to 250 μ in diameter, but most are 100 to 220 μ . They appear to consist entirely of chalcocite, but some have an exterior case (a rim in polished section) which appears to be slightly harder and somewhat lower in reflectivity than the chalcocite of the interior. These cases preferentially acquire a coating of oxide after being exposed to the air over a period of



Figure 1. Typical ellipsoidal chalcocite grain formed by pseudomorphic replacement of a partially compressed spore of *Triletes*. Long dimension of grain is about 200 μ . Polished section.

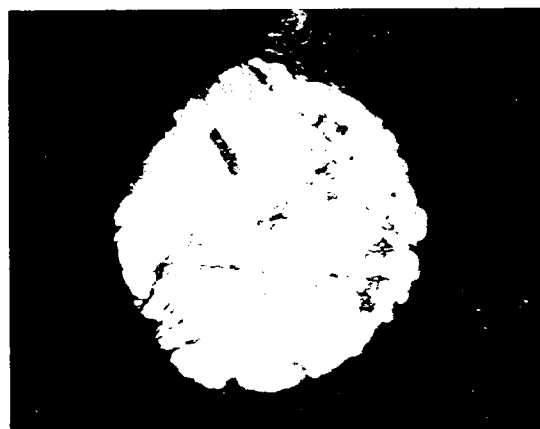


Figure 2. Nearly spherical chalcocite grain formed by pseudomorphic replacement of a spore of *Triletes*. The original spore has sustained little or no compression. Both the interior body material and the spore case are replaced. Diameter of grain is about 150 μ . Polished section.

several months (fig. 3). The exterior margins of most of the grains are relatively smooth, but some show local irregularities as illustrated in figure 4.

Most of the spores in the main ore zone are entirely replaced by chalcocite, but those which were collected one-half inch below the base of the main 8-inch ore zone contain much smaller amounts and exhibit the original character of the spores. Unreplaced spores observed in polished sections have a distinct reddish to orange color, and their polished surfaces have a pitted character (fig. 5). The internal character of the spores can best be examined in thin sections where they can be seen to consist of a colorless to light-yellow spore case that encloses a darker yellow to orange interior body material. No lines were produced when the spores were exposed to an X-ray diffraction beam. The presence of barium in the interior of the spores can be readily detected with the aid of a scanning electron microscope. P. R. Dingess, who first speculated that these bodies might be spores, submitted a few hand-picked specimens to L. R. Wilson at The University of Oklahoma. Wilson (written communication, 1972) identified the spores as belonging to the genus *Triletes*, a megaspore.

Most of the spores exhibit only a minor degree of collapse and are ellipsoidal in shape. Others exhibit no collapse and are nearly spherical (fig. 6). Less commonly, the spores are almost completely collapsed (fig. 7), but rarely are they completely collapsed. The degree of collapse is an important factor in determining the shape the chalcocite grains attain.

All stages of progressive spore replacement can be observed in specimens that were taken from the weakly mineralized, blocky mudstone beneath the main ore horizon. Chalcocite replacement usually begins in the center of the body material of the spore (fig. 8). Increasing degrees of replacement spread outward from the centers as shown in figures 9, 10, and 11, until all of the body material is replaced. The spore case is the most difficult part of the spore for the chalcocite to replace, and portions of the spore cases form the most common replacement remnants in the ore zone (fig. 12). Some chalcocite grains also contain remnants of the body material, as

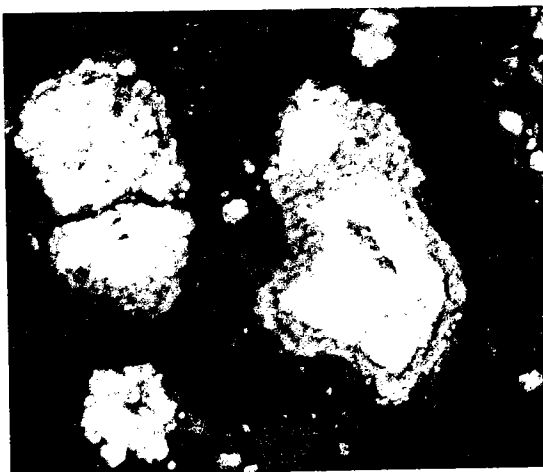


Figure 3. Two ellipsoidal spore-replacement grains showing marginal bands that have preferentially taken an oxidation coating after exposure to the air for several months. The coating develops on that portion of the copper sulfide grains that has replaced the spore case. Long dimensions of the two grains are about 200 μ . Polished section.



Figure 4. An ellipsoidal spore-replacement grain with chalcocite extending beyond the confines of the spore along its lower right margin. Long dimension of grain is about 200 μ . Polished section.

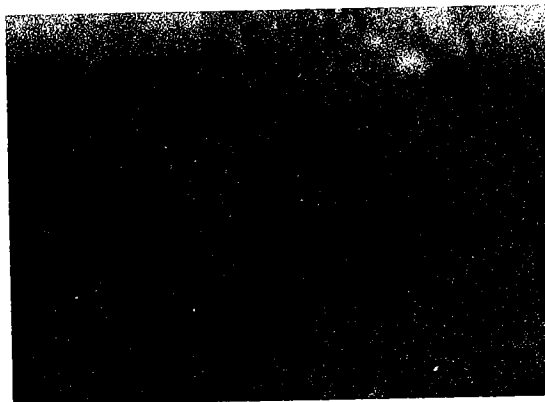


Figure 5. *Triletes* specimen as it appears in polished section. Diameter of the spore is about 150 μ .



Figure 6. Typical *Triletes* specimen in thin section. The interior body material (medium gray) is enclosed by the spore case (light gray). This spore shows almost no compression. Diameter of the spore is about 150 μ .

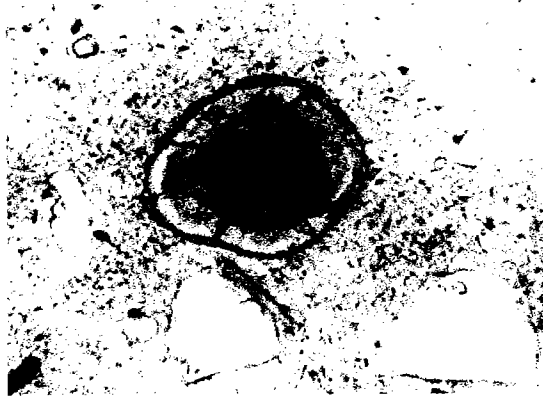


Figure 9. *Triletes* specimen showing about 35 percent replacement by chalcocite (black). Spore diameter is about 150 μ . Thin section.



Figure 7. *Triletes* specimen showing a degree of collapse unusual for spores in the Prewitt copper shale. Long dimension of spore is about 150 μ . Thin section.



Figure 10. *Triletes* specimen showing about 80 percent replacement by chalcocite (black). Only a thin band of the interior body material (dark gray) remains unreplaced. Long dimension of spore is about 200 μ . Thin section.

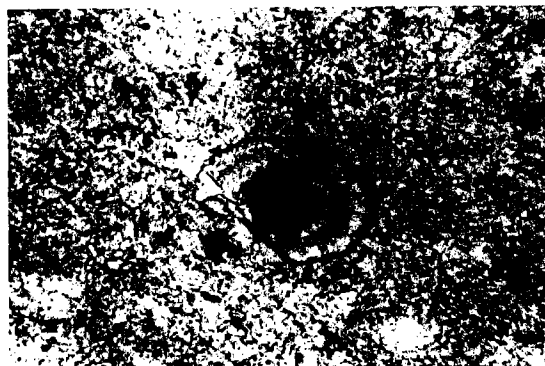


Figure 8. *Triletes* specimen showing initial replacement by chalcocite (black) in the central portion of the interior body material (medium gray). About 15 percent of this spore is replaced by chalcocite. Long dimension of spore is about 150 μ . Thin section.

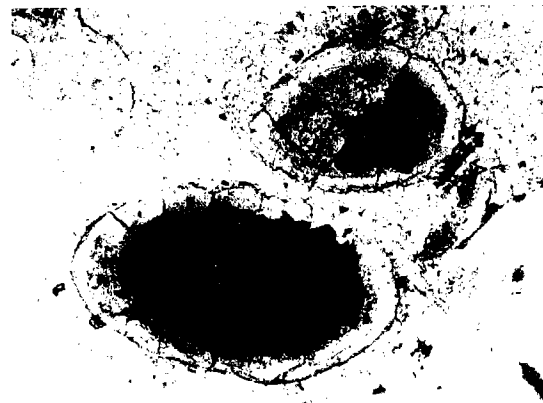


Figure 11. Two *Triletes* specimens showing varying degrees of replacement by chalcocite (black). The bottom spore illustrates that nearly all of the body material has been replaced by chalcocite and the spore case (light-gray band) is under incipient attack. Long dimension of lower spore is about 200 μ . Thin section.

shown in figure 13. Even after complete replacement of the spore, the replaced case shows a different character than that which replaces the interior, as noted previously and illustrated in figure 3.

Some of the spores that are collapsed have contiguous, irregularly shaped patches of sulfide deposited about them as shown in figure 14. This relationship suggests that the body material that had escaped from some of the fractured spores may be a factor in the deposition of some of the grains of chalcocite found elsewhere in the shale outside the spores. The presence of abundant spore fragments similar to those shown in figure 15

suggests that appreciable body material might have been released into the original mud and could have been a factor in the deposition of some of the tiny disseminated chalcocite grains described in a later section.

Because most of the spores in the ore zone are entirely replaced by chalcocite, it is rather surprising to observe an occasional spore that is completely unreplaced adjacent to other spores that are completely replaced. Some factor, such as accessibility, in that spore's condition, rendered it unfavorable for replacement.

A second type of spore is abundant in the laminated portion of the Prewitt shale; this

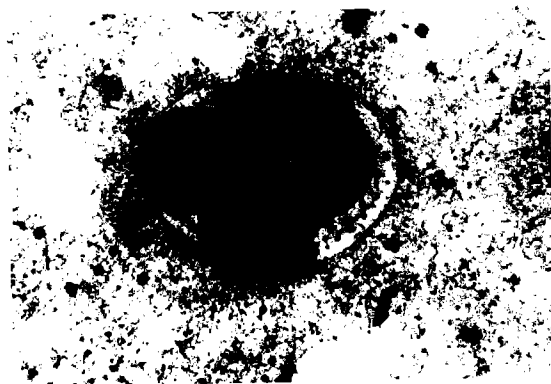


Figure 12. Remnant of a spore case within a chalcocite (black) pseudomorphic replacement grain in a sample taken from the intensely mineralized main ore horizon. Long dimension of grain is about $150\ \mu$. Thin section.



Figure 14. Three *Triletes* specimens showing varying degrees of fragmentation. Top right spore is unbroken. Top left spore is broken but retains most of its interior body material (medium gray). Lower middle spore-case fragment has lost all of its interior body material. Long dimension of unbroken spore is about $150\ \mu$. Thin section.

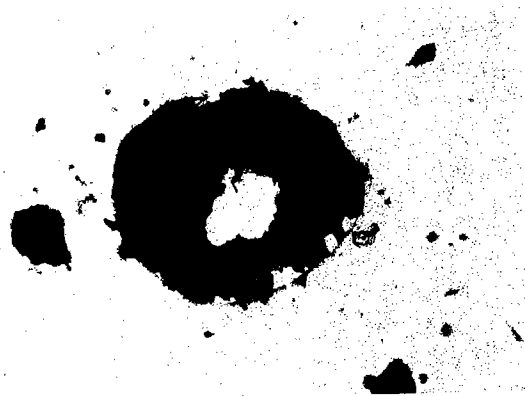


Figure 13. Remnants of interior body material (white) and spore case (light-gray band) from a pseudomorphic chalcocite (black) replacement of a spore extracted from the intensely mineralized main ore horizon. Diameter of chalcocite grain is about $150\ \mu$. Thin section.



Figure 15. Irregularly shaped grain of chalcocite deposited around a collapsed spore; deposition locus influenced by escaped body material from the spore's interior. Long dimension of chalcocite grain is about $200\ \mu$. Thin section.

type has not been recognized in the underlying, mineralized, blocky mudstone. These spores exhibit a lighter yellow color in thin section as compared to the orange megaspores (*Triletes*) discussed above. These are not megaspores; they are normal spore size and their shapes are spherical to elliptical. They are remarkably similar in shape and size to the 20- to 40- μ -diameter chalcocite granules discussed below. These spores do not seem to be favored loci for sulfide replacement. Only in rare instances, such as that shown in figure 16, do the sulfides (in this case a pyrite crystal of pyritohedral habit) replace the yellow spores.

Iron Sulfide Replacement

Pyrite is not observed macroscopically in the Prewitt copper shale, but iron sulfide can be observed with the microscope. It occurs as tiny replacement remnants in a variety of copper sulfide grains. Each of these grains is distinguished by its characteristic size and shape and by the nature of replaced grain or crystal of iron sulfide.

Clumps of Small Granules and Six-Sided Crystals.—One of the most noticeable forms of copper at Creta occurs as small clumps about one-quarter to one-half inch across. These clumps have amoeboid shapes typified by those shown in figure 17. They consist of local clusters and snake-like elongated patches which meander aimlessly in any direction. The fact that they are confined to the nonlaminated, bioturbated, blocky claystone bed suggests that they may have been formed in the digestive tracts of burrowing organisms.

Polished sections of these clumps and patches show that they consist of massive digenite and chalcocite (fig. 18). At the edges of these masses, individual copper sulfide granules have crude spherical shapes that commonly are 20 to 40 μ in diameter (fig. 19). The masses were evidently formed through coalescence of the granules. These copper sulfide granules are distinguished from the *Triletes* replacements by their smaller size and by their shapes. The most common shape of the 20- to 40- μ grains approaches a spherical shape, but the grains are never perfect spheres. Their marginal surfaces are not as smooth as those of most of the *Triletes* replacements. They commonly

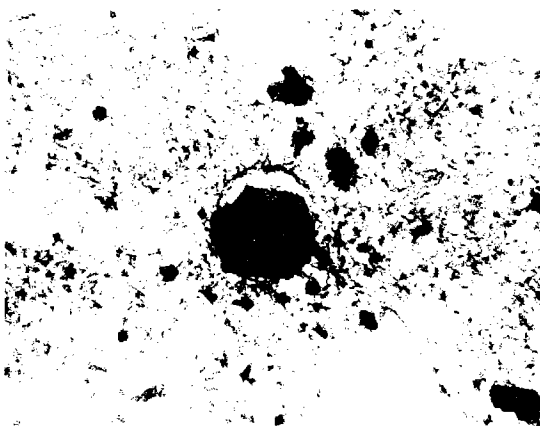


Figure 16. An unusual sulfide replacement of a small, yellow spore about 40 μ in diameter. The sulfide grain exhibits a crude six-sided character suggesting that it formed as pyrite of pyritohedral habit. Thin section.



Figure 17. Amoeboid patches and stringers of copper sulfides in the nonlaminated, blocky mudstone. Possibly these bodies developed in the burrows of the bioturbated host rock. Diameter of each polished section is 1/4 inches.



Figure 18. Patchy intergrowth of digenite (medium gray) and chalcocite (light gray) that has replaced amoeboid patches of iron sulfide. Black areas are holes. Long dimension of irregular hole in middle of field is about 40 μ . Polished section.

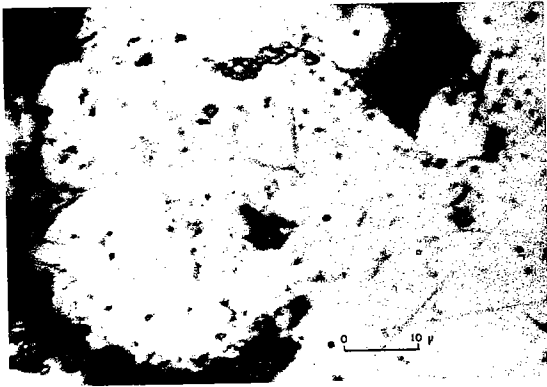


Figure 19. Partly coalesced digenite-chalcocite granules at the margins of amoeboid patches. The copper sulfide granules are pseudomorphic after original iron sulfide granules. Diameter of granules is about $30\ \mu$. Polished section.



Figure 20. Crude six-sided section (right side of photomicrograph) through a digenite-chalcocite grain pseudomorphic after an original pyrite crystal of pyritohedral habit. Oxidation skins are present on the surface of this polished section. Crystal is about $40\ \mu$ across.

exhibit rough or bumpy surfaces. Other 20- to $40\text{-}\mu$ chalcocite bodies exhibit crystalline outlines that commonly are 6-sided in polished section (fig. 20). Unlike the spore replacements, which consist only of chalcocite, both the 20- to $40\text{-}\mu$ granules and the 6-sided grains consist principally of digenite in an intimate intergrowth with about 15 percent chalcocite.

Only occasionally do these particular copper sulfide bodies reveal their origin by the presence of replacement remnants. The most common remnant is pyrite in the shape of an atoll. The atoll shapes are formed as a result of intensive chalcocite replacement of the central portions of the original pyrite grains. The marginal portions of the pyrite grains, which are more resistant to replacement by copper sulfide, initially remain as continuous or nearly continuous atolls of pyrite within the chalcocite replacement grains—as shown in figure 21. With progressive chalcocite replacement of the pyrite, atoll shapes become separated into individual, irregularly shaped, replacement remnants or sea islands of pyrite locally present in the chalcocite (figs. 22, 23, and 24). The fact that digenite is the dominant copper sulfide replacement of the iron sulfide grains is probably due to its inclusion of small amounts of iron, as shown recently by Morimoto and Gyobu (1971).

Large Clumps.—Large clumps of iron sulfide are abundant in and restricted to the

laminated shale at the top of the main ore horizon. They consist of an aggregate of pyrite grains with a degree of intergranular porosity. Some aggregates are as large as $500\ \mu$ across. Most have been only partially replaced by chalcocite. Chalcocite replacement begins at the margins of the pyrite aggregates and proceeds to form a very irregularly shaped, spotty, replacement texture (fig. 25). Suggestions of spherule shapes are locally present within these sulfide grains.

Tiny Crystals of Pyrite.—Tiny crystals of pyrite are locally disseminated through the shale. They appear to be at least partly replaced by copper sulfides. Most of these crystals are less than $10\ \mu$ in diameter. Octahedral forms are common, especially near the previously described amoeboid clumps as shown in figure 26. Cubes modified by the octahedron are less common (fig. 27).

Chalcocite Crystals

A large portion of the chalcocite that is present in the Creta ore occurs as tiny grains that range in size from about $10\ \mu$ down to the limit of resolution of the microscope. Many of the larger grains appear to show irregular shapes in polished sections of the ore, but their tiny size, together with the problem of obtaining a good polish, makes the shapes difficult to discern. One of the

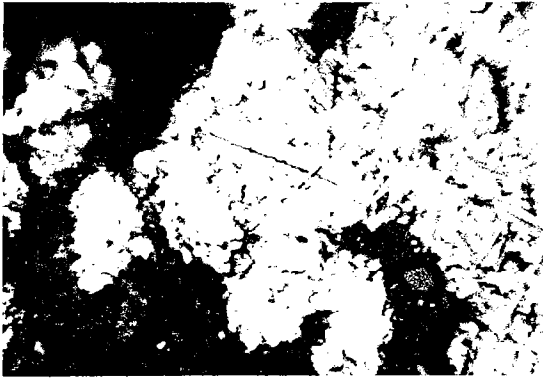


Figure 21. Atoll of pyrite (white) left as a replacement remnant in a granule composed of digenite (light gray) and chalcocite (indistinguishable from digenite in this and succeeding photomicrographs). Granule is about 40μ in diameter. Polished section.



Figure 24. Pyrite (white) replacement remnant located in the central portion of a digenite-chalcocite (light-gray) grain. The six-sided character of the pyrite remnant suggests an original grain of pyritohedral habit. The copper sulfide grain is about 40μ across. Polished section.

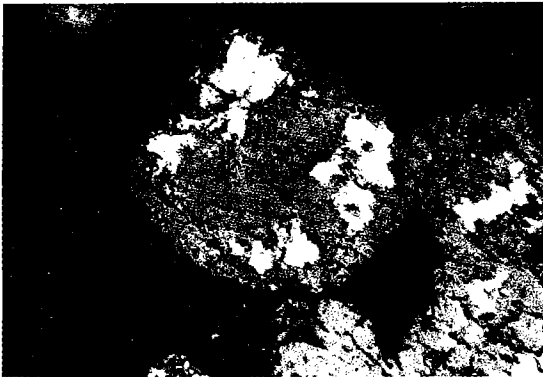


Figure 22. "Sea islands" of pyrite (white) left as remnants of progressive replacement by digenite (medium gray) and chalcocite. Granule is about 35μ in diameter. Polished section.

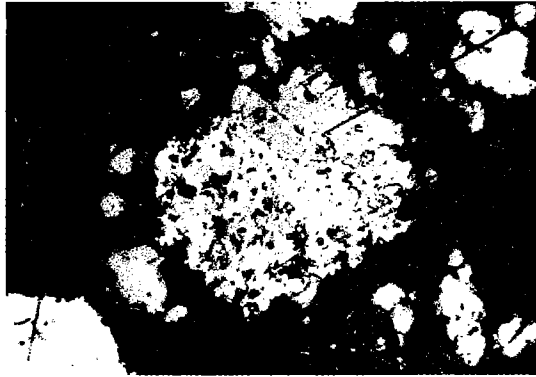


Figure 25. Clump of pyrite (light gray) partially replaced by digenite-chalcocite (medium gray). Clump in center of photomicrograph is about 200μ across. Polished section.

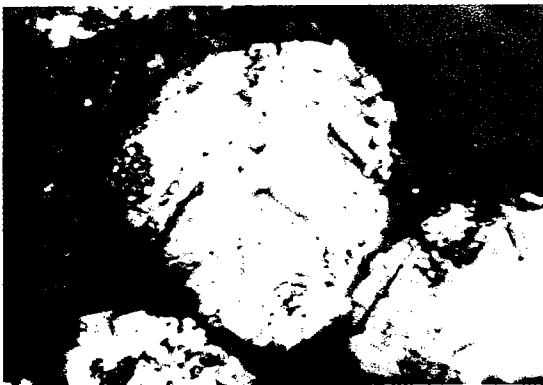


Figure 23. Granule of copper sulfide (digenite and chalcocite; light gray), containing a single small replacement remnant of pyrite (white) toward the bottom of the granule. Long dimension of the granule is about 40μ . Polished section.

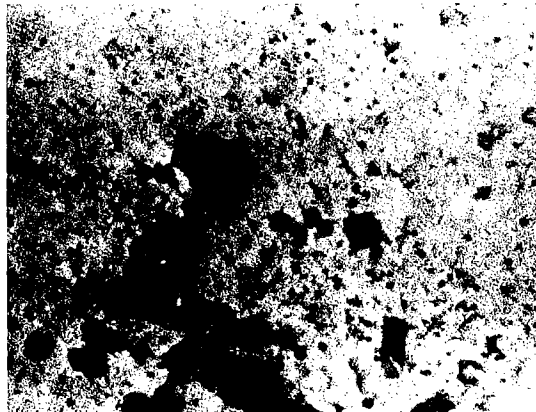


Figure 26. Amoeboid patch of copper sulfide with nearby partly replaced (?) pyrite crystals of octahedral habit. Largest octahedral crystals are about 10μ across. Polished section, crossed nicols.

more common shapes exhibited by the tiny chalcocite grains is that of 6-sided crystals, similar to some of those shown in figure 28. A single tabular shape, shown toward the left side of the figure, is an edge view of one of these platy hexagonal or probably pseudo-hexagonal crystals. Disaggregation of the shale, followed by gravity settling on a glass slide through either a column of water or cold-setting plastic, provides the best means for examining these tiny crystals. The crystals that settled upon their flat basal pinacoids commonly exhibit 6-sided shapes as shown in figure 29. Only crystals attached to gangue particles exhibit tabular character (fig. 30). These chalcocite crystals and irregularly shaped grains appear to have crystallized directly from the copper-bearing solutions. The interior body material released into the shale from broken spores may have been a factor promoting their deposition.

Veinlets

Although most of the mineralization at Creta occurs in a disseminated form, tiny veinlets are locally present within the Prewitt copper shale. They are of minor quantitative importance, but they demonstrate that copper-bearing solutions have migrated at one time along and across the ore-bearing host shale. Such veinlets transgress the bedding planes in some places, and they form bedding-plane veinlets

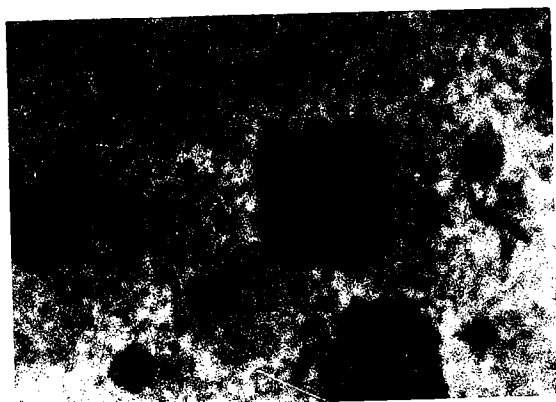


Figure 27. Pyrite cube partly replaced (?) by copper sulfide. Crystal is about 10μ across, mounted on a glass slide, and viewed with an ultrapac objective.

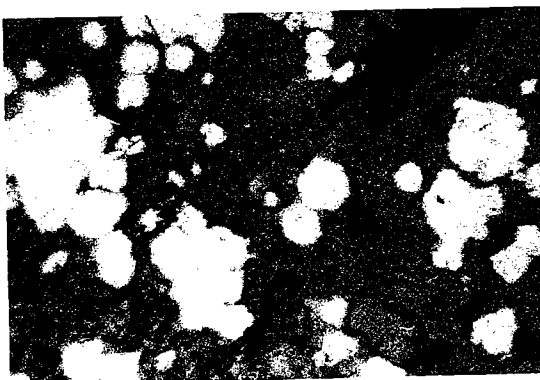


Figure 28. Chalcocite (white) grains in shale (gray). Three small chalcocite grains in the right central portion of the photomicrograph exhibit distinct six-sided pseudo-hexagonal crystal shapes. The largest of these three crystals is about 15μ across. Many of the other chalcocite grains appear to be irregular in shape. Polished section.

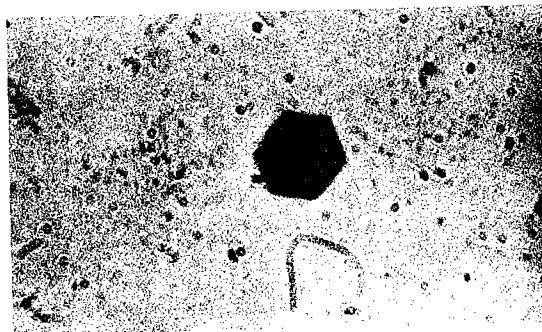


Figure 29. Pseudo-hexagonal tabular chalcocite crystal lying on its basal pinacoid on a glass plate. Crystal is about 10μ across. Viewed with an ultrapac objective.

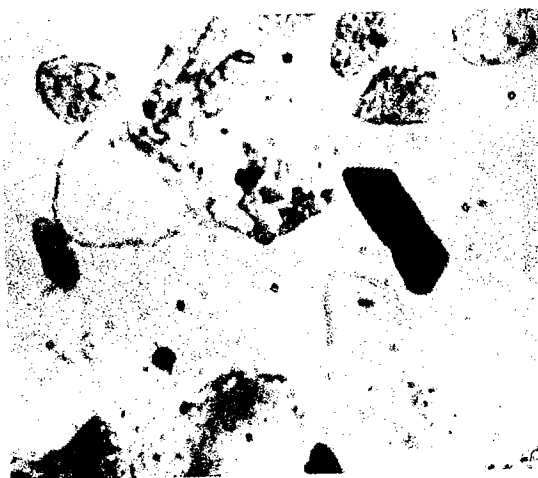


Figure 30. Edge view of pseudo-hexagonal chalcocite crystal that shows its tabular character. Crystal is about 10μ long. Viewed with an ultrapac objective.

elsewhere (fig. 31). They may have been formed by filling compaction fractures (Dingess, this volume, 1976) or, perhaps, mud cracks (Brockie, oral communication). Most of the veinlets appear to consist entirely of chalcocite and do not contain replacement remnants of materials such as pyrite.

Chalcocite Concentrations in Silty Lamellae

Local, thin, silty lamellae within the host shale contain concentrations of chalcocite as shown in figure 32. Minor amounts of

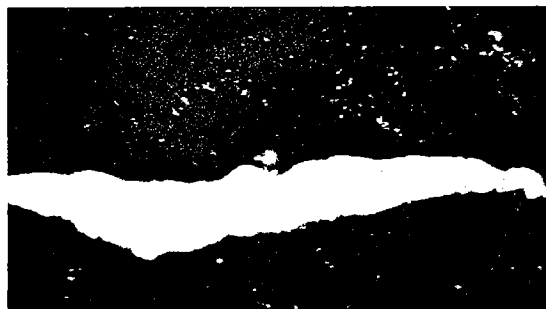


Figure 31. Bedding plane veinlet of chalcocite (white). The veinlet is about 300μ wide and is discontinuous nearly within the margins of the photomicrograph. Tiny bright spots are disseminated grains of copper sulfides. Polished section.

chalcocite are present in this mode of occurrence. The chalcocite grains show a wide range in size and partially fill the interstitial space between silt grains.

Other Ore Minerals

Bornite is rarely present in the polished sections examined thus far by the writers. It occurs as rare replacement remnants that are associated with pyrite atolls in the 20- to 40μ , digenite-chalcocite grains. Bornite probably was formed as an intermediate reaction product in the replacement of pyrite by chalcocite.

Grains of a bright white mineral were observed in a few of the polished sections prepared in the early stages of the study. Reflectance measurements on these grains exceed 60 percent and suggest that they are native silver. This mineral has not been observed in any of the polished sections of the Creta ore that the writers have subsequently studied, and the sections originally containing the mineral are no longer available for study.

Supergene minerals that have been recognized at Creta include covellite, malachite, brochantite, azurite, cuprite (?), and goethite. Covellite is present locally as

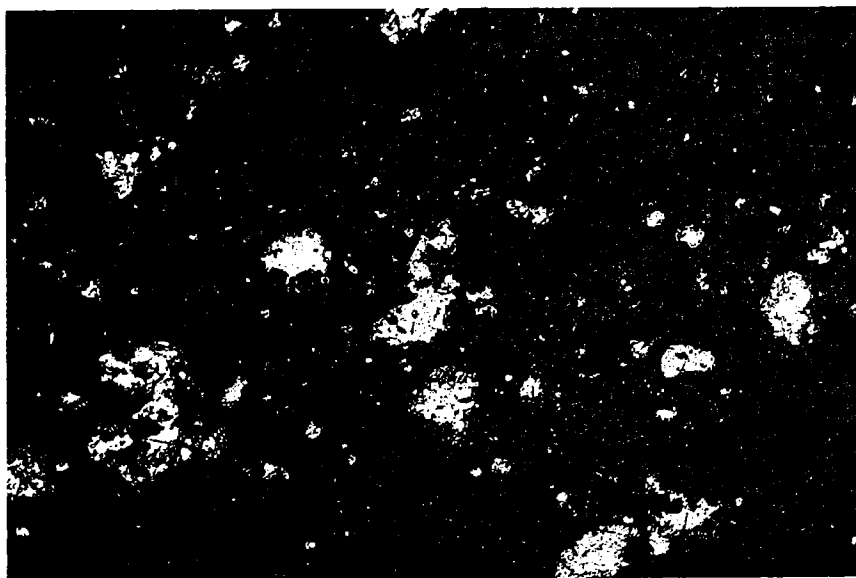


Figure 32. Chalcocite (white) deposited in silty lamellae of Prewitt shale, x 200. Clastic quartz silt grains are light gray; clay is black. Polished section.

an alteration product in some copper sulfide grains in the polished sections of some ore specimens and mill concentrates. Malachite is the most abundant copper mineral on the weathered outcrops of the Prewitt copper shale.

SUMMARY

Microscopic examination of the Creta ore shows that the copper occurs mostly as small grains of copper sulfides. Chalcocite and digenite are the principal copper sulfides. Pyrite occurs as replacement remnants in the copper sulfide grains. Bornite and native silver (?) have been observed in polished sections of the copper ore, but they are present in very minor quantities. Covellite, malachite, goethite, brochantite, azurite, and cuprite (?) formed as a result of supergene oxidation of the primary sulfide ore.

The primary copper mineralization has been observed to exhibit 10 different types of grains as distinguished by their size, shape, and nature of replacement. These types and their characteristic shapes and sizes are:

1. Chalcocite replacement of the spore *Triletes*; ellipsoidal to nearly spherical shapes, generally with smooth exterior surfaces; size range 50 to 250 μ ; most are 100 to 200 μ in diameter.
2. Digenite and chalcocite replacement of pyrite granules; nearly spherical shapes with rough or bumpy exterior surfaces; 20 to 40 μ in diameter.
3. Digenite and chalcocite replacement of pyrite crystals of pyritohedral habit; mostly 6-sided shapes in polished sections; 20 to 40 μ in diameter.
4. Partial digenite and chalcocite replacement of large clumps of pyrite occurring in the gray, laminated shale; form, very irregular patchy replacements; pyrite clumps are as large as 500 μ across.
5. Partial (?) copper sulfide replacement of pyrite crystals of octahedral habit; most are less than 10 μ in width.
6. Partial (?) copper sulfide replacement of pyrite crystals of cubic habit, often modified by the octahedron; most are less than 10 μ in width.
7. Irregularly shaped chalcocite grains; most are less than 10 μ in width.
8. Pseudo-hexagonal chalcocite crystals; 6-sided plates; most are less than 10 μ in width.
9. Thin, discontinuous chalcocite veinlets; most are less than 1 mm wide.
10. Chalcocite fillings of interstitial space in silty lamellae; variable grain size.

Most of the copper sulfide grains at Creta were formed as a result of selective replacement of certain materials in the host shale and mudstone. Their development was conditioned by the presence in the Prewitt copper shale of abundant spores of the genus *Triletes* and iron sulfide grains, both of which were very susceptible to replacement by chalcocite and digenite. Other grains of chalcocite crystallized directly from solution when the copper replacements were formed. The time period when the copper-bearing solutions were active in the shale was subsequent to that of the sedimentary deposition of the spores and the early diagenetic development of pyrite and while the host mud was still permeable. The genesis of the Creta copper ore is intimately connected to the late diagenetic history of the sedimentary rocks of the region and is not a function of magmatic processes. The action of sulfate-reducing bacteria, which used the spores and other organic content of the shale as an energy source, was an important factor in providing sulfur in the reduced state for the precipitation of both the pyrite and copper sulfides.

Most of the copper mineralization at the Creta mine is invisible to the unaided eye, and even the visible portion of the ore is very unspectacular in appearance. For this reason, geologists had overlooked the Creta ore deposit for many years. The potential for future discovery of similar copper deposits in Permian shales in Oklahoma and Texas is good.

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MINERALOGY AND MICROTEXTURES OF SULFIDES IN THE FLOWERPOT SHALE OF OKLAHOMA AND TEXAS

Albert L. Kidwell¹ and Richard R. Bower²

Abstract—Copper and iron sulfides are widely distributed within the Flowerpot Shale. (Guadalupean age) of southwestern Oklahoma and north-central Texas. However, significant amounts of copper are restricted to individual beds that are generally less than 1 foot thick.

Digenite and lesser amounts of chalcocite are the most abundant copper sulfide minerals, and they occur in the following ways: (1) crystals of 1 to 25 microns, (2) pellets and crystal aggregates up to 200 microns, (3) pore-space fillings in sand and silt laminae, and (4) nodules which sometimes reach a diameter of several centimeters. It is suggested that the familiar and established term chalcocite continue to be used when referring to these minerals in a general sense.

Chalcopyrite occurs in the form of sparse crystals and pellets in shales overlying the richest chalcocite. Chalcocite and chalcopyrite can occur in the same sample or independently. There is no direct evidence that chalcocite has formed as an alteration of chalcopyrite.

Covellite is widely distributed within the chalcocite as microscopic, secondary intergrowths. It is generally not apparent in the X-ray diffraction pattern and can completely escape detection except in polished section.

Pyrite forms crystals (generally octahedra) in the 1- to 25-micron range, and it forms pellets up to about 200 microns. It is also one of the principal primary minerals in the chalcocite nodules.

Other primary minerals that occur sparingly are galena and barite. Surface secondary minerals include malachite, azurite, cuprite, goethite, and brochantite.

Detailed study of individual mineral particles at high magnifications with the scanning electron microscope has provided information on the nature and origin of the sulfides. This and other petrographic data indicate that most of the chalcocite is an early replacement of syngenetic pyrite.

INTRODUCTION

The existence of copper mineralization in northern Texas and southern Oklahoma has been noted for over 120 years. It was first reported by Captain R. B. Marcy in 1852, in the Red River area. In 1864, troops from Fort Belknap, Texas, were guided to copper deposits in Archer County, Texas, by a group of Tonkawa Indians. We do not intend to pursue the historical aspects further except to say that numerous individuals and groups have been attracted to these copper deposits as possible commercial enterprises.

Most of the copper occurrences have been found in sedimentary rocks of the Pease River Group (previously part of the Double Mountain Group) in Texas and the

corresponding El Reno Group in Oklahoma. These units are within the lower part of the Permian Guadalupian Series. From bottom to top, the Pease River Group is comprised of the San Angelo Sandstone, the Flowerpot Shale, the Blaine Formation, and the Dog Creek Shale. Copper and iron sulfides occur in each of these formations, but they are most abundant in the lower two.

The San Angelo Sandstone is primarily a red-bed sequence of oxidized sandstones and mudstones. Most of the copper in the San Angelo occurs in clastic fluvial/deltaic deposits and is associated with organic trash that has acted as a reducing agent.

The Flowerpot Shale grades upward from interbedded reddish-brown and light-greenish-gray clastic sediments into interbedded gypsum, red shale, and greenish-gray shale, with a thin dolomite bed at the top that is generally less than 1 foot thick. In Texas, this dolomite is known as the Chalcocite dolomite because of the common presence of chalcocite and its alteration products. Below the dolomite, copper

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sulfides are disseminated within greenish-gray shales and are completely missing in the reddish-brown shale. The same dolomite occurs locally in the area of the Creta Copper Mine in Oklahoma.

This paper is based principally on a study of core samples from Hardeman County, Texas, and a few surface samples from the Creta Mine area, Oklahoma, and from various locations in north Texas, as shown in figure 1.

MINERALOGY

The principal copper mineral in the Permian sediments is a dark gray mineral that has been generally referred to as chalcocite. However, three sulfur-deficient copper sulfides are now known: chalcocite Cu_2S , digenite, $\text{Cu}_{1.79-1.76}\text{S}$, and djurleite, $\text{Cu}_{1.96}\text{S}$. The identity of digenite was established by N. W. Buerger (1941, p. 19) as the material that had been known as blue chalcocite for many years. It can occur as the pure mineral but more commonly is in-

tergrown with chalcocite. It has a characteristic X-ray diffraction pattern that is quite distinct from that of chalcocite.

Djurleite was defined as a new mineral by E. H. Roseboom (1962, p. 1181) on the basis of the close correspondence between X-ray diffraction data of natural material with those of a synthetic compound that had been prepared and described by Djurle (1958, p. 1415). Distinguishing between djurleite and chalcocite is very difficult by any means other than X-ray diffraction because of their close similarity in composition.

Our X-ray diffraction work has shown that the principal copper mineral disseminated in the Flowerpot Shale is digenite, as shown in figure 2. The X-ray diffraction pattern is simple, as is characteristic of isometric minerals. It corresponds almost perfectly with digenite from Butte, Montana. This has proved to be true for each sample of the disseminated mineral that we have X-rayed, including a composite sample of the material from Creta. There are also suggestions of chalcocite in the X-ray diffraction patterns. This was confirmed by study of several polished sections that show the presence of both chalcocite and digenite at high magnification.

Since the term chalcocite is firmly rooted, it is perhaps best to continue using it as a nonspecific family name for sulfur-deficient copper sulfides for which precise X-ray diffraction or analytical data are not available.

The disseminated copper sulfides in the Flowerpot formation are very finely divided, as will be discussed later, but the chalcocite nodules present in sandstone channel deposits of the San Angelo and lower Flowerpot formations can be several centimeters in diameter. They commonly replace wood or are associated with carbonized wood. Mineralogically, two of the samples analyzed are principally digenite, with a small amount of chalcocite. The third sample is mainly chalcocite with small amounts of digenite and what appears to be djurleite.

The other copper sulfide, covellite, was not detected in X-ray diffraction patterns of any of the disseminated sulfides. However, the polished sections show that it is commonly intergrown with chalcocite and (or) digenite in many of the samples. The in-

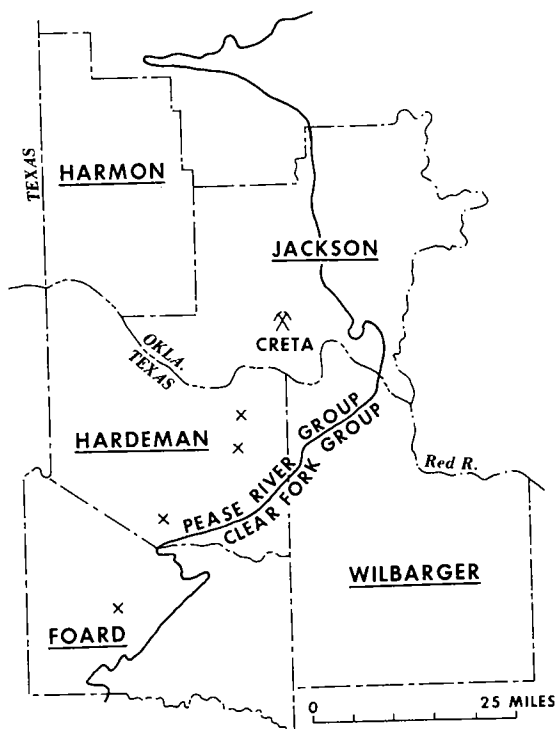


Figure 1. Location of sulfide samples from the Flowerpot Shale.

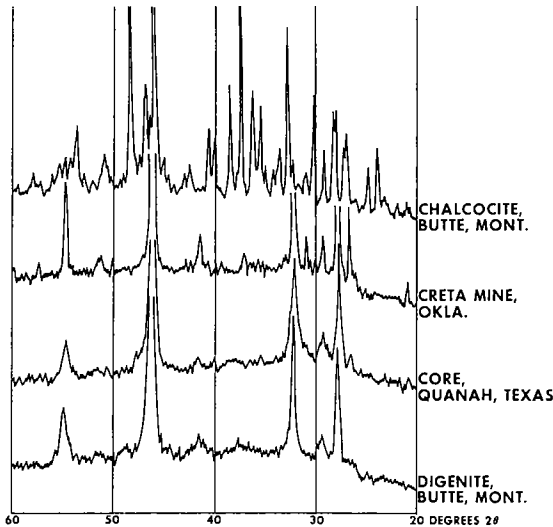


Figure 2. X-ray diffraction patterns of sulfur-deficient copper sulfides.

tergrowths are easily identified at high magnification on the basis of strong pleochroism and distinctive anisotropism. The only megascopic covellite we found was in a prospect north of Aspermont, Texas, where covellite is replacing cubic crystals of galena.

Chalcopyrite has a limited occurrence in some of the greenish-gray shales of the Flowerpot, where it occurs as tetrahedra and as rounded grains smaller than about 100 microns. It generally occurs in shales a few feet higher in the section than the chalcocite, although small amounts of both can occur together.

Native copper has been reported from various parts of the area, but the only occurrence we observed was in a thin section that showed tiny arborescent masses with chalcocite in a gypsum-filled vug.

Pyrite is a common constituent of sandstone channel-type copper deposits, where it occurs as unreplaced remnants within the chalcocite nodules. It also occurs as microscopic constituents of the Flowerpot shales, but it doesn't occur abundantly in samples containing chalcocite. This will be discussed later in more detail.

Galena is rare, but it does occur—both in cores and in some of the surface samples. In several cores from Hardeman County, a few small crystals were found about 6 feet

stratigraphically above the principal zone of disseminated chalcocite. Galena was also found with pyrite filling veinlets in dolomite nodules at an outcrop north of Aspermont, Texas.

Sphalerite and native silver have been reported from some localities, but none was found in any of our samples.

Alteration products of the copper and iron sulfides include malachite, azurite, brochantite, cuprite, and goethite.

MICROTEXTURES

The remainder of the paper will be restricted to the microtextures and mode of occurrence of sulfides within the greenish-gray shales of the Flowerpot.

Thin-Section Study

This study will be illustrated with photomicrographs taken of normal thin sections using transmitted light. The advantage is that the sulfides stand out sharply against the non-opaque rock-forming minerals. The disadvantage is that it is impossible to distinguish one sulfide from another. However, under the microscope they are easily distinguished by using reflected light.

The most characteristic mode of occurrence for chalcocite is as disseminated particles that show a distinctly bimodal and even trimodal distribution. In the first photomicrograph (pl. 1, fig. 1), at a magnification of 32x the chalcocite appears to be bimodal, in that grains occur in sizes up to about 25 microns, and there is a gap in size to about 50 microns. Plate 1, figure 2, the same field at a magnification of 200x, shows one group of grains in the 1- to 5-micron range and another in the 15-25 micron range, with a size gap in between. Most of these are individual grains in the form of cubes, octahedra, or spheres, and in these simple forms they seldom exceed about 25 microns. The reason for the size-distribution gap between about 5 and 15 microns is not clear. The larger grains (greater than 50 microns) are mostly composite grains made up of an aggregation of smaller crystals or, in some

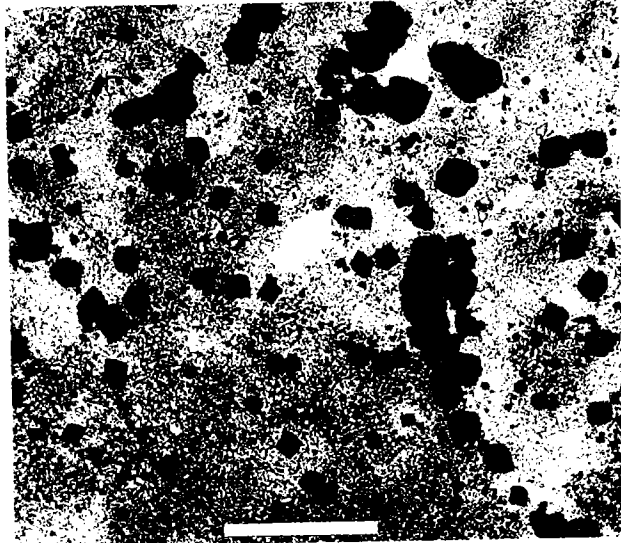
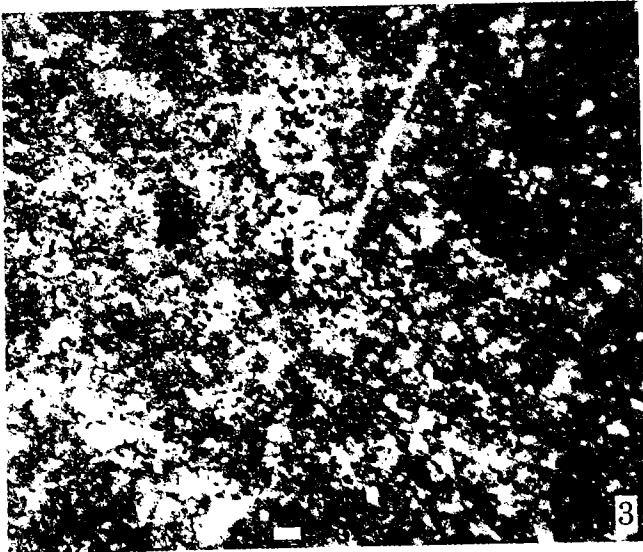
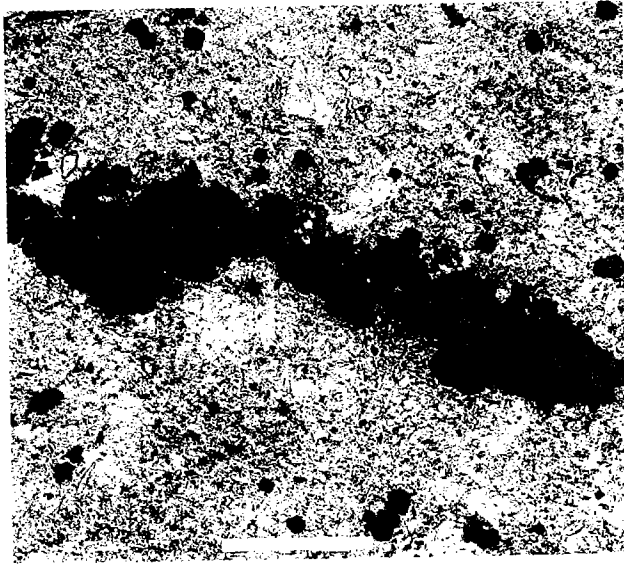
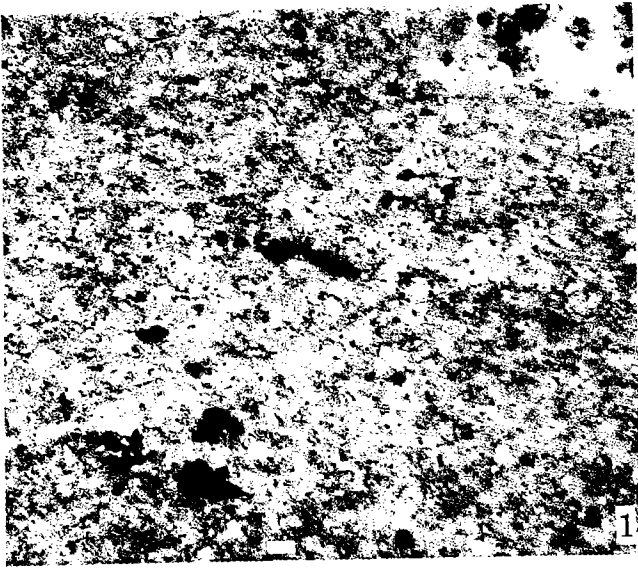


Plate 1

White bar = 100 microns in all photomicrographs

1. Chalcocite grains in mudstone. Transmitted light, X32.
2. Chalcocite grains in mudstone. Transmitted light, X200.
3. Pyrite grains in mudstone. Transmitted light, X32.
4. Pyrite grains in mudstone. Transmitted light, X200.

instances, they may be replacements of microfossils or fragments of organic matter.

A similar type of grain distribution is shown among pyrite grains in plate 1, figures 3 and 4, at magnifications of 32x and 200x. The gap in the size distribution between 5 and 15 microns is quite apparent, as is the aggregate nature of the larger grains. The pyrite is from a sample collected a few feet higher in the core than where any chalcocite was found; in fact, there is very little overlap in general between the presence of chalcocite and pyrite. Very few pyrite grains have been observed with chalcocite, and vice versa; chalcocite simply decreases in amount and disappears over a distance of a few inches upward and downward. We feel this is evidence that chalcocite has replaced pyrite in part of the section, but copper was not available to replace pyrite in other parts of the section.

Another striking feature is the consistency with which sulfides are more abundant in shale with little or no bedding, or with disturbed bedding caused by burrowing organisms, than in well laminated layers. Figure 1 of plate 2 shows a very high concentration of chalcocite within a disturbed area of the sediment. Plate 2, figure 2, shows a sharply defined discontinuity that was probably a tube caused by some burrowing organism; in this case, however, the sulfide is pyrite instead of chalcocite.

A frequent mode of occurrence is in sandy and silty lenses or laminae where chalcocite is forming the cementing material and replacing part of the clastic grains, as shown in plate 2, figure 3. A variation of this is shown in figure 4 of the same plate, where a chalcocite aggregate occurs in a lens of coarse silt and appears to have contributed to the bending of the overlying and underlying layers during growth.

One additional mode of occurrence is chalcocite in veinlets or fillings of microbreccias where there appears to have been some redistribution of the original chalcocite.

Another point bearing on the relative age of the mineralization is the presence of chalcocite smeared out along slickensided surfaces of compaction features. These were probably formed during early diagenesis before much lithification had occurred and under a fairly thin sediment load.

Scanning Electron Microscope

A number of photomicrographs of individual sulfide particles have been taken with the scanning electron microscope. A few of these are included to illustrate the type of information that can be obtained by this method.

Briefly, the equipment is an electron microscope in which the sample is scanned with a very finely collimated electron beam and the reflected electrons are picked up by a detector and form a magnified image on a sensitized screen. The image can then be photographed. In the photomicrographs, one is looking at a radar-type image instead of the object itself, and the color has no relation to the true color of the particle. At the same time, the chemical elements in the mineral bombarded by the electron beam give off their characteristic X-rays, and these can be electronically collected and displayed as a continuous spectrum. For example, when observing a particle under the microscope, one cannot distinguish between pyrite, chalcopyrite, and chalcocite (except by shape of the grain), but the elemental spectrum can be obtained quickly from a spot a few microns in diameter.

Some of the chalcocite particles in the photomicrographs leave little doubt that pyrite crystals have been replaced. Plate 3, figure 1, shows 2 octahedral crystals about 15 microns across that have been partly uncovered from the enclosing shale. Plate 3, figure 2, shows an individual octahedron about 10 microns across that has been replaced by chalcocite. These are unquestionably isometric crystals, and pyrite crystals formed under these conditions are frequently octahedral rather than cubical. Figure 3 of plate 3 shows a 20-micron crystal of a somewhat different crystal habit that was also probably pyrite originally. Plate 3, figure 4, shows a mass of chalcocite about 50 microns in diameter that appears to be a very rough and irregular isometric crystal.

Chalcocite also occurs in larger pellets or nodules which show no particular crystal form but which also were probably pyrite, originally. Plate 4, figure 1, shows a pellet that is about 200 microns in diameter and is obviously a granular aggregate. It contains what appear to be shrinkage cracks, a

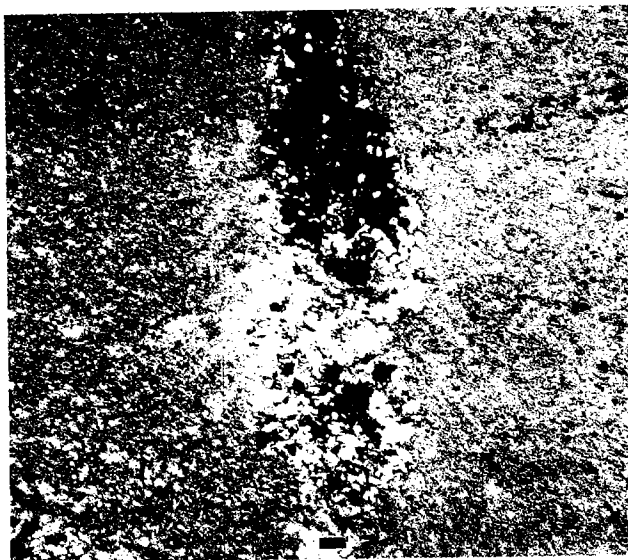
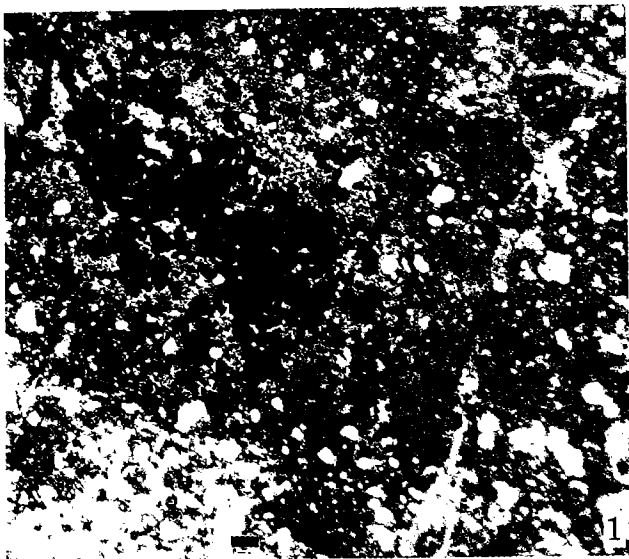


Plate 2

Bar = 100 microns in all photomicrographs

1. Chalcocite in disturbed sediment. Transmitted light, X32.
2. Pyrite in burrow filling. Transmitted light, X32.
3. Chalcocite cementation in lens. Transmitted light, X32.
4. Chalcocite aggregate in silt lens. Transmitted light, X80.

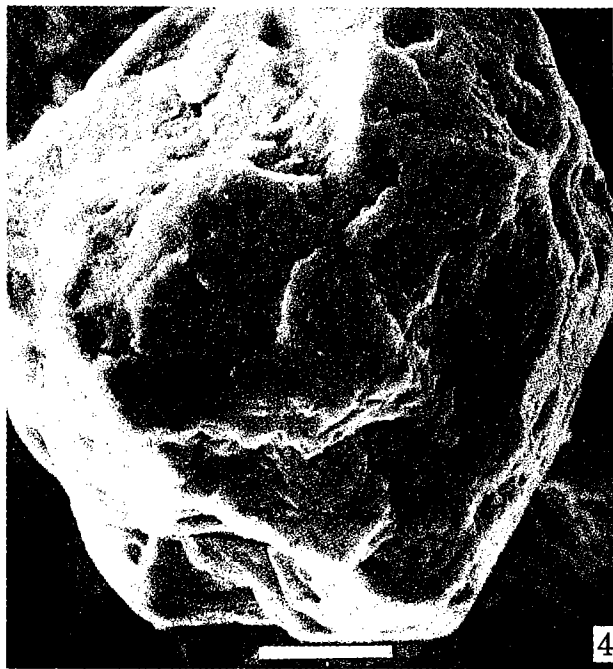


Plate 3

White bar = 10 microns in all photomicrographs

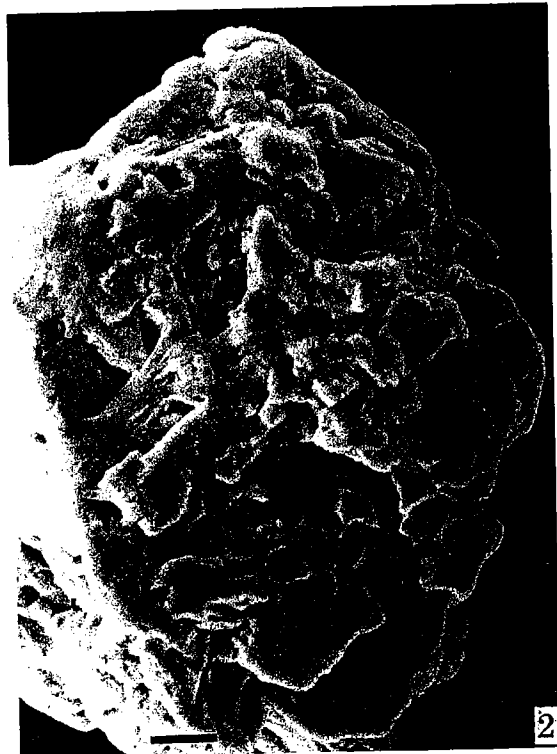
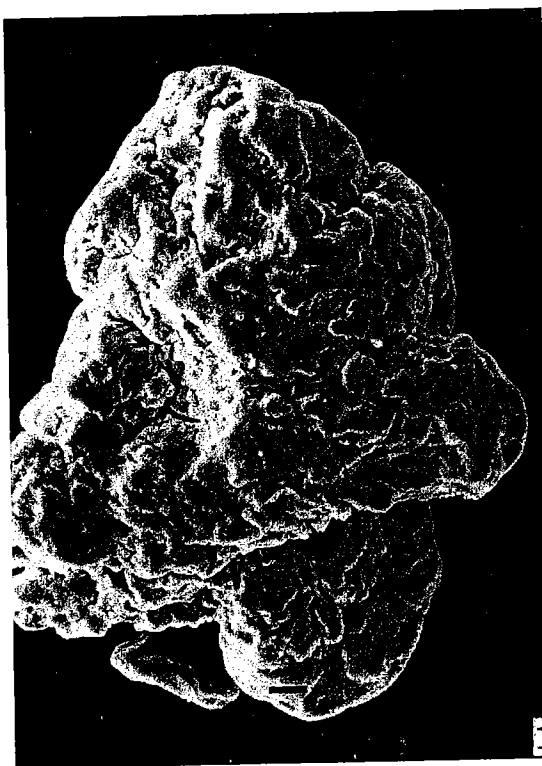
1. Chalcocite in octahedral crystals. Scanning electron microscope, X1780.
2. Chalcocite in octahedral crystal. Scanning electron microscope, X8500.
3. Chalcocite crystal from mudstone. Scanning electron microscope, X4300.
4. Chalcocite grain from mudstone. Scanning electron microscope, X1780.

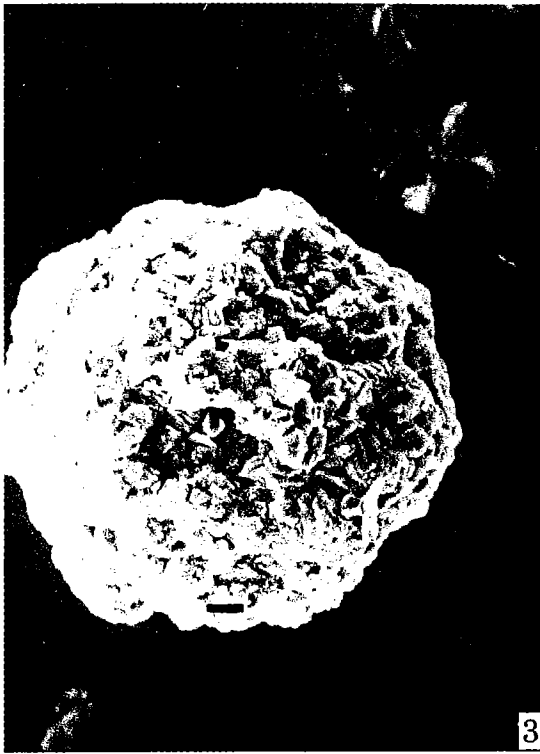
Plate 4

Bar = 10 microns in all photomicrographs

1. Chalcocite pellet showing shrinkage cracks. Scanning electron microscope, X440.

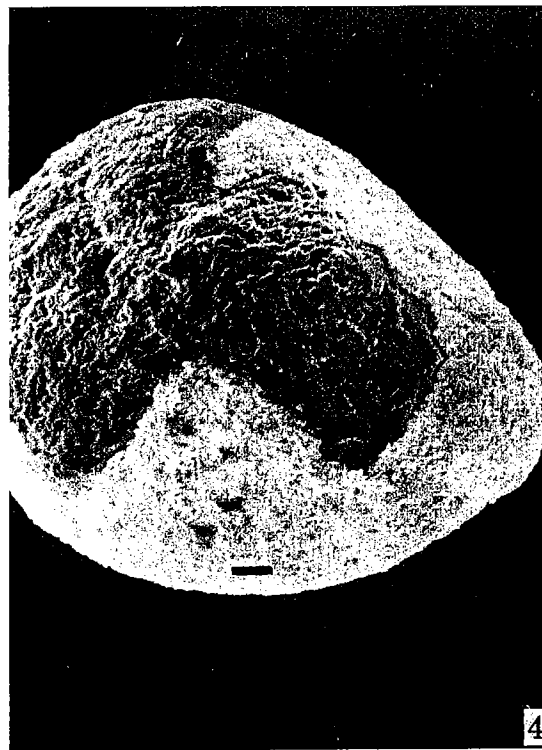
2. Crystallized chalcocite pellet. Scanning electron microscope, X880.





3. Crystallized pyrite pellet. Scanning electron microscope, X440.

4. Pellet of chalcocite with barite. Scanning electron microscope, X420.



feature that many of these pellets possess. Plate 4, figure 2, portrays an aggregate of recognizable crystals of chalcocite replacing pyrite, together with some prismatic needles that are probably gypsum. Figure 3, plate 4, is a crystal aggregate of pyrite that is about 150 microns in diameter. Its general appearance is similar to that of the chalcocite pellet in the preceding photomicrograph. Plate 4, figure 4, illustrates a somewhat larger, rounded grain that has been replaced by chalcocite and coated with a thin layer of barite (white outer layer). These grains are quite common, and their shape may range from almost perfect spheres to ellipsoids. Some of them are hollow, and they probably represent some type of microfossil.

CONCLUSIONS

1. Based on X-ray diffraction data and the study of polished sections, the principal copper sulfide mineral present in the Flowerpot Shale is digenite.

2. Both chalcocite and covellite occur with digenite but are distinguishable only at high magnification in polished sections.

3. Djurleite was tentatively identified by X-ray diffraction as a constituent of chalcocite nodules collected from the channel-type deposits.

4. The most common mode of copper occurrence in shale is disseminated grains of bimodal- or trimodal-size distribution that are replacing pyrite crystals.

5. Other modes of occurrence are as cementation of sandy or silty laminae, as veinlets, and as cementation of microbreccias.

6. Based on mineralogical and textural evidence presented, we conclude that mineralization is of early diagenetic origin.

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GEOCHEMISTRY AND PETROLOGY OF SOME OKLAHOMA RED-BED COPPER OCCURRENCES

Richard P. Lockwood¹

Abstract—Two copper-rich shales are being developed or mined in southwestern Oklahoma, the Mangum deposit in Ts. 3 and 4 N., R. 22 W., and the Creta deposit in Ts. 1 and 2 S., R. 22 W. The principal ore mineral at Mangum is malachite and at Creta is chalcocite. Both deposits are in the upper part of the Permian Flowerpot Shale, which consists of reddish shale with interbeds of gray shale, gypsum, and dolomite. The Flowerpot is of late Leonardian or early Guadalupian age.

Samples of ore and non-ore rock were analyzed for quartz, gypsum, K_2O , CaO , Pb , V , Co , Ni , Fe , CuO , ZnO , MoO_3 , and organic matter. Two gypsum and 7 chalcocite samples from Creta were analyzed for $\delta^{34}S/^{32}S$.

The patterns of correlation coefficients are similar for shales of the same color in each deposit and for each deposit as a whole. There are two sets of correlations in each deposit: positive correlations between K_2O and Co , Ni , V , Ag , Fe (and ZnO , at Mangum) and negative correlations between gypsum and the same metals. The positive set is interpreted as due to the structural or interlayer position of these metals in illite. The negative set is interpreted as products of illite dilution by gypsum.

Sulfur-isotope analyses revealed a wide range of $\delta^{34}S/^{32}S$ values for chalcocite and higher, and more uniform values for gypsum. This is consistent with a bacteriogenic origin of the sulfide. Since there are no Pb - Zn zones of the Schurmann type, the chalcocite at Creta is interpreted as diagenetic. The overburden is thicker at Creta; where it is thin, the ore has oxidized to malachite. The Mangum malachite deposit is interpreted as an oxidized analogue of the Creta deposit.

INTRODUCTION

The following report is concerned exclusively with two copper shale deposits in Oklahoma. The first is located near Mangum, in Greer County, in Ts. 3 and 4 N., R. 22 W. The other deposit, located near the railroad siding of Creta, lies in the western two-thirds of Ts. 1 and 2 S., R. 22 W.

Stratigraphy

Both copper shale deposits are in the upper part of the Permian Flowerpot Shale of the El Reno Group. The formation consists of reddish-brown shales and siltstones with interbedded gypsums (Ham and Johnson, 1964, p. 9). Postulated depositional environments are marine (Ham and Johnson, 1964, p. 9-10) or shallow marine or brackish (Wilson, 1962, p. 33).

The copper shale in the Creta area is called the Prewitt bed, and the copper shale in the Mangum deposit is called the Meadows bed (Johnson, elsewhere in this volume).

Structural Geology

No folding or faulting was observed in pit walls or outcrops during the mapping and sampling. There are no structural elements known in the area that could provide a path for mineralizing solutions.

Methods of Investigation

Particulars of the sample collection, treatment, and analysis for this study are described in Lockwood (1972, p. 20-35).

Acknowledgments

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Oklahoma, along with Dr. K. S. Johnson and others of the Oklahoma Geological Survey were a great help.

RESULTS

Minor Element Statistics

The following discussion of results and hypotheses will be based on relations between variables, as expressed by correlation coefficients, mean variables, and standard deviations of the means for the variables.

Because the computer program does not provide for inputting accuracy and reproducibility for each variable, all correlation coefficients have numerical values higher than they would otherwise have been. There is no way to estimate the amount of change this problem causes. I have attempted to diminish the effect by ignoring correlation coefficients whose absolute values did not exceed 0.50.

In the case of the Mangum deposit, the standard deviations of quartz, chlorite, and malachite are relatively small compared to those at Creta (tables 1 and 3). The rocks are composed of illite, gypsum, quartz, chlorite,

and malachite; however, because the percentages of quartz, chlorite, and malachite do not vary much, gypsum and illite dilute each other. For this reason, there are 2 sets of correlation coefficients: 1 for correlation with K_2O (interpreted to be illite), and 1 with the opposite sign for correlations with gypsum (tables 2 and 4). The situation is complicated slightly in the case of the Creta deposit by the increased variance of quartz, but this dual classification of correlations between gypsum and illite is still appropriate. Because of this dilution we shall deal with only one set of coefficients. The non-redundant lists of important correlation coefficients are as below (table 5).

A number of interpretations explain the correlation coefficients in the upper part of table 5. There are 5 or 6 elements (Creta and Mangum, respectively) that are probably associated with illite in 3 types of positions—in the structure, in interlayer positions on the clay mineral grain, or adsorbed on the clay mineral surface. There are, then, 15 or 18 separate hypotheses for the distribution of these elements.

The most direct method of locating the 5 or 6 elements associated with illite is to

Table 1.—Composition Means and Standard Deviations (in Parentheses)
by Shale Type in the Mangum Deposit
(All values weight percent unless otherwise noted)

	Mottled shales	Copper-rich shales	Gray shales	Red shales	Maroon shales
Quartz	26.4 (7.6)	26.0 (5.0)	26.2 (6.0)	26.9 (7.2)	23.6 (5.5)
Gypsum	18.4 (19.3)	13.2 (12.1)	13.0 (11.9)	16.3 (14.2)	17.4 (24.8)
Illite	44.6 (11.4)	48.5 (6.7)	47.9 (9.4)	43.6 (11.0)	45.7 (13.5)
Chlorite	11.2 (8.7)	8.8 (5.7)	11.2 (10.3)	12.4 (11.0)	14.9 (13.1)
Malachite	0.0 (0.0)	3.6 (2.3)	1.7 (2.1)	0.1 (0.5)	0.0 (0.0)
Ag ppm	30.9 (10.2)	31.0 (14.9)	34.7 (12.5)	25.9 (11.3)	33.1 (9.7)
Pb ppm	23.5 (8.0)	87.8 (71.0)	52.0 (55.8)	21.1 (6.6)	19.3 (6.2)
V ppm	124.9 (40.4)	124.0 (32.7)	119.3 (35.8)	107.3 (34.3)	115.0 (50.6)
Co ppm	17.7 (10.8)	24.0 (14.8)	19.1 (11.5)	18.6 (9.7)	18.0 (11.1)
Ni ppm	44.7 (16.9)	55.3 (9.6)	51.2 (12.8)	38.5 (12.3)	44.4 (17.2)
CuO	0.19 (0.04)	2.59 (1.61)	1.29 (1.49)	0.18 (0.09)	0.19 (0.05)
Fe ₂ O ₃	5.66 (1.35)	5.17 (0.99)	5.21 (1.25)	6.44 (1.73)	6.06 (2.16)
K ₂ O	3.46 (0.89)	3.77 (0.52)	3.72 (0.73)	3.38 (0.85)	3.55 (1.04)
CaO	5.62 (3.58)	4.74 (2.97)	4.77 (3.42)	6.92 (4.59)	2.58 (1.40)
Organics	1.22 (0.57)	1.75 (0.48)	1.71 (0.88)	1.69 (0.41)	1.45 (0.35)
ZnO	.035 (.005)	.035 (.005)	.036 (.005)	.037 (.003)	.038 (.004)
U	.010 (.001)	.008 (.002)	.009 (.002)	.009 (.001)	.009 (.001)
MoO ₃	.012 (.002)	.010 (.002)	.011 (.002)	.010 (.002)	.009 (.002)

Table 2. — Significant Correlation Coefficients by Shale Type in the Mangum Deposit (Absolute values less than 0.50 are omitted)

Gypsum	Illite	Chlorite	Malachite	Ag	Pb	V	Co	Ni	CuO	Fe ₂ O ₃	K ₂ O	CaO	Organic Matter	ZnO	U	MoO ₃		
-.58						.61		.52		.58								Quartz
.87-.55	.66			.66	.51	.54 .56	.74	.72		.71	.65	.78		.54				Gypsum
	.64-.87	-.59		-.54-.51	-.61	-.60-.87	-.51	-.64-.81	-.50	-.69-.74	-.64-.87	.78 .74		-.61	-.59	-.76		Gypsum
	-.72			-.50	-.61	-.75	-.73	-.72	-.59	-.73	.75			-.70	.58			Gypsum
	-.66-.90	-.53-.67		-.79-.63	-.69	-.63-.80	-.72	-.74-.85	-.63	-.68-.89	-.66-.90	.0 .93		-.54-.76		-.51		Gypsum
				.67	.64	.87 .95	.66	.91 .95	.63	.93 .86		-.92-.88		.70		.64		Illite
				.55	.71	.94	.90	.90	.63	.83		-.91	.73	.85				Illite
				.85	.60	.73	.93 .78	.98	.98	.89		-.88-.90		.97 .76				Illite
				.60			.53	.61		.69		-.57		.67	.81			Chlorite
				.54								-.98						Chlorite
				-.69	.58													Malachite
						.54		.77	-.55	.55		.67	-.72	.61		.59		Ag
				.81	.89	.57	.79	.88	.68	-.71	.83 .74	.86 .61	-.68-.57	.81 .70		.68		Ag
					.66	.75		.57		.57	.64			.57	-.87			Pb
					.69	.69		.68	.56	.58	.71	-.59		.69				Pb
					.68	.70 .83	.75		.70	.74				.63	-.89			Pb
					.54	.82 .92		.87	.62	.83 .88	.87 .95	-.80-.89		.64		.64		V
					.95	.88		.87	.62	.87	.94	-.95	.53	.87				V
					.87	.94 .65		.86	.76	.93 .78	-.75-.80		.53	.89 .56				V
					.58	.65		.60	.75		.67				-.58			Co
					.80			.94	.90		-.91	.61		.89				Co
					.96			.99	.63	.98				.94	-.68			Co
								.66	.85 .83	.91 .95	-.85-.94			.68	-.58	.59		Ni
								.66	.90	-.92				.82				Ni
								.94	.87 .98	.87	-.83			.90 .83				Ni
									.52	.62	-.56	.54						CuO
															-.50			CuO
										.94 .86	.90 .63			.75	.78			Fe ₂ O ₃
										.83	-.77	.73		.97	.85		-.55	Fe ₂ O ₃
										.98 .90	-.90							Fe ₂ O ₃
											-.92-.87			.71				K ₂ O
											-.91	.73		.85				K ₂ O
											.89 .93			.97 .77				K ₂ O
													-.50	-.65	-.62			CaO
														-.86	-.71			CaO
														-.82-.79				CaO
															.62			Organic Matter
																		ZnO
																		U

r-gray shales r-mottled shales
 r-red shales
 r-maroon shales r-Cu>avg.

Table 3. — Composition Means and Standard Deviations (in Parentheses) by Shale Type in the Creta Deposit (nd = not determined; all values weight percent unless otherwise noted)

	Gypsums	Copper-rich shales	Gray shales	Red shales	Maroon shales
Quartz	1.0 (0.0)	19.2 (8.3)	25.7 (10.8)	24.7 (2.1)	29.8 (9.9)
Gypsum	90.0 (3.0)	15.7 (16.0)	10.2 (16.5)	5.0 (4.0)	1.6 (1.0)
Illite	9.0 (3.0)	47.9 (10.8)	51.6 (10.2)	47.3 (5.1)	56.4 (5.5)
Chlorite	0.0 (0.0)	15.7 (15.4)	11.8 (10.9)	23.0 (9.2)	12.0 (4.7)
Chalcocite	0.0 (0.0)	3.0 (1.56)	1.0 (1.6)	0.0 (0.0)	0.0 (0.0)
Ag ppm	1.3 (2.3)	26.0 (17.1)	41.5 (19.0)	23.0 (2.6)	41.5 (5.7)
Pb ppm	23.0 (33.8)	97.1 (82.2)	55.5 (65.6)	28.0 (4.6)	16.5 (2.9)
V ppm	2.0 (3.5)	93.9 (35.2)	113.0 (37.4)	106.0 (24.1)	130.9 (20.5)
Co ppm	0.3 (0.6)	19.6 (14.0)	19.5 (10.8)	30.7 (6.0)	24.7 (6.9)
Ni ppm	1.0 (1.0)	48.0 (13.8)	48.5 (11.9)	31.7 (9.5)	45.8 (4.7)
CuO	0.27 (0.15)	3.17 (1.56)	1.26 (1.61)	0.16 (.01)	0.15 (0.02)
Fe ₂ O ₃	0.68 (0.18)	4.30 (1.30)	5.04 (1.38)	9.30 (0.91)	7.10 (1.34)
K ₂ O	0.70 (0.20)	3.71 (0.84)	4.01 (0.79)	3.68 (0.39)	4.38 (0.44)
CaO	nd	5.34 (3.85)	3.06 (2.95)	4.82 (4.46)	1.48 (1.24)
Organic	1.06 (nd)	1.29 (0.78)	1.48 (0.75)	0.99 (0.50)	1.83 (0.83)
ZnO	.021 (.012)	.028 (.008)	.029 (.009)	.037 (.001)	.037 (.010)
U	.008 (.002)	.007 (.002)	.009 (.002)	.009 (.001)	.010 (.001)
MoO ₃	.006 (.003)	.009 (.002)	.010 (.002)	.007 (.001)	.009 (.001)

Table 6. — Test of Metal Adsorption on Shales from the Mangum and Creta Deposits
(Numbers represent ratios of counts from illite flakes, made on JEOL-Princeton
Gamma Tech nondispersive analyzer, and include analyses made before and
after ion exchange)

Mangum Specimens:	K/Si+K	V/Si+K	Fe/Si+K	Co/Si+K	Ni/Si+K	Ag/Si+K	Zn/Si+K
MA (41.25-52.25)							
before	0.225	0.075	0.208	0.052	0.049	0.022	0.043
after	0.322	0.066	0.330	0.052	0.044	0.019	0.037
MC (46.25-49.25)							
before	0.212	0.085	0.216	0.077	0.068	0.033	0.053
after	0.190	0.042	0.140	0.029	0.025	0.012	0.020
ME (62.75-65.75)							
before	0.227	0.036	0.133	0.027	0.023	0.011	0.019
after	0.144	0.027	0.106	0.018	0.016	0.007	0.013
MI (12.25-17.25)							
before	0.251	0.064	0.351	0.051	0.042	0.020	0.038
after	0.186	0.038	0.149	0.025	0.024	0.010	0.019
MG (52.00-55.00)							
before	0.196	0.032	0.120	0.022	0.020	0.009	0.016
after	0.210	0.040	0.177	0.027	0.027	0.011	0.022
Creta Specimens:	K/Si+K	V/Si+K	Fe/Si+K	Co/Si+K	Ni/Si+K	Ag/Si+K	
CN-100 (54.75-60.75)							
before	0.132	0.039	0.219	0.029	0.025	0.011	
after	0.272	0.041	0.187	0.031	0.028	0.011	
CSP-1 (56.00-62.00)							
before	0.249	0.045	0.132	0.036	0.037	0.014	
after	0.295	0.054	0.254	0.042	0.036	0.014	
CSP-5 (60.75-76.25)							
before	0.271	0.054	0.252	0.044	0.041	0.018	
after	0.154	0.031	0.112	0.022	0.019	0.008	
A (0.00-3.00)							
before	0.251	0.056	0.125	0.044	0.040	0.017	
after	0.229	0.050	0.223	0.037	0.034	0.016	
D (3.00-6.00)							
before	0.230	0.053	0.165	0.042	0.038	0.017	
after	0.223	0.038	0.112	0.026	0.022	0.011	

siderations of their electro-negativities and bond lengths, either may be a possibility for some.

Sulfur-Isotope Data

A few general principles and findings should be considered before discussing conclusions derived from the sulfur-isotope analyses of the specimens from Creta. Modern sulfate-reducing bacteria can live in significant numbers where the characteristics of the chemical environment vary widely (Baas Becking and others, 1960, p. 270) and the burial depth is moderate (Feely and Kulp, 1957, p. 1838). Some types of sulfate-reducing bacteria probably have been

present throughout much of the history of the earth, particularly in view of the postulated exceedingly early evolution of anaerobes (Cloud, 1971, p. 527).

It has been observed that there is little difference between the $\delta^{34}\text{S}/^{32}\text{S}$ of a sulfate solution and the $\delta^{34}\text{S}/^{32}\text{S}$ of a sulfate mineral, such as gypsum or anhydrite, precipitated from that solution (Holser and Kaplan, 1966, p. 98).

Nakai and Jensen (1964, p. 1899) have shown that the equilibrium constant for interchange of ^{34}S and ^{32}S between sulfate ion and sulfide ion is strongly temperature dependent. As a result, the sulfur-isotope ratios of high-temperature

sulfide deposits converge, and the spread of $\delta^{34}\text{S}/^{32}\text{S}$ values is relatively small. Conversely, for low-temperature deposits, any initial difference of $\delta^{34}\text{S}/^{32}\text{S}$ will be preserved (Nakai and Jensen, 1964, p. 1899).

Modern experiments on cultures of *Desulfovibrio desulfuricans* indicate that the isotopic composition of sulfur in bacteriogenic sulfide ions is always much lower than that of the original sulfate ions. Furthermore, these experiments also indicate that when the sulfur-isotope ratio of the dissolved sulfate is constant, the sulfur-isotope ratio of the sulfide ion varies with the rate of sulfide production (Jensen and Nakai, 1964, p. 311).

Based on the history of sulfur isotopes in sea water (fig. 1) as constructed by Holser and Kaplan (1966, p. 120), and the fractionation of approximately 1 part per mil between aqueous sulfate ion and gypsum, we should expect that the northern and southern gypsum specimens, which are about 230 million years old, would both have $\delta^{34}\text{S}/^{32}\text{S}$ values of about +11. The two specimens

have $\delta^{34}\text{S}/^{32}\text{S}$ values of +6.25 and +4.67, respectively. The narrow range of $\delta^{34}\text{S}/^{32}\text{S}$ is as expected, although the sulfur is several parts per mil lighter than was expected.

The range of $\delta^{34}\text{S}/^{32}\text{S}$ for chalcocite concentrates from Creta is from -0.86 to -34.59 parts per mil (table 7). All of the sulfur-isotope ratios of sulfide are lower than those of sulfate, which is consistent with formation of the sulfide by bacterial reduction of sulfate. Moreover, this range is large compared to the $\delta^{34}\text{S}/^{32}\text{S}$ range of hydrothermal deposits.

In view of the absence of any correlation between copper content of the Creta and Mangum specimens and any other variable, the interpretation of these sulfur-isotope ratios is that the copper minerals present in the unweathered Prewitt copper shale at Creta were originally localized due to reaction with sulfide ion produced by the bacterial reduction of sea-water sulfate ion. This localization could have been either syngenetic or diagenetic. The diagenetic hypothesis suggests that the copper

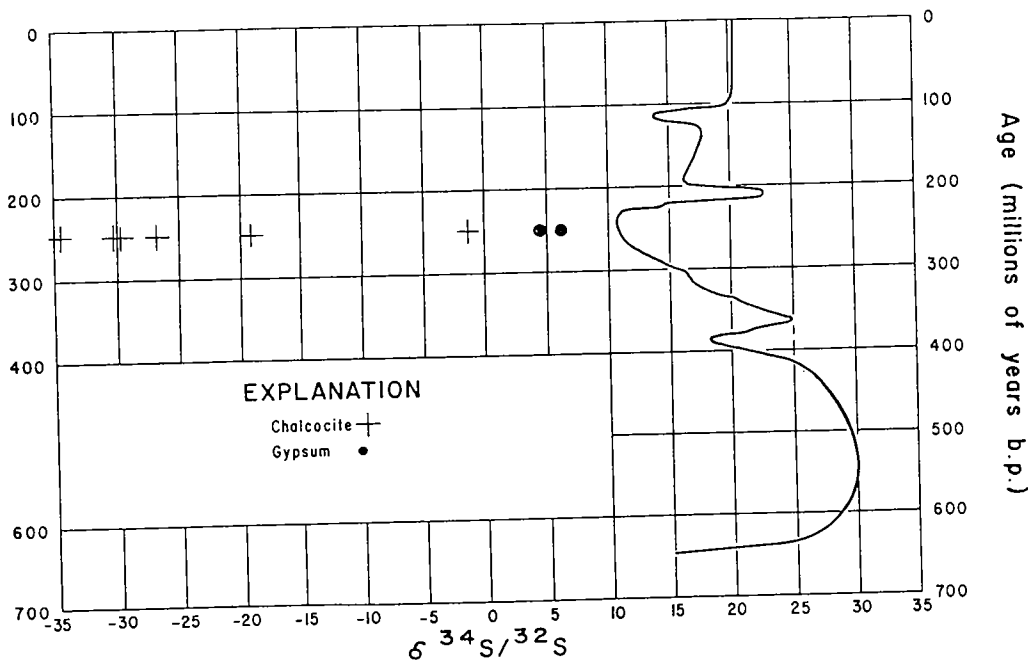


Figure 1. Relationship between sulfur isotope history of sea water, represented by curve (Holser and Kaplan, 1966, p. 120), and Creta gypsums, from the bottom of the gypsum, and chalcocites, from the laminated ore bed below the gypsum.

Table 7. — Results of Sulfur-Isotope Analyses of Gypsum and Chalcocite Concentrates from the Creta Deposit

Chalcocite Concentrates:		
CN-100	(54.75-60.75)	-34.59
CSP-1	(56.00-62.00)	-19.17
CSP-1	(62.00-67.00)	- 0.86
CSP-5	(60.75-76.25)	-26.77
B	(4.10- 7.10)	-19.07
C	(1.20- 4.20)	-29.72
D	(3.00- 6.00)	-30.27
Gypsum Specimens:		
L-16	southern	+ 4.67
L-17	northern	+ 6.25

minerals may have replaced iron sulfide minerals that had already been precipitated. Cubiform crystals in the Prewitt bed that might be chalcocite pseudomorphs after pyrite are reported elsewhere in this volume (Hagni and Gann article, Johnson article, and Kidwell and Bower article). The only crystal forms that were recognizable were hexagonal shapes of poor quality, considered to be the forms found on pseudo-hexagonal, orthorhombic chalcocite.

The vertical sections of samples at Creta show only the most diffuse trace of Schurmann-Series zoning, such as has been found in the Kupferschiefer (Wedepohl, 1964, p. 187). There is no segregation of lead and zinc in succeeding zones of shale above the copper. There are sample sections that have a maximum concentration of silver below the maximum concentration of copper, but this relationship is not consistent throughout the deposit. Because of the apparent lack of zoning, the syngenetic hypothesis, as strictly interpreted, is rejected in favor of the diagenetic origin of chalcocite.

If chalcocite was precipitated either syngenetically or diagenetically, then a minimum activity of bisulfide ion must have obtained. Only with a pH greater than 7 (at 25°C and 1 atmosphere pressure) will the proper form of sulfur (bisulfide ion) be present. Based on the sulfur-isotope evidence for a sedimentary origin of the chalcocite, the

temperature and pressure will be assumed to be 25°C and 1 atmosphere. If we assume an activity for total dissolved sulfur species of 10^{-1} (fig. 2), the fields where chalcocite and the bisulfide ion are stable do overlap within the fields containing most of the known Eh-pH measurements on natural waters. As a first approximation, the region of overlap defines the approximate range of chemical conditions in which the chalcocite of the Prewitt copper shale at Creta were deposited. Although the actual activity of total dissolved sulfur species may not have been exactly 10^{-1} at Creta, this is a geologically reasonable value.

CONCLUSIONS

Because there is no indisputable evidence of unique concentrations of most of the analyzed variables, and because of uncertainty regarding concentrations of several

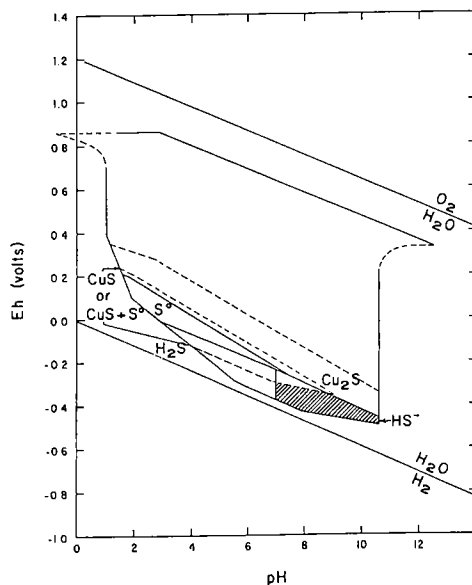


Figure 2. Eh-pH plots for copper and sulfur, activity of dissolved sulfur = 10^{-1} . One atmosphere pressure, 25° Centigrade, all boundaries for activity equal to 10^{-1} . Cross-ruled portion of diagram indicates probable character of diagenetic water that precipitated Creta chalcocites. (Baas Becking and others, 1960, p. 276; Schmitt, H. H., 1962, p. 110, 199).

elements on marine and nonmarine clays, we cannot assign a generalized paleosalinity to either the Prewitt or Meadows copper shales. The work of Wilson (1962, p. 33) and Clapham (1970, p. 168-170) suggests a brackish or marine environment during deposition of gray shales in the formation. In addition, we may infer hypersalinity at Creta during deposition of the Prewitt copper shale, as evidenced by the gypsum bed immediately overlying the ore.

The large grains of gypsum in the samples from both Creta and Mangum are far out of hydraulic equivalence with the accompanying small clay and quartz particles: this is taken as evidence that gypsum precipitated diagenetically in the mud.

The range of $\delta^{34}\text{S}/^{32}\text{S}$ values of chalcocite concentrates from Creta and the maximum value being lower than the normal marine gypsum lead me to conclude that the chalcocite is syngenetic or diagenetic. Moreover, the absence of Schurmann's Series of metal enrichment above the Prewitt copper shale, as is found in the Kupferschiefer, leads me to conclude that the chalcocite is diagenetic.

The shales in the Creta and Mangum deposits are "normal" in many respects; indeed, only copper and lead are in abnormally high concentrations in the copper-rich shales. No geochemical criteria for assigning specific environments of deposition to any of the shales sampled in either of the deposits were discovered.

The copper shales in the Mangum deposit have the same general pattern of compositional relationships as do the shales in the Creta deposit. This is true also of the noncupriferous shales in each deposit. This observation and the observation that the copper shale at Creta contains malachite instead of chalcocite when the overburden is less than 10 to 20 feet suggest that the Meadows copper shale at Mangum was oxidized by meteoric waters and is the analogue of the Prewitt copper shale at Creta.

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GEOCHEMICAL EXPLORATION FOR RED-BED COPPER DEPOSITS IN NORTH-CENTRAL OKLAHOMA

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Abstract—Copper mineralization has been reported from several locations in north-central Oklahoma (Payne, Pawnee, and Noble Counties). The copper-bearing zone occurs in the Doyle and Matfield Shales (Chase Group) and the Garrison Shale (upper part of Council Grove Group) of Permian age. Chalcocite is the dominant unoxidized copper mineral; malachite and subsidiary azurite are the most common oxidized materials. The chalcocite is reported to contain minor quantities of silver and gold.

Initial field work revealed additional copper occurrences. Therefore, a geochemical exploration program was initiated to evaluate potential ore deposits in north-central Oklahoma. Stream sediments and bedrock samples were collected from an area of approximately 300 square miles with a sampling density of 4 samples per square mile. The finer sieve fraction (—80 mesh) of the samples was digested in aqua regia (1 part nitric acid and 3 parts hydrochloric acid, by volume) and then analyzed for copper content.

The preliminary results seem to indicate that the geochemical copper anomalies delineate the known occurrences of copper mineralization. Additional copper anomalies were found in areas where no copper mineralization was reported. Trend-surface analysis of the copper distribution in bedrock was carried out to determine factors controlling mineralization patterns in the area.

GENERAL GEOLOGY

The study area is in parts of Payne, Pawnee, and Noble Counties, Oklahoma, and includes all or part of Tps 19-22 N. and Rs. 3-5 E. (fig. 1). The area is part of the Central Oklahoma Platform, where during much of the Paleozoic Era, favorable conditions existed for cyclic sedimentation.

The age of the surface rocks is Early Permian, and they become progressively younger in a westwardly direction. The section exposed within the study area consists of about 700 feet of almost entirely Wolfcampian rocks and extends from the base of the Admire Group to the top of the Herington Limestone (top of Chase Group).

The section in the study area is characterized by cyclically deposited shales, lenticular sandstones, and thin limestone beds. Eastern Payne County is described by Ross (1970) as a sand-rich, tide-dominated, deltaic sequence during regression and a supratidal zone of a carbonate tidal flat

during transgression. The sandstones in the area have erosional bases, initial dip, and small- and medium-scale cross-bedding. Grain size in the sandstone units decreases upward; most sands are well sorted, subangular, feldspathic quartz arenites. Limestones in the lower part of the section are continuous and fossiliferous and are believed to be the transgressive units of the cyclic sequence. Carbonates above the Neva Limestone are discontinuous, nodular dolomites and suggest the existence of supratidal conditions during desiccation cycles.

MINERALIZATION

Copper mineralization in the study area has been known since 1901 (Merritt, 1940; Tarr, 1910; Rogers, 1916; and Craig, 1959). Many attempts have been made to develop the prospects, but none have met with success. Anomalous copper occurrences are primarily confined to shale and sandstone.

Copper in shale occurs as disseminations of chalcocite, malachite and azurite, and as chalcocite concretions with a thin covering of malachite. The shales are predominantly gray to white and contain abundant carbonaceous material between laminae.

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The mineralization in the sandstones occurs almost entirely in paleochannel deposits. The channels are generally filled with clay and sand, show an upward decrease in grain size, exhibit initial dip, and contain rocks that are white to buff. The general trend of these channels is approximately N. 50° W. (Ross, 1970, p. 70). The mineralization occurs as replacement of carbonaceous wood by chalcocite, as blebs of malachite and azurite, and as disseminations. Concretions of chalcocite and pyrite were also observed in a few locations. Tarr (1910, p. 225), reported high values of gold and silver in the concretions at one of these locations. In the present study, the average silver content of sulfide concentrate is 34.8 ppm. A few bedrock samples show relatively high values in lead and zinc, and above-background radioactivity was detected in several locations in Payne and Pawnee Counties.

SAMPLING AND ANALYTICAL PROCEDURES

More than 1,200 stream-sediment and bedrock samples were collected. The stream-

sediment samples collected consisted mainly of silts and clays. Each was taken from a depth of 1 to 3 inches, in the middle of the stream, and along relatively straight segments of it. Dry sediments were collected from beds of intermittent streams, but the great majority of the samples were collected wet.

All available outcrops were sampled; special emphasis was placed on outcrops along the drainages where anomalous copper values were detected.

The samples were dried by placing them inside the oven on aluminum-mesh racks at 110° C within 10 hours of collection. The minus-80 fractions were digested in aqua regia for 24 hours and then analyzed for copper, using a Perkin-Elmer 403 Atomic Absorption Spectrophotometer. Selected bedrock samples were analyzed for lead and zinc.

An IBM/360 computer was used extensively in data interpretation. Computer programs for trend-surface analysis, contouring of irregularly spaced map data, and basic statistics were obtained from Koch and others (1972) and Davis (1973).

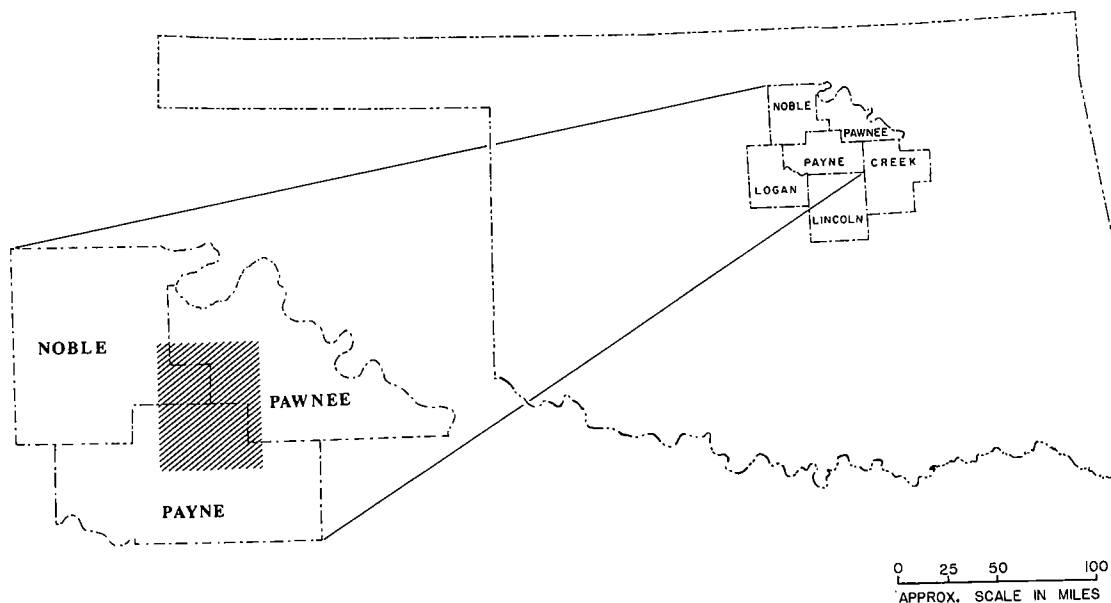


Figure 1. Index map of study area.

PRESENTATION AND INTERPRETATION OF GEOCHEMICAL DATA

The results of the analysis of the copper content of stream sediments and bedrock samples are presented as histograms and geochemical maps. Trend-surface analysis was utilized as an interpretive mathematical method of separating geochemical map data into those of a large-scale nature and those involving local fluctuations.

Histograms, Thresholds, and Anomalies

The frequency distributions of copper content in stream sediments and bedrock samples are illustrated as histograms (figs. 2a, 2b, and 2c). The copper populations are approximately log normal and are positively skewed. The geochemical threshold for an element is defined by Hawkes and Webb (1962, p. 27) as the upper limit of normal background fluctuation. The values above the threshold are considered anomalous. The threshold value for a given element varies for each rock type, and a single value may be too high for some rocks and too low for others. Nevertheless, for this study the geometric mean plus two standard deviations has been chosen as the geochemical threshold. As a result, the copper content of 92 percent of the stream-sediment and bedrock samples is below geochemical threshold, whereas 8 percent of the stream-sediment and bedrock values are anomalous. Mean values, standard deviations, and thresholds were calculated for copper in stream sediments and bedrock samples and are listed in table 1.

Geochemical Maps

Geochemical maps are powerful tools in the interpretation of spatially distributed data. The map, as described by Levinson (1974, p. 474), should be viewed as being either purely objective or largely interpretive. Geochemical maps that illustrate the copper distribution in stream sediments and bedrock samples (figs. 3-5) represent the purely objective approach. The maps give the location of each sampling point and the copper content at that point. It is readily noticeable that the anomalous copper concentration of the stream sediments (fig.

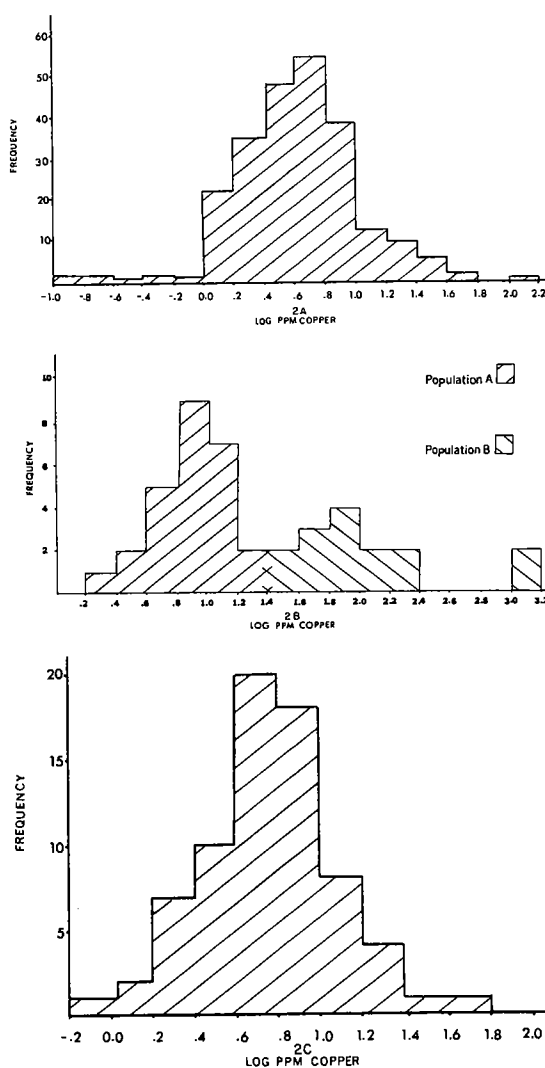


Figure 2. Histograms: A, copper distribution in stream sediments; B, copper distribution in shale; C, copper distribution in sandstone.

Table 1.—Statistical Parameters for Copper Distribution in Stream Sediments and Bedrock Samples

	Geometric Mean	Standard Deviation	Threshold ¹
Sandstone	6.0	2.0	24.0
Shale			
a. Predominantly red	8.0	4.1	134.48
b. Predominantly (copper rich) green	108.0	83	—
Stream Sediments	5.0	2.4	28.8

¹Thresholds are antilogs of values computed on the basis of lognormal distribution (log threshold = log mean + 2 log-standard deviations).

3) matches that of the bedrock (figs. 4-5). This clearly indicates that the copper in the stream sediments is derived from Wolfcampian sandstones and shales that underlie the study area.

The trend-surface maps derived from the data in figures 4 and 5 illustrate the interpretive approach. In this study, first-, second-, third-, and fourth-degree trend surfaces were fitted to the data. Goodness of fit, expressed as apparent total sum of squares (Harbaugh and Merriam, 1968, p. 75), ranges from 22 percent for the first-order trend surface to 54 percent for fourth-order trend surface. Table 2 shows that all copper trends have confidence levels equal or higher than 97.5 percent.

The copper linear surface shown in figure 6a trends south-southeast and dips east-northeast. The copper increases west-southwest and decreases east-northeast. The curvatures of the higher order trends (figs. 6b, 6c, and 6d) are approximately ridges,

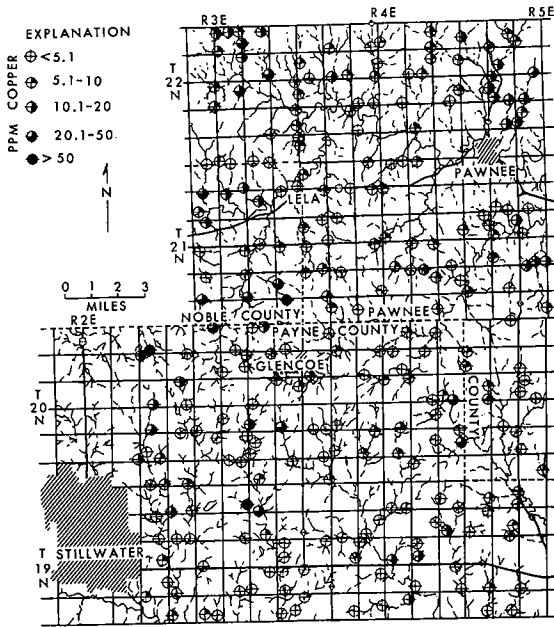


Figure 3. Copper distribution in stream sediments.

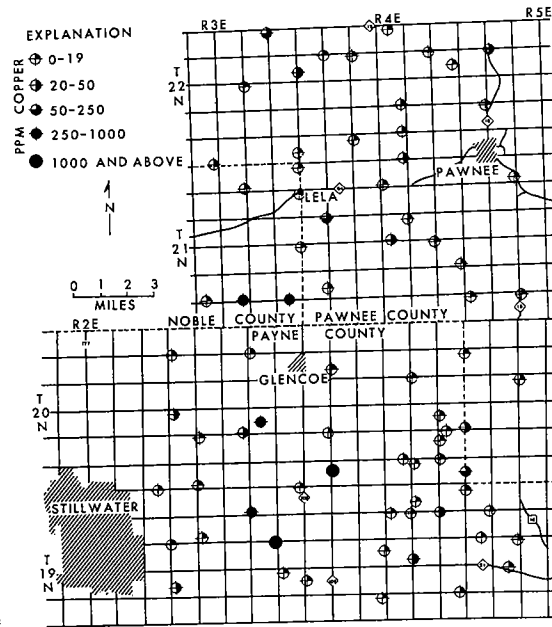


Figure 4. Copper distribution in sandstone.

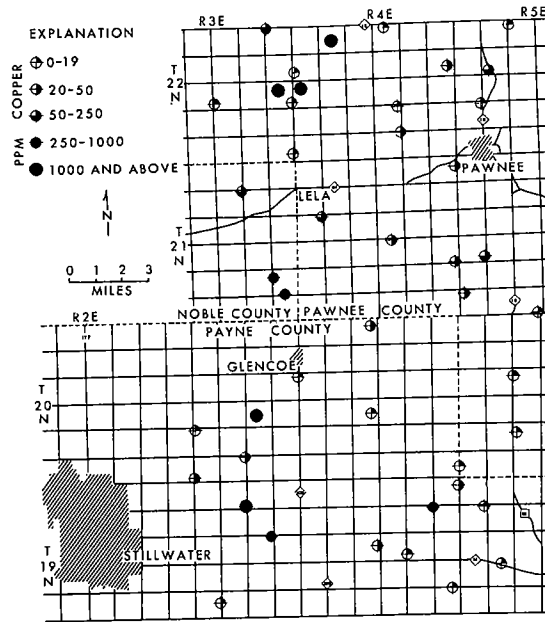


Figure 5. Copper distribution in shale. (See fig. 4 for explanation of symbols.)

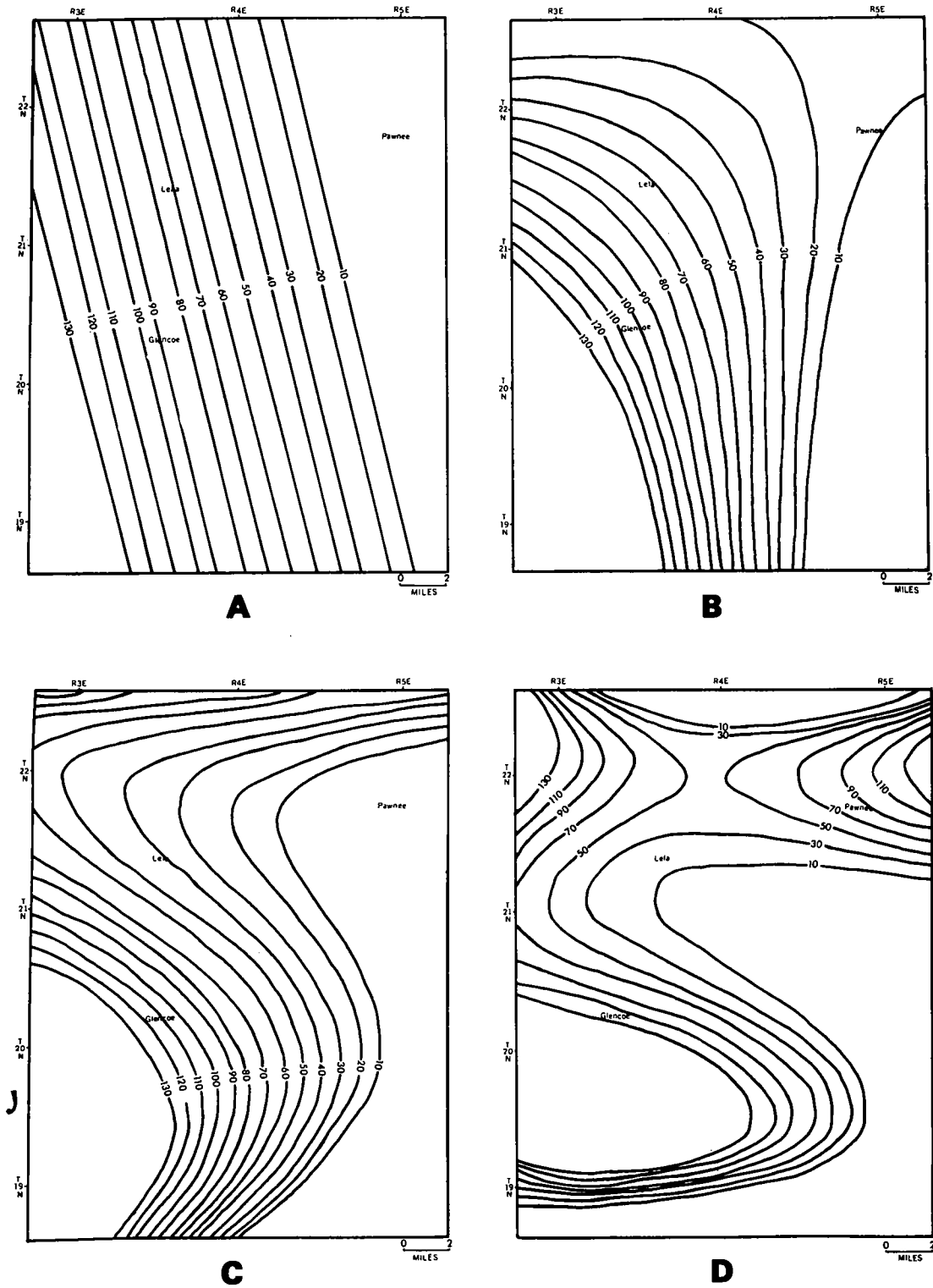


Figure 6. Geochemical maps showing trend surfaces for copper: A, first-order surface; B, second-order surface; C, third-order surface; D, fourth-order surface.

Table 2.—Statistics for Trend-Surface Fit to Average Copper Content of the Bedrock.

Degree of Equation	% Correlation Coefficient	F-Test	% Confidence Level
1	47.94	5.074	97.5
2	54.41	4.346	97.5
3	57.18	3.278	97.5
4	73.62	5.203	99.5

valleys, and partial-positive ellipsoids where the known deposits and prospects seem to be clustered around their major axes.

The residuals or the deviations from the fitted linear trends describe principally the local geochemical fluctuations and also include the variability inherent in sampling and analytical procedures. The behavior of these fluctuations may be a critical phase in the interpretation of geochemical anomalies and in locating mineralized areas.

Examination of the residuals map (fig. 7) reveals two important observations:

1. The high-positive-anomalies zones in the western part (fig. 7) represent sites favorable for mineralization. This fact was verified by field examination. The only exception is to the northeast, where no mineralization was observed.

2. A comparison of the residuals map and the subsurface structural-contour maps of the top of the Red Eagle Limestone of Early Permian age (Ross, 1970) and the Checkerboard Limestone of Pennsylvanian age (Clare, 1963) indicates that all the high-positive residuals coincide with pronounced subsurface structural features. These features are described by Ross (1970, p. 45) as noses and saddles formed by local changes in the regional dip. This indicates that the subsurface structure might play an important role in localization of copper mineralization. Feokistov and Kochin (1972), proposed similar hypotheses for localization of sedimentary copper deposits in the Dzhezkagan District, USSR.

CONCLUSIONS AND RECOMMENDATIONS

The sediments of the Wolfcampian Series of the Lower Permian in north-central

Oklahoma proved to be a favorable host for copper mineralization. Several areas of positive geochemical anomalies were located by using analysis of stream sediments with subsequent bedrock analysis. The stream-sediment survey proved to be capable of producing results of great practical value. It can be clearly seen that the distribution of copper in stream sediments was consistent with the distribution of areas of high copper mineralization.

Trend-surface analysis, particularly the residuals treatment, has shown that the localization of mineralization can be controlled by the subsurface structure. Therefore, detailed study of the subsurface structure along with paleogeographic conditions should be seriously considered for further geochemical investigations. The shallow marine facies beyond the delta margin, where copper-bearing channels are located, might be good exploration targets for economical copper-shale deposits.

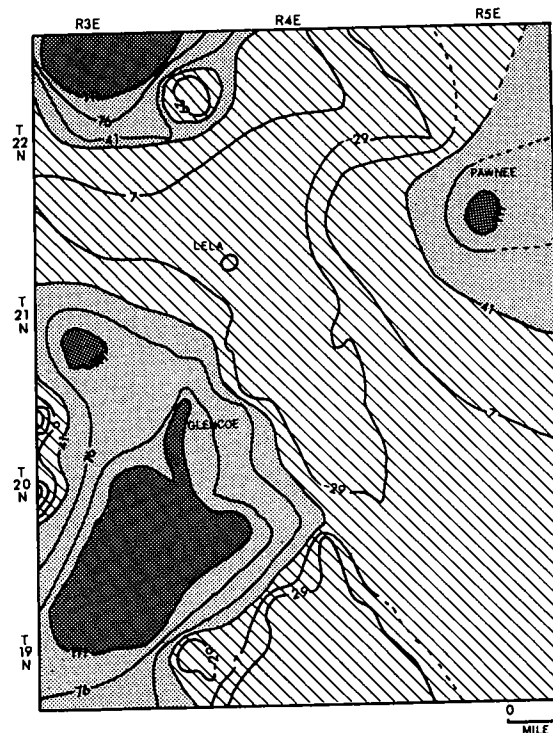


Figure 7. Geochemical maps showing residuals of linear surface for copper.

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COPPER OCCURRENCES ASSOCIATED WITH PERMIAN ROCKS IN SOUTH-CENTRAL KANSAS

Truman C. Waugh² and Lawrence L. Brady²

Abstract—Preliminary investigations of sedimentary copper occurrences in Kansas were made by the Kansas Geological Survey in the Permian Ninnescah Shale and the Milan Limestone Member of the Wellington Formation. Reports by earlier workers of copper carbonate mineralization in the red-bed sequence of Permian rocks led to geological and geochemical investigations in Harper, Kingman, Sedgwick, and Sumner Counties in south-central Kansas.

Malachite was the common copper mineral found in outcrop and shallow auger borings in the study area. X-ray spectrographic examination of samples obtained during field investigations shows that concentrations of copper are present in the Runnymede Sandstone Member of the Ninnescah Shale and in portions of the Milan Limestone Member of the Wellington Formation. Significant mineralization occurs in the Ninnescah Shale within a few feet, stratigraphically, of these two units. Copper mineralization (> .05 percent) is associated with some of the gray-green shales of the Ninnescah Shale but is not present in the red shales.

Copper concentrations in one area sampled ranged up to 4.2 percent. This high concentration occurs in a 2.5-inch-thick zone of the Runnymede in Harper County. With the exception of this one location, the mean copper value for samples obtained from 18 locations having copper values of 0.05 percent or higher was 0.12 percent, with a standard deviation of 0.05 percent.

INTRODUCTION

Preliminary investigations of sedimentary copper occurrences in Kansas were made by the Kansas Geological Survey in several Permian units in south-central Kansas. Reports by earlier workers (Norton, 1939; Moore and others, 1951) of copper carbonate mineralization in the red-bed sequence of Permian rocks led to geological and geochemical investigations in Harper, Kingman, Sedgwick, and Sumner Counties (fig. 1). A summary of these investigations was reported by Hill (1967).

The Permian units studied in this survey were the Milan Limestone Member of the Wellington Formation, the Ninnescah Shale, and the Runnymede Sandstone Member of the Ninnescah Shale (fig. 2). The Milan Member forms the upper boundary of the Wellington Formation, and the Runnymede Member forms the upper boundary of the Ninnescah Shale. These units are distinctly lower, stratigraphically, than the principal

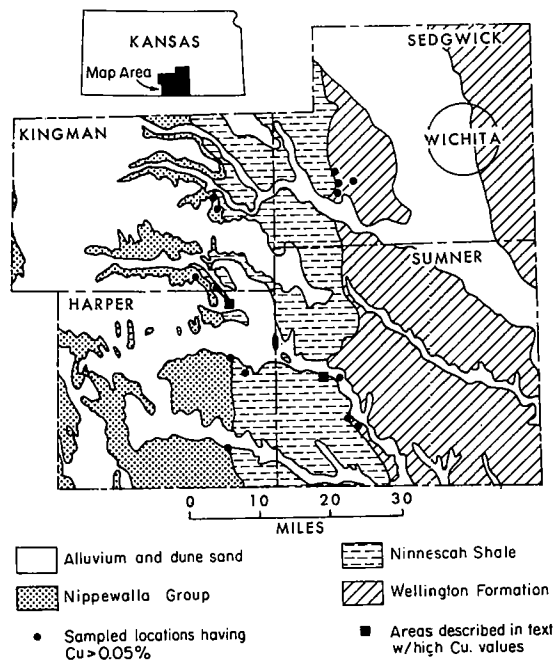


Figure 1. General geology of study area showing sample locations where copper values are greater than 0.05 percent.

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²Kansas Geological Survey, Lawrence.

copper occurrences in the Flowerpot Shale of Oklahoma and Texas.

LITHOLOGIC DESCRIPTION OF UNITS STUDIED

The Ninnescah Shale consists principally of silty shale with thin beds of argillaceous limestone, argillaceous dolomite, siltstone, and very fine-grained sandstones. The unit is

mainly reddish brown, with thin beds and irregular areas of greenish gray.

The base of the Ninnescah Shale marks the stratigraphic position commonly considered the base of the "redbeds" in Kansas (Swineford, 1955, p. 30, 36), although reddish-brown zones exist in the underlying Wellington Formation.

At the top of the Ninnescah Shale is the Runnymede Sandstone Member. This unit is approximately 8 feet thick and is composed of gray to greenish-gray shale and siltstone in the study area.

Underlying the Ninnescah Shale is the Wellington Formation, a unit consisting locally of gray to greenish-gray and reddish-brown shales with beds of limestone, dolomite, siltstone, salt, and gypsum. The Hutchinson Salt Member, a salt unit extensively mined in central Kansas, occurs in the central part of the formation in the subsurface only. In portions of the study area the upper boundary of the Wellington is marked by the Milan Limestone Member. The Milan consists of thin dolomite beds separated by shale. At the type locality, which is in the section adjacent to the sample location, the Milan is 8 feet thick (Norton, 1939, p. 1757). Most field workers place the top of the Wellington at a general color change from gray beds to overlying red beds (Moore and others, 1951, p. 40).

For a detailed stratigraphic and petrographic discussion of these Permian units, see Swineford (1955).

KANSAS

	Whitehorse Formation 270'
Group	Dog Creek Formation 50'
	Blaine Formation and Flowerpot Shale 230'
Nippewalla	Cedar Hills Sandstone 180'
	Salt Plains Formation 265'
	Harper Sandstone 220'
Summer Group	Stone Corral Formation 5'
	Runnymede Sandstone } Member
	Ninnescah Shale 450'
	Milan Limestone } Member
	Wellington Formation 700'

Figure 2. Stratigraphic section of outcropping Permian rocks in Kansas, modified from Zeller, 1968.

SAMPLING TECHNIQUE AND OBSERVATIONS

Over 400 samples were obtained in 5 east-west traverses across the study area, from outcrops or shallow auger holes at 120 localities. Individual samples of approximately 100 grams were crushed and split to approximately 3 grams. This material was ground in a mortar to a -200-mesh size. Twenty milligrams (mg) of the sample was added to 180 mg of graphite, and 20 mg of this mixture was then analyzed by emission spectrography to screen out samples with little copper. Only samples showing a potential for 0.05 percent or more copper were analyzed on an X-ray spectrograph. The percentage of copper present was determined by establishing standards of

known amounts of copper in a prepared matrix of dolomite and clay.

Of the 120 localities sampled, 19 locations—represented by 69 individual samples—showed copper values that exceeded 0.05 percent copper (fig. 1). All samples having copper values higher than 0.05 percent occurred in dolomite or shales and siltstones that were gray to gray-green or mottled with red. No high copper values were found for red to reddish-brown shales and siltstones.

Of the 19 locations showing significant copper content, only 2 localities, 1 in Harper County and the other in Sumner County (fig. 1), had samples with copper-content values greater than 0.26 percent. The Harper County site, an anomalous area located east of Runnymede, yielded samples with copper concentration ranging up to 4.2 percent. However, the average copper value of samples from the other 18 locations having a copper concentration of 0.05 percent or higher showed a mean copper value of 0.12 percent, with a standard deviation of 0.05 percent.

DISCUSSION OF MILAN AREA SUMNER COUNTY

In reviewing the two areas having significant copper mineralization, the Sumner County occurrence, SE $\frac{1}{4}$ SE $\frac{1}{4}$ SE $\frac{1}{4}$ sec. 30, T. 32 S., R. 3 W., showed a copper content as high as 0.69 percent. Copper mineralization occurs as malachite, with minor amounts of azurite present in small vugs, fractures, and along bedding planes in the dolomite beds, or along bedding planes of the underlying shale beds. The dolomite beds containing copper are less than 9 inches thick, and they occur in the Milan Limestone Member of the Wellington Formation (fig. 3) and in the lower 30 feet of the Ninnescah Shale. Mineralization was found at 4 distinct levels at this location—2 levels in the Milan and 2 in the Ninnescah Shale.

DISCUSSION OF RUNNYMEDE AREA HARPER COUNTY

The Runnymede site, previously mentioned, had the highest copper values of any location in the study. The area is 1 $\frac{1}{2}$ miles east of Runnymede (SW $\frac{1}{4}$ NW $\frac{1}{4}$ NW $\frac{1}{4}$ sec. 18, T. 31 S., R. 5 W.), in Harper County

(fig. 1). Mineralization is associated with argillaceous dolomite beds and adjacent shales in the upper part of the Ninnescah Shale and in the siltstones and shales of the Runnymede Sandstone Member of the Ninnescah Shale (fig. 4). Copper content of 0.33 percent was determined for the 3 to 4 inches of dolomite in the Ninnescah Shale shown in figure 5. The siltstones and shales of the Runnymede Sandstone Member, which are slightly higher, stratigraphically, than the dolomite examined, had copper values ranging up to 4.2 percent in selected samples from a mineralized zone 2.5 inches thick (fig. 6). The copper mineral observed at this location was malachite, which was present as thin films on the bedding planes.

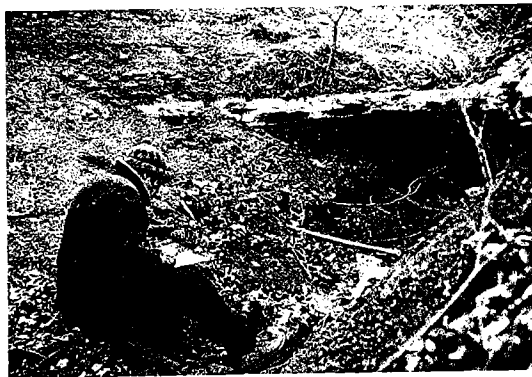


Figure 3. View of Milan Limestone Member of the Wellington Formation, Sumner County, showing copper mineralization. The 3 to 4 inches of shale just below the dolomite bed contains .69-percent copper; the dolomite bed contains .3-percent copper.



Figure 4. Ninnescah Shale outcrop in Harper County (sec. 18, T. 31 S., R. 5 W.), collection site for samples having the highest copper content found in study area.



Figure 5. Dolomite of the Ninnescah Shale, exhibiting malachite mineralization along bedding planes (same location as fig. 4).



Figure 6. Outcropping siltstone and shale beds in the upper part of Ninnescah Shale and Runnymede Sandstone Member (same location as fig. 4).

CONCLUSIONS

1. Over 400 samples were obtained from 120 localities in the Ninnescah Shale, the Runnymede Sandstone Member of the Ninnescah Shale, and the Milan Limestone Member of the Wellington Formation of 4 south-central Kansas counties. Of the 120 localities where samples were collected, 19 locations, represented by 69 samples, had copper values larger than 0.05 percent. Of these 19, samples from 2 locations had copper values greater than 0.26 percent.

2. After excluding the Runnymede locality in Harper County from consideration, the average copper value of

samples from the remaining 18 locations with greater than 0.05 percent copper showed a mean value of 0.12 percent with a standard deviation of 0.05 percent.

3. All samples having a copper content higher than 0.05 percent were obtained from dolomite or shale and siltstones that were gray to gray green or ones with red mottling. No significant copper content was present in samples of red to reddish-brown shales or siltstones.

4. The mineralization observed was secondary malachite with a small amount of azurite. Copper mineralization occurred mainly along bedding planes in all lithologies and in vugs and fractures found in dolomite of the Milan area, Sumner County.

5. The highest copper values were found in selected samples from the Runnymede Sandstone Member of the Ninnescah Shale in Harper County, and in dolomite beds of the Ninnescah Shale that are close, stratigraphically, to the Runnymede Member. All mineralization was secondary at this location.

6. All analyses by the Kansas Geological Survey were of samples collected from outcrops or from shallow auger borings.

7. Only preliminary work has been completed; further surface and subsurface work is needed before the economic potential of the red-bed areas of Kansas is discounted.

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A COMPARISON OF SELECTED SANDSTONE COPPER DEPOSITS IN NEW MEXICO

Dennis J. LaPoint¹

Abstract—In New Mexico, sandstone-type copper deposits usually occur in Permian or Triassic rocks. The Permian Abo Formation contains many small deposits such as those found in the Scholle and High Rolls districts. Typical mineralization consists of chalcocite replacing woody material in arkoses that represent small channel deposits and as chalcocite nodules in the underlying organic-rich shales and shaly sands. Red arkoses and muds are abundant, but host rocks for mineralization are white to light brown. In both districts, deposits are concentrated in the lower, coarser, arkosic part of the Abo. Major Triassic deposits are found at the Nacimiento mine near Cuba and the Stauber mine near Santa Rosa. Primary mineralization consists of chalcocite replacing coarse organic debris in a white to gray, often clay-rich, channel sandstone. These channels are much larger than Permian channels and are also less arkosic. The sandstones are nearly equivalent in age and lie near the base of the Chinle Formation or equivalent. Deposits in the Meseta Blanca Sandstone Member of the Yeso Formation (Permian), in the Rayo district, differ because of their lack of organic material, but the occurrence is similar to the Lisbon Valley deposits in Utah. At Pintada Canyon, chalcocite replaces very fine organic material in fine-grained, gray sandstones of the Grayburg-Queen formation (Permian).

Precambrian netavolcanic terrains in Permian and Triassic uplifts are believed to be the source of the copper. Migration of the copper may occur as copper-organic and copper-organic-clay complexes carried by streams and by copper carbonate complexes carried by ground water. Permian deposits associated with fluvial sediments may be related to migration of copper by streams and deposition in quiet-water environments. Triassic deposits may be related to migration of copper in ground water derived from the diagenesis of arkosic sediments. Organic material controls precipitation of copper in both types of occurrences.

INTRODUCTION

New Mexico contains many small occurrences of sandstone copper deposits (fig. 1). Typically, the deposits are associated with sandstones of Pennsylvanian, Permian, and Triassic age. The inactive Stauber mine and the operating Nacimiento mine have been major producers. Besides copper, silver has been reported from the Nacimiento mine (Woodward and others, 1974, p. 112) and the Scholle district (Anderson, 1957, p. 144). Lead has been mined, and minor amounts of zinc have been reported from the High Rolls district (Jerome and others, 1965, p. 13). Uranium has been found in the Coyote district (Tschanz and others, 1958) and in small amounts in the Scholle district.

This paper compares some of the features of selected deposits, in order to present a

cross section of the types of mineralization found in sandstone copper deposits of New Mexico. Deposits described include the Scholle, High Rolls, and Rayo districts and the Pintada, Nacimiento, Eureka, and Stauber mines (fig. 1). Features that may relate to the origin of these deposits are emphasized.

SCHOLLE DISTRICT

The Scholle district (fig. 2) lies north of the small town of Scholle, on the southeast side of the Manzano Mountains (fig. 3). Mineralization, consisting of chalcocite, malachite, and azurite, is found in the lower part of the Permian (Wolfcampian) Abo Formation. The Abo is underlain by marine limestones and arkosic sandstones of the Permian Bursum Formation and is overlain by sandstones and shales of the Permian (Leonardian) Yeso Formation. Although Precambrian rocks have been thrust over Pennsylvanian rocks only a short distance to

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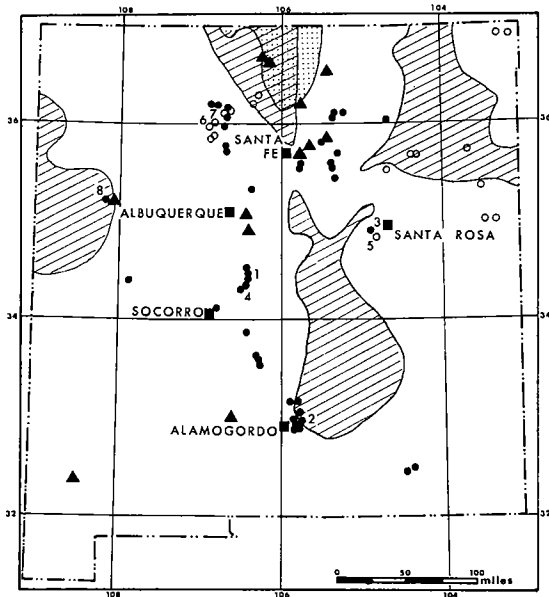


Figure 1. Index map of New Mexico showing sandstone copper deposits, Precambrian ore deposits, and approximate extent of Early Permian (adapted from Mallory, 1972, and Turner, 1962) and Late Triassic (adapted from McKee and others, 1959) landmasses. Diagonal lines represent Permian uplifts and the stipple delineates Triassic uplifts. Solid circles represent Pennsylvanian-Permian sandstone copper deposits, and open circles represent Triassic deposits. Deposits shown on map and discussed in text are (1) Scholle district, (2) High Rolls district, (3) Pintada mine, (4) Rayo district, (5) Stauber mine, (6) Nacimiento mine, (7) Eureka mine, and (8) Zuni district. Triangles represent Precambrian ore deposits. Data are from Lindgren and others (1910), Reiche (1949), Schilling (1960), and Bingler (1968). Squares represent major towns.

the west, forming the Manzano Mountains, the formations in the district have only a slight dip to the east of 1-2 degrees.

Coarse, red arkosic sandstones and conglomerates interbedded with red mudstones and siltstones are major rock types of the lower Abo Formation. Basal conglomerates may contain quartz, feldspar, gneiss, and limestone pebbles. Higher in the section, the conglomerates are composed mainly of limestone pebbles from underlying Pennsylvanian and Permian limestones, with minor additions of arkosic pebbles. The sand matrix of the conglomerates and the coarse sandstones consists of quartz and red, iron-stained feldspars. The coarse units are interbedded with more abundant, but poorly

exposed, red mudstones and siltstones. Higher in the lower Abo Formation, a badlands type of topography may exist as soft underlying shales erode, leaving jumbled blocks of sandstone and conglomerate. Dark-red, arkosic sandstone and conglomerate and limestone-pebble conglomerate decrease in abundance higher in the section and to the north, away from the major concentration of mines and pits. Also, upward in the section, excellent sedimentary structures are shown by the sandstones, which become finer grained and reddish brown. An informal division between the upper and lower Abo Formation is marked by a well defined bench and sharp break in slope about two-thirds (400 feet) up the slope of the Abo Formation (fig. 3). Above this slope break, few prospect pits are

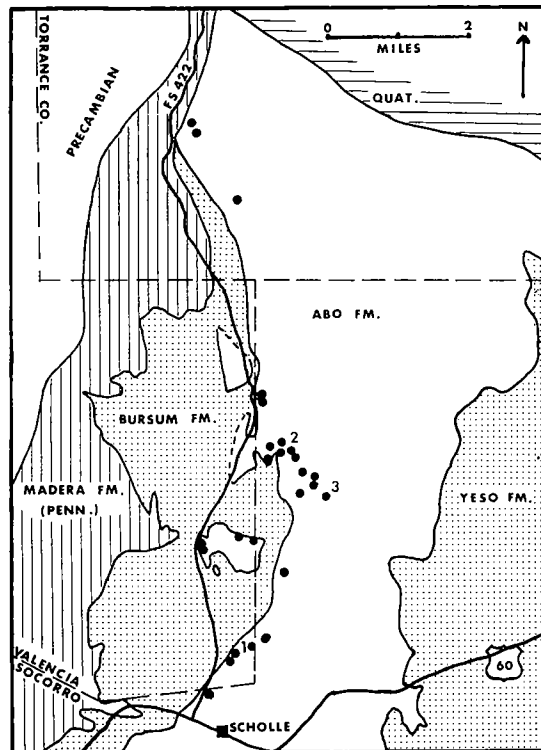


Figure 2. Index map of the Scholle district. The Bursum, Abo, and Yeso Formations are Permian in age. Mines and prospect pits are represented by circles. Deposits mentioned in text include (1) Blue Star mine, (2) Long Shale Cut, and (3) Cole mine. References for the map are Read and others (1944), Wilpolt and others (1946), Stark (1956), and Phillips (1960).

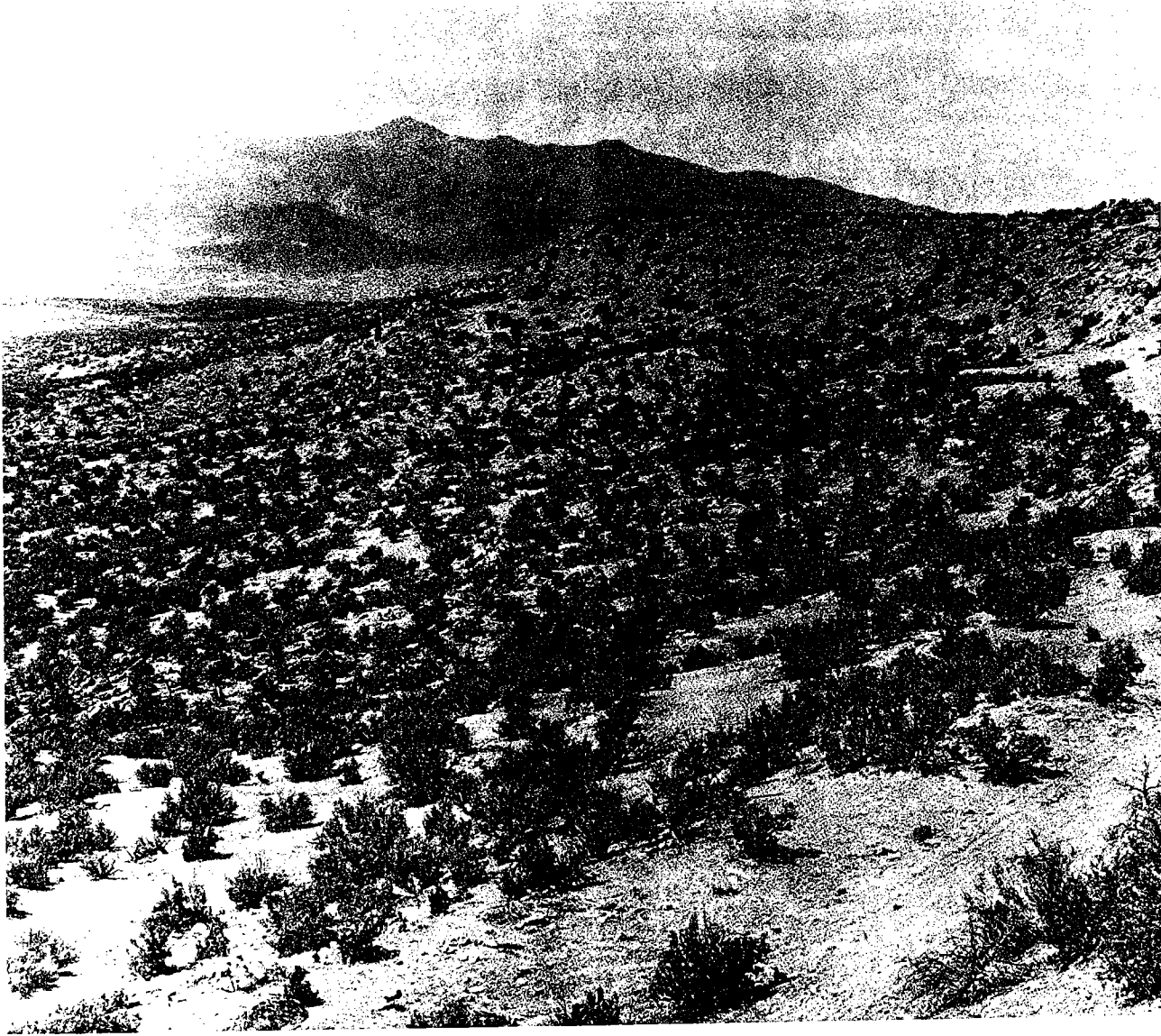


Figure 3. View, looking northward, of the Abo Formation and Precambrian rocks of the Manzano Mountains. The lower Abo has a gentler slope than the upper Abo. A road, lower right corner, and the Cole mine, at upper right, lie along the break in slope and bench used to divide the Abo into upper and lower members.

found, and the rocks consist mostly of red mudstones and fine-grained, reddish-brown, cross-bedded sandstones.

Mineralization may be associated with the red, arkosic sandstones or conglomerates; however, the red units are not mineralized except for malachite along fractures. Some sandstones appear red, owing to red-stained feldspars, but the matrix is not oxidized, and these beds may be mineralized. Typical mineralization consists of chalcocite as nodules in organic gray shales and siltstones, chalcocite that

has replaced woody debris in siltstones and gray arkosic sandstones, and chalcocite that has replaced limestone fragments and nodules. Malachite and azurite occur along bedding planes in shales and siltstones, as a cement in sandstones, as a halo around chalcocite, and along fractures in the sandstones.

The Blue Star mine is one of the most extensive underground operations in the district. Mineralized shales and siltstones, with up to 7 percent copper, are overlain by red shales that are capped by red, arkosic,

channel sandstones (fig. 4). At the western end of the area, the red shales may have been exposed and a calcareous zone developed before deposition of the overlying sandstone.

To the north, at a cut referred to as the "Long Shale Cut," a brown, poorly exposed sandstone is overlain by green and purple shales with abundant limestone nodules. Mineralization is found in calcareous, organic siltstones that form a small lens about 50 feet long and 3 feet thick within the shales. Chalcocite, as nodules in dense calcareous siltstone and as replacement of woody material in the calcareous, organic siltstones, represents primary mineralization (fig. 5).

Operations at the Cole mine are at the stratigraphically highest in the area (fig. 6). A lower bench has exposed two channels: the bedding in the lower channel dips to the north and consists of dense, gray sandstone

with limestone pebbles that increase in abundance to the south; the upper channel cuts the lower and contains abundant limestone pebbles that grade into a brown sandstone, both updip and to the south. The upper part of this channel contains woody debris that is replaced, commonly, by chalcocite that is removed during weathering (fig. 7). The sandstone units are overlain by a gray, thin-bedded, calcareous siltstone that contains an adit with minor amounts of malachite. Red mudstones overlie this sequence.

Deposits that lie to the north, 300-400 feet above the base of the Abo, are small and poorly exposed. They consist of small beds of gray, organic shales with copper mineralization. These beds may be associated with limestone-nodule conglomerates in which chalcocite is replacing the nodules. The limestone nodules appear to have been transported only a short distance, if transported at all.

In general, the lower part of the Abo Formation consists of a fluvial sequence of sandstones and shales. The conglomerates and arkosic sandstones represent small stream channels, usually only 200 to 300 feet wide, in a broad flood plain consisting of red muds and silts. Organic shales and siltstones and calcareous shales and siltstones represent small lakes or swampy backwater deposits. At least two sources contributed material: a nearby source, perhaps meandering streams cutting through slightly older sediments near the flood plain, contributed the limestone pebbles, and a more distant source from the Precambrian rocks of the Pederal uplift to the east (fig. 1) contributed the arkosic sand detritus and the quartz, feldspar, and gneissic pebbles. Mineralization is associated with shales and siltstones, representing quiet-water deposition, and with organic debris in channel sandstones.

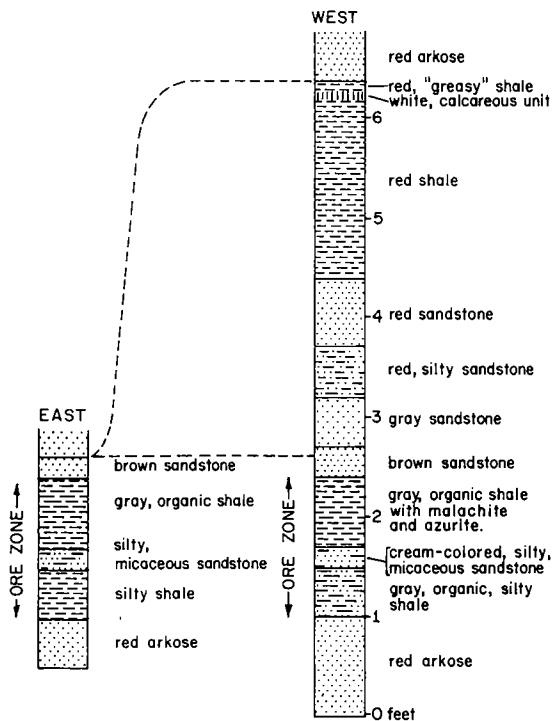


Figure 4. Generalized section at the Blue Star mine. The copper—as chalcocite, malachite, and azurite—occurs in gray, organic shales and siltstones. A red, arkosic, sandstone channel cuts out the overlying strata from the western to the eastern end of the mine.

HIGH ROLLS DISTRICT

The High Rolls district, east of Alamo-gordo on the west flank of the Sacramento Mountains (fig. 1), also features mineralized Abo Formation. Lead as galena, cerussite, and anglesite, plus copper as chalcocite, chalcopyrite, and copper carbonates are the dominant ore minerals. Jerome and others

(1965) have presented an excellent study of the deposits, one that emphasizes the lead mineralization. Phillips (1960) has also studied the deposits and their mineralogy.

In general, the stratigraphy of the Abo Formation in this area is similar to its stratigraphy in the Scholle district, except that here the Abo can be divided into three units. A basal conglomerate is found in local basins cut into the underlying, deformed Pennsylvanian carbonates. The Pennsylvanian formations were deformed before deposition of the Abo Formation, and although the Abo is part of the Sacramento Mountains uplift, its structure consists only of gentle folds and small faults. In the southern part of the district, near the Warnock mine, the conglomerate consists mainly of limestone pebbles and cobbles, with some quartz pebbles and cobbles, in an arkosic sandy matrix. North of the town of High

Rolls, the conglomerate consists of quartz with some granite and rhyolite porphyry pebbles and and cobbles (Phillips, 1960, p. 96). The conglomerates of the Abo Formation in the Scholle district are more discontinuous, contain smaller pebbles, and extend higher in the section rather than concentrating at the base of the formation. Mineralization is confined to the middle arkose member. This unit varies from 50 to 200 feet in thickness and contains 40 percent arkose with the remainder of the unit red and brown shales and siltstones (Jerome and others, 1965, p. 8). The environment is similar to that of the Scholle area; small stream channels, which are represented by arkosic sands, cut into a broad flood plain, represented by red muds and silts (Pray, 1961, p. 104). The upper member of the Abo, referred to as the red shale member by Jerome and others (1965, p. 9), consists of



Figure 5. Calcareous, organic siltstone with chalcocite from the "Long Shale Cut." Chalcocite occurs as nodules in the dense siltstone at left and as replacement of organic fragments at right (only the unreplaced organics, not the chalcocite, is obvious at this angle).

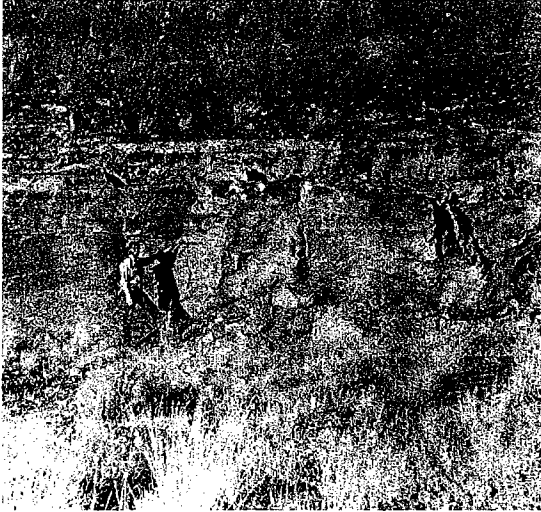


Figure 6. Hammer marks contact between two sandstone channels at the Cole mine. The bedding of the lower channel dips to the left (north) and the bedding of the upper channel dips to the right (south). Calcareous, thin-bedded siltstones with malachite lie above the channels; red shales cap the sequence.

poorly exposed red shales and siltstones. The overlying Yeso Formation often slumps over this unit and obscures the contacts.

Lead mineralization is confined to cream-colored arkoses of the middle unit. Major mines include the Warnock and East Warnock, from which most of the lead production has come. Other mines, such as the Ady and Sacramento, also have lead mineralization. Galena and cerussite appear to replace the matrix of the sandstones and plagioclase grains, and anglesite may coat grains of galena. Although the arkoses represent channels which are not traceable from one mine to another, the mineralized zones all seem to lie at a similar stratigraphic level, according to Jerome and others (1965, p. 26). Cerussite is not always associated with galena, and, as shown in cross-sections by Jerome and others (1965), seems to have migrated downdip and terminated against joint surfaces and foreset beds of crossbedding.

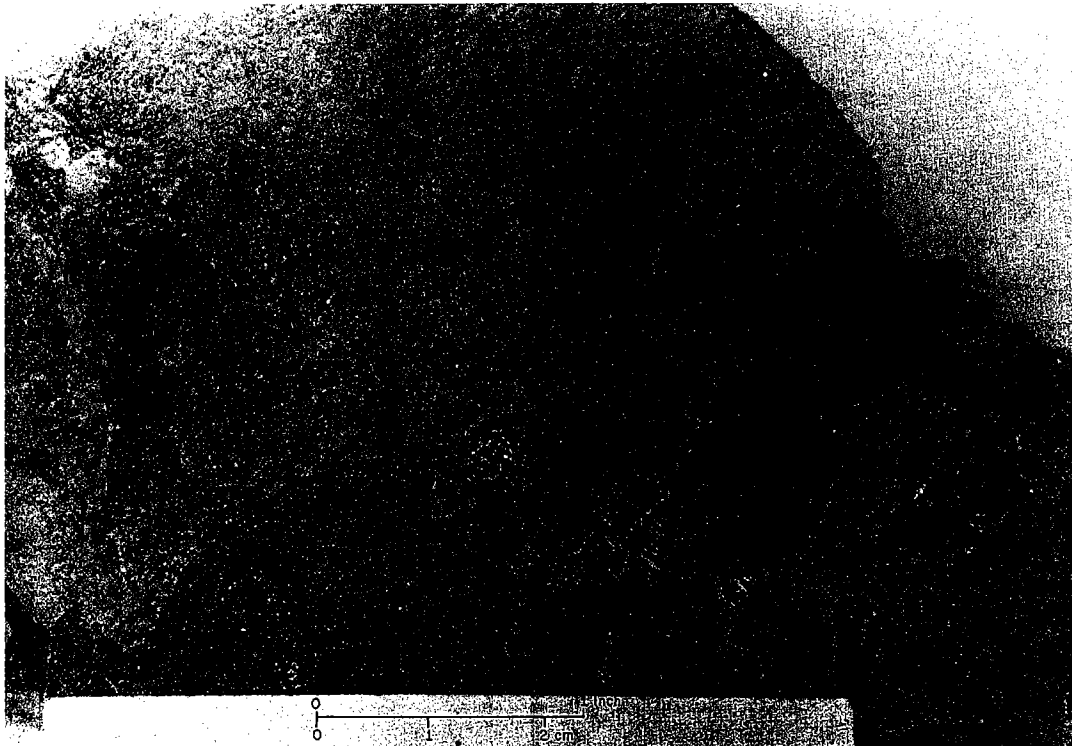


Figure 7. Specimen from the upper channel at the Cole mine shows a wood fragment replaced by chalcocite, then partially weathered. A limestone fragment, partially replaced by chalcocite, is at left center.

Significant copper mineralization is found at the Courtney mine and the Ady mine. At the Courtney mine, near the center of the district, mineralization is below a thick sandstone channel (fig. 8), in an arkosic, organic, gray shale. Copper occurs as chalcocite nodules and replacement of organic debris. Malachite and azurite represent oxidation products that replace chalcocite and occur along bedding planes and fractures. The shale is deformed, and it wraps around the underside of the sandstone. Minor amounts of malachite are found in the sandstone, and the amount decreases upward. Only small amounts of oxidized organic debris were noted in the sandstone. This type of occurrence is typical of copper deposits in the High Rolls district (Jerome and others, 1965) that can no longer be seen underground. The major mines were usually noted either for their lead (Warnock mine) or copper (Courtney mine) mineralization, although high values of copper and lead may both occur. In the lead-bearing arkoses, there is no evidence of organics associated with mineralization, and the copper consists of copper carbonates and chalcopyrite. Pyrite was found with coaly material near lead and copper carbonates in an arkose from the Ady mine (fig. 9). At the Ady mine, the lead-bearing arkoses lie above the organic shales containing most of the copper mineralization (Jerome and others, 1965, p. 25).

In summary, the copper mineral assemblage of chalcocite, malachite, and azurite is found in an environment similar to the Scholle district. The lead mineralization does not appear to be affected by organic material and may, at least in part, represent later mineralization than the copper.

PINTADA MINE

Mineralization at the Pintada mine, west of Santa Rosa in Pintada Canyon, occurs in the Grayburg and Queen Formations (treated as one unit, the Grayburg-Queen, in this paper) which are part of the Artesia Group of Permian (Guadalupean) age (fig. 10). The deposits differ from those previously discussed in that the rocks are slightly younger, although still Permian, and the deposits are not associated with fluvial sediments.



Figure 8. Sandstone channel overlying organic, copper-bearing shales at the Courtney mine, High Rolls district.



Figure 9. Arkosic sandstone sample from the Ady mine of the High Rolls district contains a lens of galena and a lens of malachite. Pyrite has replaced coaly material above the sandstone.



Figure 10. View of the Pintada mine, showing 3 of the 5 mineralized sandstones in the area, separated by red shales.

The Grayburg-Queen formation is underlain by gypsum, dolomite, and red mudstones of the San Andres Formation. Bedding is flat lying with only a few minor faults and folds near the deposit. The Grayburg-Queen can be divided into 3 units in the area of the mine; a basal, massive gypsum 60-75 feet thick, a lower sandstone unit, also 60 to 75 feet thick, which contains the mineralization, and an upper sandstone, 150 to 170 feet thick, composed of red to brown, fine-grained sandstone and interbedded siltstone, mudstone, and shale. The Triassic Santa Rosa Formation unconformably overlies these units (Sandusky and Kaufman, 1972, p. 176).

Chalcocite replaces very fine organic material in 5 fine-grained, gray sandstones, averaging 5 feet thick, which are separated by red shales (fig. 11). Numerous gypsum veins cut through the sandstones and shales. Near the top of each sandstone bed, the chalcocite may be oxidized to malachite; other beds show a thick concentration of chalcocite along the upper bedding surface. Sandusky and Kaufman (1972, p. 176) note that fine pyrite is often associated with the organic material.

Sedimentary structures are not obvious, although the organic material may show signs of reworking (Sandusky and Kaufman, 1972, p. 176). The general environment may be near-shore marine, with a restrictive environment as indicated by gypsum beds. The red mudstones may represent periods of continental deposition. Algal mats, although not preserved, may have contributed to the organic material in the sandstones. The copper was introduced after deposition of the sandstones.

RAYO DISTRICT

The Rayo district is 5 to 15 miles south of the Scholle district. Mineralization is found in the Meseta Blanca Sandstone Member of the Yeso Formation, which overlies the Abo Formation and is composed of red mudstones and siltstones. The Meseta Blanca is the lower member of the Yeso Formation of Permian (Leonardian) age. The brown sandstone is medium grained, with ripple marks and crossbedding. In outcrop, the sand forms a persistent layer for many miles and may represent a beach or marine sand-

stone. There is no obvious organic material. Malachite and minor amounts of chrysocolla occur as cement and around brown to black concentrations of iron and copper oxides (fig. 12). Overall, the deposit is very low grade.

Several similarities exist between the sandstone copper deposits of the Rayo district and those of the Dakota Sandstone at Lisbon Valley, Utah. Chalcocite concentrations are found in brown, medium-



Figure 11. Photomicrograph of mineralized fine-grained sandstone from the Pintada mine, composed of quartz and potassium feldspar. Black areas are where chalcocite is replacing organic material.



Figure 12. Blebs of copper and iron oxide and possibly chalcocite, disseminated in a weathered sandstone from the Rayo district.

grained Dakota Sandstone (fig. 13). There is a lack of obvious organic material. In the higher levels of the mine, oxidation of chalcocite has left malachite and azurite as a cement in the sandstone and as a fracture filling. The copper in the Lisbon Valley deposits was originally introduced along faults into the porous sandstones (Schmitt, 1968). In the Rayo district, faults are not observed, but the Meseta Blanca is a porous sandstone through which copper-rich solutions could easily pass. Neither deposit is found in a typical unit for sandstone copper deposits, and both lack organic material to control deposition of the copper.

NACIMIENTO AND EUREKA MINES

At the Nacimiento and Eureka mines, east of Cuba, New Mexico, on the west flank of the Nacimiento Mountains, copper mineralization is found in the Agua Zarca Sandstone Member, the basal member of the Upper Triassic Chinle Formation. Triassic rocks unconformably overlie the Permian Cutler Formation, which is equivalent to the



Figure 13. Chalcocite concentrations in sandstone from the Dakota Sandstone at Lisbon Valley, Utah. A narrow halo of malachite or azurite may surround the chalcocite.

Abo Formation and contains minor mineralization associated with sandstone channels. The Agua Zarca is overlain by red, gray, and variegated shales of the Chinle Formation. The Poleo Sandstone Lentil, a sandstone similar to the Agua Zarca, divides the shales of the Chinle into a lower shale member, the Salitral Shale Tongue, and an upper shale member.

When fresh, the Agua Zarca consists of a white, medium- to coarse-grained, friable quartz sandstone with a clay matrix and minor amounts of feldspar. Throughout the unit, but more abundant near the base, is a quartz pebble and cobble conglomerate. Clay fragments, some up to a foot in length, are found throughout the sandstone. Carbonaceous material ranges from compressed organic debris to large fossilized logs. Much of the carbonaceous material, especially the logs, is now replaced by chalcocite (figs. 14, 15). Malachite, chrysocolla, and azurite form a cement in the sandstone. The amount of chalcocite increases downdip, toward the water table, where native silver is also found.

The Eureka and Nacimiento mines are located in a large fluvial-channel complex that trends from the northeast to the southwest. Crossbedding, cut-and-fill structures, and lenticular channels usually 2 to 6 feet thick and 20 to 50 feet wide constitute the complex (Woodward and others, 1974, p. 110). Quartzite pebbles, ripped-up clay fragments, and woody debris are associated with the coarse sandstone in the channels. The source area for the sediments is the Uncompahgre uplift, composed of Precambrian rocks, to the northeast (fig. 1).

The Eureka mine is perched on the south side of the nearly flat lying Eureka Mesa. Mineralization is found in the lower, more conglomeratic portion of the Agua Zarca. Chrysocolla and malachite as cement are the major ore minerals (fig. 16). Chalcocite may be present as replacement for organic debris in the coarse- to medium-grained, green sandstones. The deposit represents an erosional, oxidized remnant of a larger deposit. Contacts between the mineralized sandstones and conglomerates and the brown, oxidized beds on both ends of the exposed workings are abrupt.

Mineralization at the Nacimiento mine (fig. 17) extends throughout the entire thickness of the Agua Zarca. Chalcocite

replaces the organic debris, both the compressed material and logs, as well as the sandstones surrounding the organic material (fig. 18). Copper carbonates and silicates form a cement for the sandstone (fig. 19). Surface waters have oxidized some of the sandstone. The copper has been leached from the sandstone and organic debris, leaving a brown sandstone with iron relicts of woody debris.

Structure has played an important role in mineralization at the Nacimiento mine. The Agua Zarca dips 24 to 50 degrees to the west and is cut by the Nacimiento fault west of the present pit. The unit also lies in a graben, referred to as the El Cajete-Blue Bird graben (Antony, 1972, p. 24). Besides preserving the channel complex by downdropping the beds, ground water may be channeled and confined by the graben to enhance mineralization. Shales above and below the sandstone would also help confine the waters (Antony, 1972, p. 43). The waters are funneled downdip, toward the Nacimiento fault.

STAUBER MINE

The Stauber mine lies south of the Pintada mine, near the south rim of Pintada Canyon. The deposit occurs in sandstones that form low hills surrounded by alluvium on all but the north side. Mineralization lies in the Santa Rosa Formation, which is considered an equivalent of the Agua Zarca. The Santa Rosa consists of a series of sandstone units separated by shales.

The mine lies in the second sandstone above the base of the Santa Rosa. A bed of plastic clay underlies most of the deposit. The ore-bearing sandstone may be up to 12-feet thick; above the sandstone, up to 40 feet of shale may be present (Holmquist, 1947, p. 4). Exposures at the mine are poor, but based on samples and reports (Holmquist, 1947; Soule, 1956), mineralization consists of chalcocite replacing organic debris, and malachite, azurite, and chrysocolla cementing the sandstone (fig. 20). Weathered logs, similar to those found at the Nacimiento



Figure 14. Log replaced by chalcocite in pinkish-white, medium-grained sandstone from the Nacimiento mine.

mine, can be found along the outcrop of the sandstone (fig. 21). The sandstone also appears to represent a fluvial sequence, similar to that of the Agua Zarca. However, the Stauber deposit does not contain sandstone or conglomerate that is as coarse as that at the Nacimiento mine. Clay fragments are also much smaller. The source of the detritus is unknown, although the deposition of fluvial sandstones unconformably on top of Permian shales indicates renewed uplift.

MODELS FOR GENESIS OF SANDSTONE COPPER DEPOSITS

A great many factors control the localization of sandstone copper deposits. These include source areas for the sediments and the copper, methods of copper migration, geochemistry of the depositional environment of the copper minerals, and the effect of sedimentary environment, structure, and later weathering.

Permian and Triassic deposits at Scholle, High Rolls, Nacimiento, Eureka, and Stauber are all associated with organic



Figure 16. Coarse conglomerate from the Eureka mine with malachite and azurite as mineralization.



Figure 15. Photomicrograph, from the Nacimiento mine, of fossilized wood partially replaced by chalcocite. Mineralization extends into the sandstone where the clay matrix is replaced.



Figure 17. View of the Nacimiento mine, looking north. Mineralization is found in the white Agua Zarca Sandstone Member of the Chinle Formation. Permian red beds lie below (to the right), and shales, limestones, and sandstones of the Chinle Formation lie above.

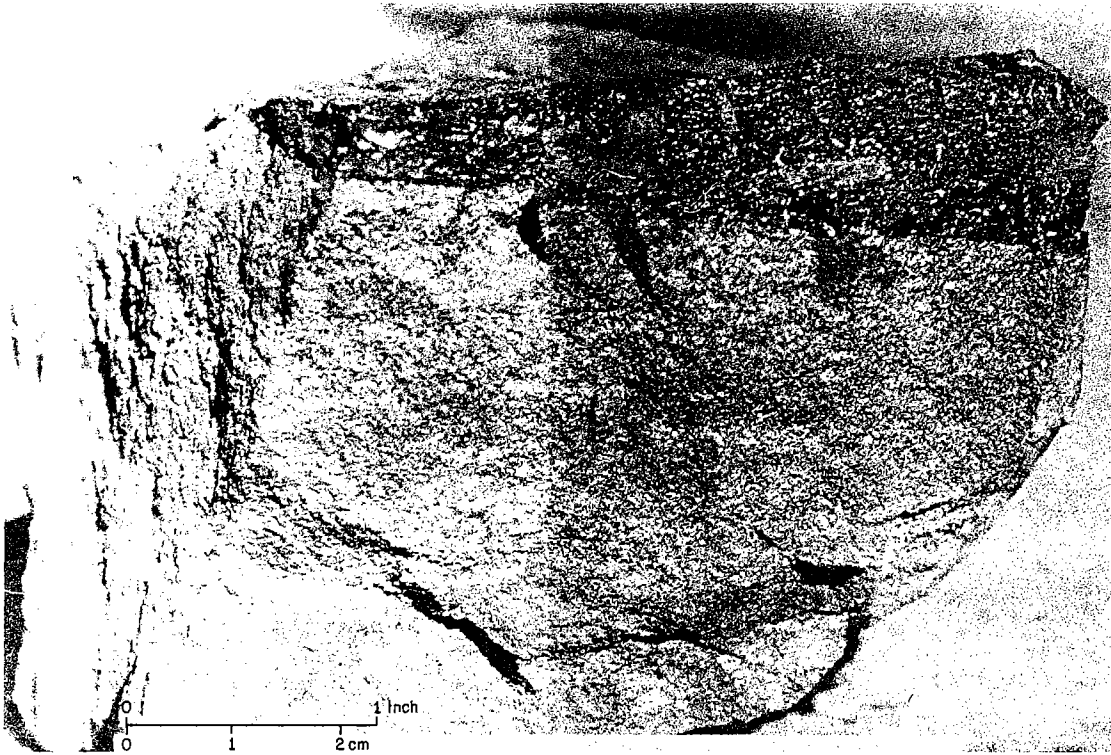


Figure 18. Specimen from Nacimiento mine shows chalcocite replacing wood and surrounding sandstone.

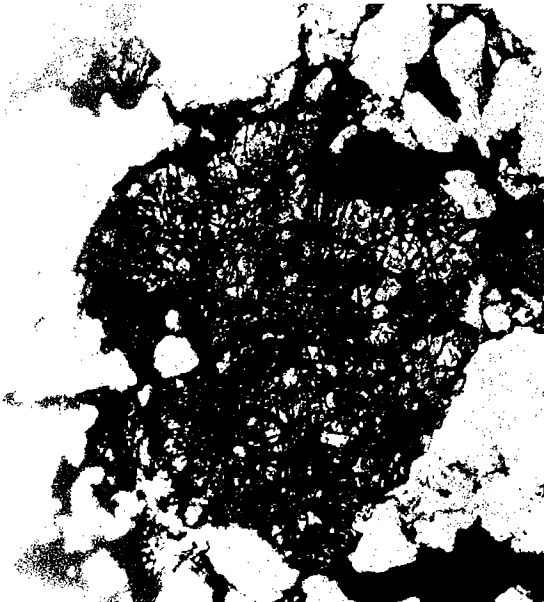


Figure 19. Photomicrograph of badly fractured potassium feldspar in a quartz sandstone from the Nacimiento mine. Note the etched edges of quartz where malachite is replacing the matrix.



Figure 20. Photomicrograph of chrysocolla and malachite cement in quartz sandstone from the Stauber mine.

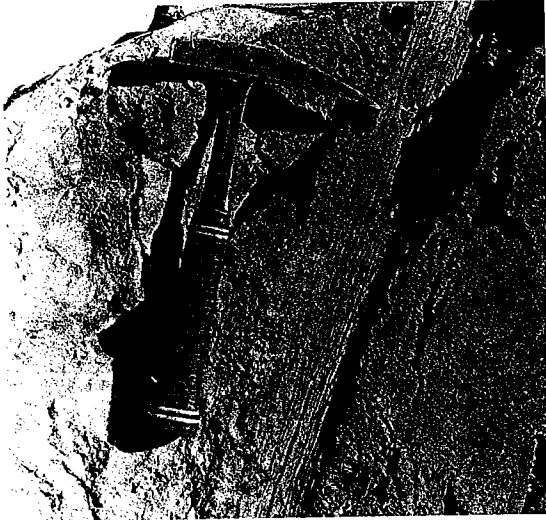


Figure 21. Fossilized wood relict with a malachite coating, taken from the Stauber mine.

material in a fluvial sequence. The Permian deposits have copper mineralization in gray, organic shales and siltstones as well as replacement of organic debris in sandstone channels. The Triassic deposits differ in that mineralization is associated only with the channel sandstones. In both cases, mineralization appears to be early diagenetic. Do these differences reflect different solutions and origins, or differences in the sedimentary environment?

The fluvial sediments associated with copper deposits had their sources in Precambrian terrains. There is good evidence (LaPoint, 1974) to suggest that Precambrian metavolcanic rocks are the source of the copper, rather than water derived from younger (Cenozoic) igneous activity or leaching of copper from Mesozoic or late Paleozoic volcanic rocks.

There is no evidence of feeder channels, hydrothermal alteration, or complex ore mineralogy associated with these sandstone copper deposits, despite the fact that the Jemez Caldera lies close to the Nacimiento and Eureka mines, the Sierra Blanca intrusive is close to High Rolls, and dikes occur south of Scholle. In addition, the fact that mineralization is restricted to rocks of a certain age, rather than existing in sandstones throughout the section, is further evidence that younger intrusives did not

supply the fluids. At Lisbon Valley, where faults controlled mineralization, rocks throughout the section are mineralized (Schmitt, 1968).

Volcanic rocks have been proposed as the source for many uranium deposits in the western United States (Harshman, 1972, p. 71). During the late Paleozoic and Mesozoic, volcanism took place in California, Nevada, and southeastern Arizona. Altered volcanic rocks originating in southeastern Arizona are found throughout the Triassic Chinle Formation (Stewart and others, 1972, p. 58). Volcanic rocks have not been reported in the Permian formations.

A comparison of chemical analyses of Cenozoic and Mesozoic ash-flow tuffs shows that both are low in copper (table 1), and the copper content decreases with increasing silica content. Volcanic rocks near the copper deposits are from ash that must have traveled through the air several hundred miles and represent the lighter, more silicic, copper-poor fraction of an eruption. There is no evidence of leaching of copper when comparing Cenozoic and Mesozoic volcanic-rock analyses for silicic rocks.

Because the source areas for copper-bearing sediments are uplifted areas composed of Precambrian rocks (fig. 1), the Precambrian must be considered an attractive source for the copper. Deposits of copper are restricted to certain locations (fig. 1), and there are large areas of similar types of sediments that are not mineralized. Therefore, rather than considering all Precambrian rocks as a source, preexisting ore deposits as proposed by Lindgren (1908), Phillips (1960), and Woodward and others (1974) and (or) rocks high in copper values (Samama, 1973; LaPoint, 1974) are proposed as the source.

Figure 1 shows some of the Precambrian ore deposits found in New Mexico. Many of these are massive sulfide occurrences in a Precambrian metavolcanic terrain. Silver (1974) has shown that the Precambrian of central Arizona, northern New Mexico, and southwestern Colorado is a meta-igneous terrain with ages of 1.7 to 1.8 billion years. The majority of central New Mexico lies in a slightly younger terrain (1.65 to 1.72 billion years) composed of sediments with associated metavolcanic and intrusive rocks. The older terrain, which was part of the

Table 1.—Chemical Analyses of
Rhyolitic Ash-Flow Tuffs

RECENT ASH-FLOW TUFFS

San Juan Mountains (66 samples):
18 ppm Cu — 68.2% SiO₂

Nevada test site (127 samples):
5.5 ppm Cu — 74.0% SiO₂

Total (including samples from other areas,
254 samples): 10 ppm Cu — 68.9% SiO₂

MESOZOIC ASH-FLOW TUFFS

Total — southeast Arizona (14 samples):
5 ppm Cu — 74.1% SiO₂

Source: Lipman (written communication), 1973;
Lipman and others, 1966; Ratte and Steven, 1967;
Greene, 1973; Lindsey and others, 1973; Sheppard
and Gude, 1973; Drewes, 1971; and Simons, 1972.

Permian and Triassic Uncompahgre uplift, contains numerous massive sulfide deposits in northern New Mexico and in central Arizona. The younger terrain, which was part of the Zuni and Pedernal uplifts, also contains Precambrian ore deposits associated with metavolcanic rocks, although not as well developed.

In addition to ore deposits, the metavolcanic rocks themselves may have high copper values. Data from the Eagle Nest quadrangle in northern New Mexico (table 2) show that mafic gneiss, believed to represent both metasediments and metavolcanic rocks, contains an average of twice as much copper as the associated granites and quartzites (Misaqi, 1968). Banks (1974) shows that chlorite, altered from biotite near mineralized areas, can contain high copper values. The copper may be located on exchangeable cation sites or incorporated in the lattice. Mafic igneous rocks average higher copper values than silicic rocks; basalt may average 100 ppm copper (Vinogradov, 1962). In these rock types the copper may occur as sulfides, as a replacement of Fe⁺⁺ and Mg⁺⁺ in the silicates, or on cation exchange sites in minerals (Rabinovich and Badalov, 1971). High concentrations may also occur in

plagioclase, especially along crystal lattice discontinuities (Göni and Guillemin, 1964).

Figure 1 outlines Permian and Triassic uplifts in New Mexico. Sediments with copper mineralization were derived from newly uplifted, eroding landmasses composed of Precambrian rocks. The sediments would be composed of clays and weathered silicates from the previously exposed rocks and soils and fresh silicates and other minerals from newly exposed rocks.

Copper may have been transported in several ways. Weathered sulfides would release copper into the streams and ground water. These waters would be acidic, and as they equilibrate with the normal stream environment, deposition of copper carbonates, oxides, and silicates would occur in alluvial sediments (Newberg, 1967). A similar situation to that proposed by Newberg (1967) for cementation of gravels by copper minerals adjacent to porphyry copper deposits may have existed in the Abo Formation adjacent to the Permian Zuni uplift. Malachite and azurite, but only minor sulfides, form abundant cement in arkosic sandstones and conglomerates derived from nearby Precambrian metavolcanic rocks that contain copper deposits. Rhyolite fragments and quartz eyes from the rhyolites are very common in the sandstone. The arkoses appear to be very close to their source,

Table 2.—Precambrian Rock Analyses from
Eagle Nest Quadrangle, New Mexico

MAFIC GNEISS: (35 samples)	Average: 72 ppm copper Range: 20-345 ppm copper
6 anomalous samples: 95, 100, 110, 150 160, 345 ppm copper	
QUARTZITE: (20 samples)	Average: 36 ppm copper Range: 20-70 ppm copper
no anomalous samples	
GRANITE: (40 samples)	Average: 34 ppm copper Range: 10-60 ppm copper
no anomalous samples	

Source: Misaqi, 1968.

because volcanic detritus is not diluted by quartz and feldspar grains from adjacent granites and gneisses. Chalcocite is not an important ore mineral, due to a lack of organic debris.

Copper in weathered silicates and sulfides could also be bound as copper-organic complexes (Veitch, 1972) or copper-organic clays (Steger, 1973). This material could be carried downstream during erosion of weathered silicates and soil. Because the clay and organic material is very fine, deposition would occur in backwater environments or lakes.

The copper in fresh silicates or sulfides would be deposited with the coarse sandstones and conglomerates in alluvial channels. These sediments would contain abundant mafic silicates and feldspars as well as rock fragments and quartz. During diagenesis, a reaction of the silicates with ground water would release copper and other metals, including iron. The sediments would be stained red owing to development of iron and clay minerals from the primary silicates (Walker, 1967). An alkaline, oxidizing ground water would result that could carry copper down dip as copper carbonate complexes.

Sandstone channels would form paths for the movement of ground water. In addition to copper derived from the breakdown of silicate minerals during diagenesis, copper carbonates or oxides previously deposited in the channels (such as the Zuni deposits) could be remobilized. Precipitation of the copper would occur in reducing environments such as those found around concentrations of organic debris in sandstone channels. Later ground-water movements and oxidation would modify the form of the deposits.

Deposits in organic shales and siltstone may be the result of local remobilization of the copper from copper-organic and copper-organic-clay complexes during dewatering and compaction of the sediments. The copper would migrate to form chalcocite nodules, probably around nuclei, and to replace organic material in the shales and siltstones and perhaps in nearby channel sandstones.

The Triassic deposits fit the model of copper derived from ground water, while the Permian copper deposits fit the model of local mobilization of copper from clay and

organic complexes. The models are based on the assumption that Precambrian rocks are the source and that copper can be carried either as an ionic species or as a type of complex. All of the deposits are diagenetic in their present form, so later movements of the copper must be considered.

If the copper-rich ground waters previously described continue to migrate down dip in the channels, assuming structure has not changed the ground-water flow, a facies change to marine conditions will eventually be encountered. A mixing of waters in an environment similar to that proposed by Renfro (1974) may form deposits such as those of the Pintada mine.

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RED BEDS AND COPPER DEPOSITS—WHY THE ASSOCIATION?

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Abstract—The color of most red sedimentary rocks is due to finely disseminated hematite coating other mineral grains. Hematite is the end product of oxidation of divalent iron minerals either in soil (syngenetic) or after burial of the sediment (diagenetic or epigenetic). Oxidation releases minor elements such as copper into solution while iron remains as insoluble oxides. If the oxidation occurs at the surface, the minor elements are carried away in surface runoff. If the oxidation is post-depositional, then the mobilized minor elements possibly can be redeposited and concentrated as an orebody by circulating ground water in nearby green, gray, or black beds. Thus, the dispute over the origin of red beds is directly applicable to the search for copper deposits.

In fluvial sandstones, copper deposits occur at an oxidation-reduction interface, usually associated with carbonaceous matter, analogous to the occurrence of uranium deposits. The copper deposits in fluvial sandstones are generally small, but those in deltaic or marine sediments may be large. Moreover, the origin of the large deposits in deltaic or marine sediments probably is similar to that of the fluvial deposits in that the copper sulfides were precipitated in a reducing environment by circulating ground water. Where stratiform copper deposits occur in gray marine strata in association with red beds, the deposits are probably diagenetic or epigenetic—where red beds are absent they may be syngenetic.

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**CENTRAL EUROPEAN VERSUS SOUTH-CENTRAL U.S.A.
GEOLOGIC SETTINGS OF THE PERMIAN BASINS
AND ASSOCIATED COPPER MINERALIZATION**

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Abstract—A thorough study of the Permian basin in central Europe, including the North Sea, and of the Permian basin in the south-central U.S.A. indicates that despite their geographic separation by the vast Atlantic Ocean, both basins have numerous geologic features in common.

One of the most important features common to both basins is the presence of a variety of economic mineral resources. In the European basin enormous reserves of copper and associated economic minerals are known, while in the U.S. basin, although we cannot talk yet in term of reserves, the frequency of copper and other mineralization is very encouraging.

An interesting observation that should be mentioned is the possible relationship between nonferrous metallic mineralization, the potassium-magnesium salts and hydrocarbons.

One of the differences between the two basins is in their structural development and igneous activity. During Variscan orogeny, the region later to be occupied by the European Permian basin was strongly deformed and invaded by volcanic and plutonic rocks. Volcanic activity, however, continued into Permian but ended in mid-Rotliegendes (mid-Lower Permian). On the other hand, it appears that the south-central U.S. region was much less deformed, mainly during the Pennsylvanian.

It is interpreted and considered significant that both Permian basins are located within Precambrian foreland (*sensu lato*) and are nearly surrounded by crystalline masses.

In both Permian basins there is evidence of paleoenvironmental similarities at regional but not local scale.

Also from a metallogenic point of view there are similarities as well as differences. The presence of copper mineralization associated with similar types of sediments in both basins is considered important. A significant difference is that in the central European Permian basin prosperous mines have been known and operated since the 13th century (e.g., Mansfeld mining district, East Germany), while in the south-central U.S., Permian-basin copper-silver mineralization has been known for over a century, but deposits of similar magnitude are yet to be found. It is also interesting to note that although the economic mineral deposits of central Europe are known and have been exploited for so long, it is only recently that the largest polymetallic ore deposit was discovered in the Lubin area (southwestern Poland). This is undoubtedly the result of persistent exploration in a relatively well known region.

In conclusion, it is considered that the difference in magnitude is only apparent. Based on the data available, it is considered that there is still potential for additional discoveries in the European Permian basin. More importantly, even greater potential exists for discovery of similar, large, economic mineral deposits in the Permian basin of the south central U.S.A.

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THE GEOLOGY, EXPLORATION, AND DEVELOPMENT
OF THE STRATIFORM COPPER DEPOSIT
LOCATED NORTHWEST OF CROWELL, TEXAS

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Abstract—This deposit is located 10 miles northwest of Crowell, Texas, near the southeast bank of the Pease River. The topography consists of a highly dissected escarpment with prominent hills and gullies. The mineralization occurs in the lowest part of the Blaine Formation of the Double Mountain Group of Permian Age. Three copper-bearing siltstone horizons are present: the “upper” bed, consisting of the bottom 3-22 inches of a 2½- to 3½-foot gray siltstone; the “lower” bed, averaging 6 inches in thickness; and the “lower-lower” bed, averaging 8 inches in thickness. The beds are separated, respectively, by 2½ feet and 2 feet of mixed green and red clay. The copper occurs as very-fine-grained chalcodite, with its oxidation products malachite and azurite near the surface.

Hundreds of samples have been taken and assayed from the surface, 470 backhoe trenches, and 85 drill holes. The average grade of the 1,788,000 tons of the proven, probable, and possible ore developed to date is .94 copper. Metallurgical testing has shown an 81-percent recovery of copper and silver values by straight flotation. No exploitation has been started.

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