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PERMIAN COPPER SHALES OF SOUTHWESTERN UNITED STATES

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ABSTRACT

Many stratiform copper deposits are known in Permian shales and sandstones of Texas, Oklahoma, and Kansas, but the most important of these are six copper-shale ore bodies exposed in the Flowerpot Shale and San Angelo Sandstone along a total distance of some 200 km in Oklahoma and Texas. Individual ore bodies range from 15 to 45 cm thick and cover about 30 km^2. Chalcocite is the primary ore mineral, and malachite is the main oxidation product. The average grade of different deposits is 1 to 2 % copper: other metals are present only in small amounts, generally less than 500 ppm.

The flat-lying ore beds are medium-gray laminated silty shales that are interbedded with red-bed clastics and evaporites. One ore body is being strip mined, another is being developed, and the other four are being prospected.

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

INTRODUCTION

Permian sedimentary rocks crop out over a substantial part of the southwestern United States, with some 2 000 meters of red beds and evaporites being the major constituents in north Texas, Oklahoma, and Kansas. Reddish-brown shales, siltstones, and sandstones are interbedded with gypsums and thin dolomites on the outcrop, whereas thick sequences of salt (halite) are interbedded with red beds and gypsum in the subsurface.

Copper minerals have been noted in these red beds since the middle of the 19th century (Marcy, 1854; Fath, 1915; Richard, 1915; Fischer, 1937; Merritt, 1940). Chalcocite and malachite are the most common minerals, occurring in sandstone and shale as encrustations, impregnations, veinlets, small nodules, and mineralized wood. The few early attempts at mining resulted in failure, owing to the lean grade of ore and the small size of deposits, but a new concept of copper mineralization was introduced in 1962 with discovery of malachite disseminated in a persistent 18-cm-thick shale bed along an outcrop distance of 5 km at Creta in

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southwestern Oklahoma (Ham and Johnson, 1964). Initially called the "lower copper bed," with a copper content of 2.6 to 4.5 % at the outcrop, it was the first United States report of a bedded copper shale in Permian strata.

Eagle-Picher Industries began mining and milling operations at Creta in 1965, and this 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 several other significant discoveries in the three States attest the likelihood that other stratiform copper deposits will be brought into production.

PALEOGEOGRAPHY AND STRUCTURAL SETTING

The study area is on the east side of the Permian basin, a broad epicontinental sea that covered much of the southwestern United States during the middle of Permian time (fig. 1). The sea was approximately 650 km wide and 1 100 km long, and 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. Epeirogenic 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 in southwestern Oklahoma, was a more stable crustal block, extending westward beneath the sea.

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

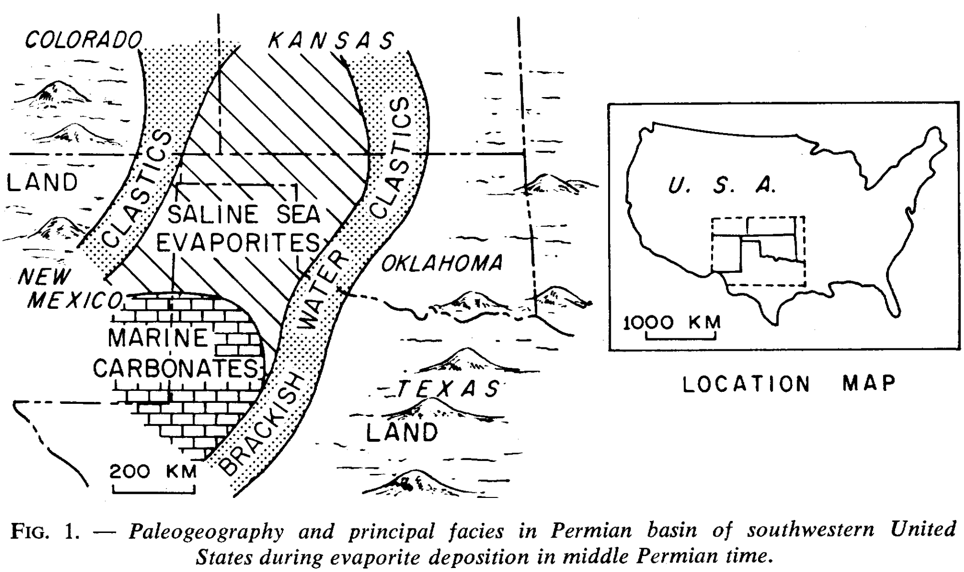

FIG. 1. — *Paleogeography and principal facies in Permian basin of southwestern United States during evaporite deposition in middle Permian time.*

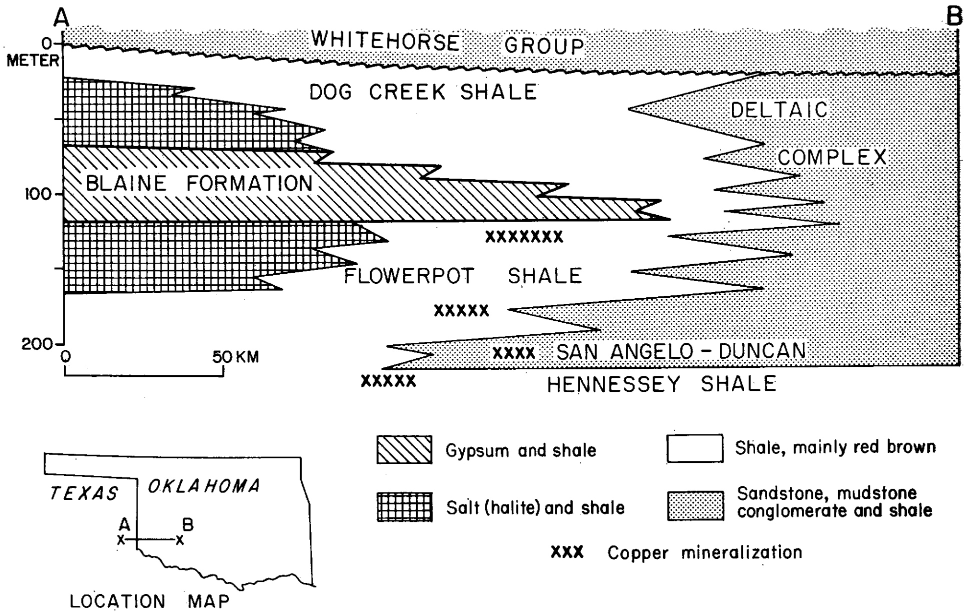

FIG. 2. — *Stratigraphic cross section showing copper mineralization in Permian strata of southwestern Oklahoma and north Texas.*

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 gray shale, gypsum, and siltstone; and (3) an evaporite facies of interbedded gypsum, shale, salt, and dolomite. Outcrops of the San Angelo (Duncan) Sandstone comprise a deltaic-alluvial facies, those of the Flowerpot Shale comprise a brackish-water and marine facies, and the Blaine Formation represents an evaporite facies (fig. 2). Each of these formations is commonly 30 to 60 m thick. Clays and sands in the Flowerpot and associated formations were derived from the largely concealed Ouachita Mountain system of Texas and southeastern Oklahoma: the nearby Wichita Mountains were sufficiently buried by earlier Hennessey time that they contributed little or no detritus to the Flowerpot.

Outcropping rocks on the east side of the Permian basin are essentially flat lying. They have been disturbed only by small-scale block faulting (throws of 3 to 30 m) and gentle folding, and dips are typically less than one-half degree: no evidence of mineralization has been found associated with faults or folds. Beneath the copper-shale outcrops are 1 000 to 4 000 m of Paleozoic sedimentary rocks resting unconformably upon a basement complex of Cambrian and Precambrian igneous and metasedimentary rocks. The full section of Paleozoic strata has been penetrated in oil and gas tests at many places, and evidence of magmatic or hydrothermal activity following Middle Cambrian time in any part of the region is lacking. The Wichita Mountains comprise granites, rhyolites, and gabbros emplaced in Middle Cambrian time, 525 to 535 million years ago (Ham, Denison, and Merritt, 1964).

STRATIGRAPHY

The principal formations related to copper-shale occurrences in the region are, in ascending order, San Angelo (Duncan) Sandstone, Flowerpot Shale, and Blaine Formation (fig. 2). They have an aggregate thickness of 150 m and are of late Leonardian or early Guadalupean age.

The San Angelo 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 laterally to shale westward into the Permian basin. The name "San Angelo" is applied to the unit in north Texas and in Oklahoma south of the Wichita Mountains, whereas equivalent and similar strata north of the Wichitas are called "Duncan." The outcrop thickness of both the San Angelo and the Duncan is generally 20 to 50 m.

The Flowerpot Shale, which contains the main copper shales, consists mainly of reddish-brown shale with thin interbeds of gypsum, dolomite, siltstone, sandstone, and greenish-gray shale. It crops out in southern Kansas, western Oklahoma, and north-central Texas (fig. 3). In the subsurface to the west, about 50 m of rock salt and salty shale are interbedded in the upper part of the formation. The total thickness of the formation is typically 30 to 60 m in outcrops throughout the region.

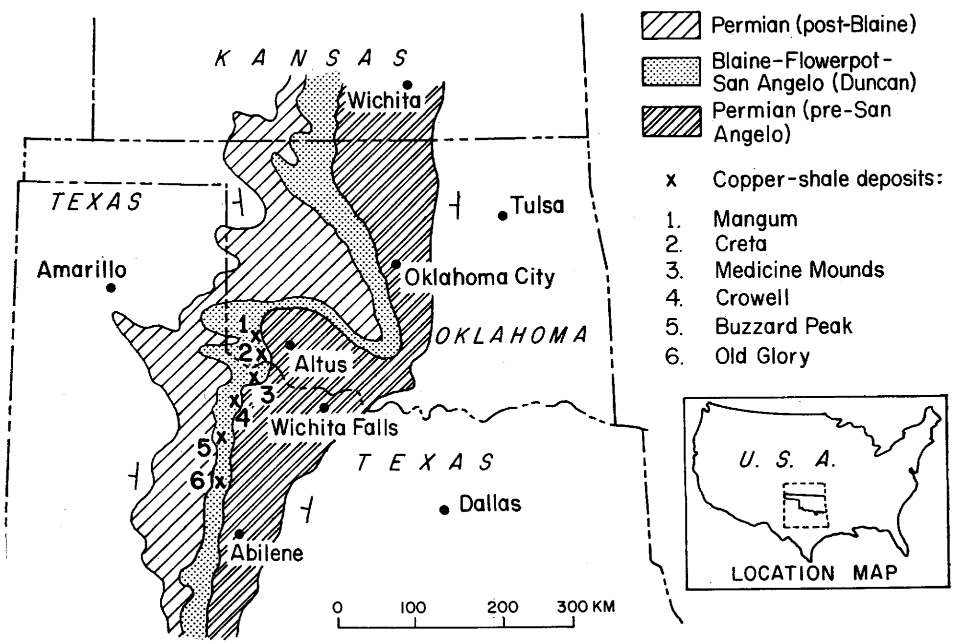

FIG. 3. — *Areal extent of Permian outcrops in southern Kansas, western Oklahoma, and north-central Texas.*

Most Flowerpot strata apparently were deposited in marine or brackish water. Evaporite beds, each 1 to 100 cm thick, aggregate about 15 % of the top half of the formation in most outcrops: gypsum makes up 80 to 90 % of these thin evaporites, and the remainder is light-gray microgranular dolomite. In north Texas, gypsum beds 1 to 5 m thick made up much of the Flowerpot. Flowerpot strata grade southeastward into deltaic and alluvial deposits, which are now eroded at most places.

Shales of the Flowerpot are typically reddish brown, blocky, slightly silty, gypsiferous, and lacking in fossils. About 85 % of the shale is red brown, and the remaining 15 % is light gray, green gray, and medium gray: red-brown beds are commonly 0.3 to 2 m thick, whereas gray beds are mostly 0.1 to 0.5 m thick and generally underlie thin evaporites.

The Blaine Formation 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 separate gypsum layers. Evaporites in the Blaine were deposited during the maximum transgression of the sea before its regression in later Dog Creek time. The thickness of the Blaine Formation ranges from 20 m in the north (Kansas) to 60 m in southwestern Oklahoma and Texas.

COPPER MINERALIZATION

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; Lockwood, 1972; Johnson and Brockie, 1973; Dingess, in preparation; and Smith, in preparation). The first copper-shale discovery was the Creta deposit in southwestern Oklahoma, and it alone is now being mined (by Eagle-Picher Industries, Inc.): the Creta deposit also has been investigated most thoroughly. A second find by Lobaris Copper Company south of Mangum in Oklahoma is being investigated, and so also are four other significant copper shales in Texas at sites near Medicine Mounds, Crowell, Buzzard Peak, and Old Glory (fig. 3).

Creta District

Preliminary outcrop study of the Creta deposit established that an 18-cm-thick copper-bearing shale in the upper part of the Flowerpot Formation extended 5 km along the outcrop, and that the grade ranged from 2.6 to 4.5 % copper (Ham and Johnson, 1964). Subsequent core drilling and exploration by Eagle-Picher established that chalcocite is the primary ore mineral under moderate overburden, and that an ore body averaging 2.3 % copper (undiluted) could be strip mined (Johnson and Brockie, 1973; Dingess, in preparation).

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 8 to 30 cm and averages about 18 cm. The Prewitt bed is about 12 m below the top of the Flowerpot Shale and is about 2.5 m below the thin but persistent Marty Dolomite (fig. 4).

The ore bed consists of two basic lithologies: the upper 10 to 13 cm is laminated, thereby differing petrologically from other gray shales in the Flowerpot, whereas the lower 8 to 10 cm 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 mm thick and constitute 10 to 20 % of the unit. Thin-section study reveals that the ore bed consists mostly of microcrystalline clay minerals. Quartz grains, chiefly 10 to 40 μ in diameter, make up 10 to 20 % 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 % in laminated shale and 26 % in blocky shale), gypsum (28 and 3 %), illite (45 and 63 %), chlorite (5 and 6 %), and chalcocite (4 and 2 %). Other analyses indicate that the ore bed also contains 0.1 to 3 % carbonate minerals, chiefly dolomite and some calcite: the organic carbon content ranges from 0.09 to 0.56 % and averages 0.3 %, or about twice as much as in non-cupriferous shales of the region.

Principal copper minerals in the Creta deposit are chalcocite (Cu_2S) and malachite [$CuCO_3 . Cu(OH)_2$]. Chalcocite, the primary ore mineral, occurs mainly as small grains (commonly 2 to 20 μ) 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

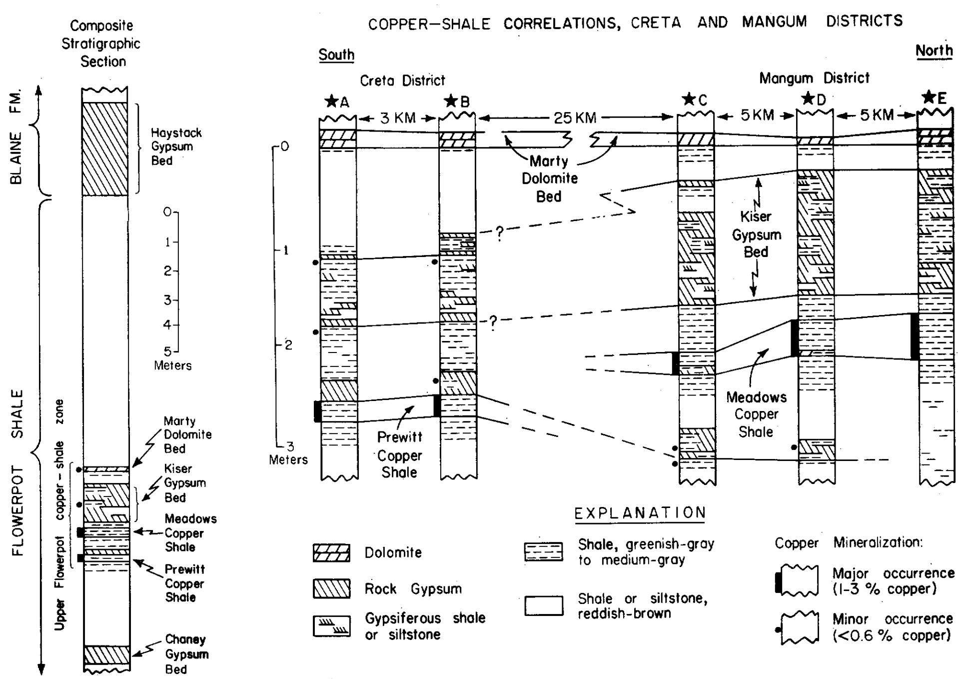

FIG. 4. — *Stratigraphy of the upper Flowerpot copper shales in southwestern Oklahoma.*

pseudomorphs after pyrite. Malachite and brochantite [$CuSO_4 . 3\,Cu(OH)_2$] are oxidation products found on the outcrop where the overburden is less than 3 m: malachite occurs as films and granules, and brochantite occurs with malachite in nodules locally present on the outcrop.

The grade of the Prewitt bed in the mined sulfide zone averages about 2.0 % copper and ranges from about 0.5 % to as much as 4.5 % copper. Other metals, present only 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 or underlying "barren" shales that contain only 0.1 to 0.3 % 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.

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,

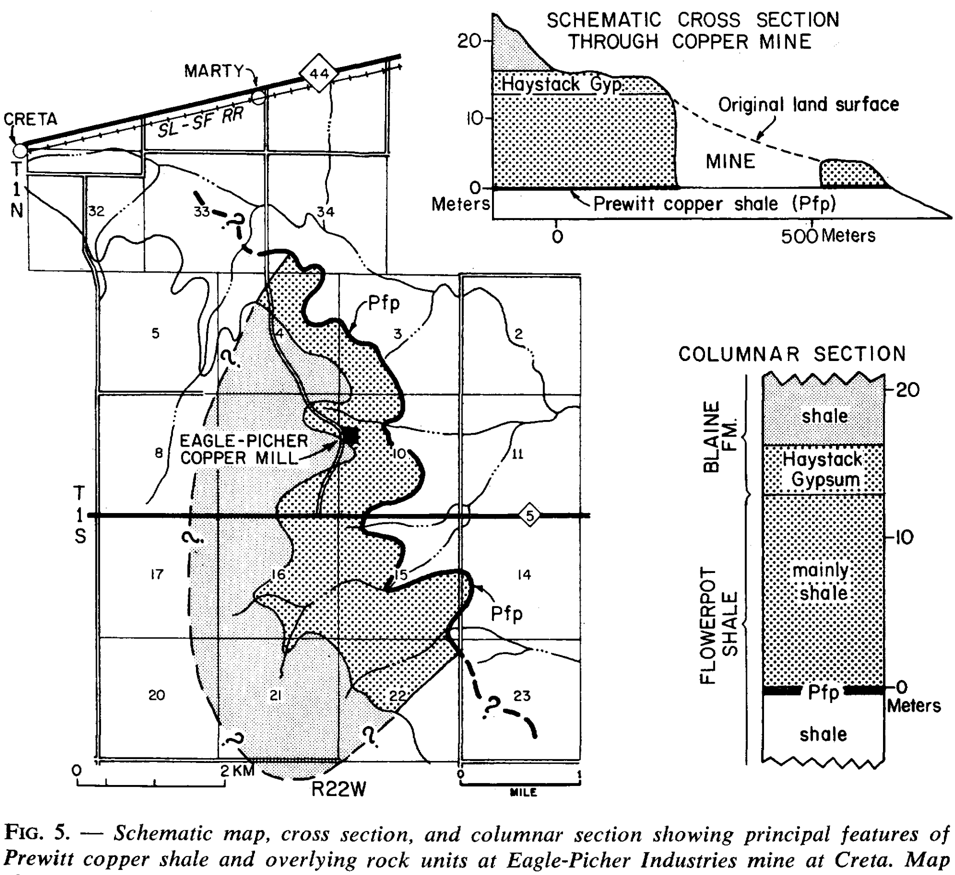

FIG. 5. — *Schematic map, cross section, and columnar section showing principal features of Prewitt copper shale and overlying rock units at Eagle-Picher Industries mine at Creta. Map shows areas where ore bed has shale and gypsum overburden of 0-16 m (dense stippling) and greater than 16 m (light stippling).*

FIG. 6. — *Oblique aerial photograph of Eagle-Picher Industries copper-shale strip mine at Creta. Highwall here is 13 m high.*

just 1.5 m above the Prewitt bed, is thinner (2 to 10 cm 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 (fig. 5). The present reserve area extends about 5 km north-south and 2.5-3.0 km east-west, although mineralized shale with some economic potential underlies a total area of some 30 km^2. Increasing depth of overburden becomes a limiting factor along the western edge of the reserve area. As much as 20 m of overburden has been removed in places. Strip mining is favored by the gentle westward dip of 2 to 4 m per km and the lack of faults or folds in the area (fig. 6). 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

The second major copper-shale discovery in Oklahoma was made in 1965 about 25 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 Formation.

The ore bed, called the Meadows copper shale, is a medium-gray laminated silty copper-bearing shale and mudstone. It is 9 to 11 m below the top of the Flowerpot and about 2 m below the thin Marty Dolomite (fig. 4). The thickness of the Meadows bed ranges from 10 to 45 cm, averaging about 30 cm, and it is the middle part of a green-gray shale which at the top and bottom is blocky and without significant copper. Mineralization in the Meadows bed extends about 10 km north-south and as much as 5 km east-west.

Petrographically, the Meadows bed is somewhat similar to the Prewitt bed at Creta. Lockwood (1972, appendix 2) determined the following average mineral components: quartz (27 %), gypsum (11 %), illite (49 %), chlorite (5 %), and malachite (3 %). More recent data show that organic carbon comprises an average 0.17 % of the ore bed and that dolomite and some calcite commonly make up about 5 to 10 % of the bed.

Malachite is the dominant copper mineral known so far, because nearly all the testing done to date has been at the outcrop or under only several meters of overburden. Chalcocite has been identified at several test localities under 3 to 5 m 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 % copper and ranges from 0.5 to more than 2 % copper. Lockwood (1972, appendix 3) found other metals commonly in the following low concentrations: lead (20-90 ppm), silver (25-45 ppm), cobalt (15-40 ppm), nickel (35-65 ppm), uranium (70-100 ppm), vanadium (100-140 ppm), and zinc (300-400 ppm).

Strata in the Mangum district dip westward gently at 2 to 4 m per kilometer and are not disturbed by faults or folds. It is possible that the deposit could be strip mined in the same manner as the Creta deposit.

Copper Shales in North Texas

The several copper-shale deposits in north Texas have undergone initial stages of exploration, but only a small amount of information has been released to date. Deposits explored include those referred to as the Medicine Mounds, Crowell, Buzzard Peak, and Old Glory prospects. They extend a total of 150 km along the outcrop of Flowerpot and San Angelo strata in Texas (fig. 3).

Ore beds are typically 15 to 45 cm thick, and different beds average 20 to 25 cm. Individual deposits are traceable for 3 to 10 km along the outcrop (generally north-south or northeast-southwest) and appear to be 1 to 4 km wide (east-west). Ore beds are shales and mudstones associated with gypsum and dolomite; they appear similar in most respects to the deposits at Creta and Mangum.

Chalcocite is the primary ore mineral, and oxidation products at and near the outcrop are malachite and azurite. The copper content of individual deposits averages between 1 and 2 %, although at various locations the copper content ranges from 0.5 to about 6 %. There is no indication of significant concentrations of other metals with these deposits.

Ore bodies are flat lying or dip gently to the west, and there is no indication of faulting, folding, or hydrothermal activity associated with any of the deposits.

Copper mineralization in Texas occurs at several stratigraphic levels. Some copper shales are in the upper part of the Flowerpot Formation (as they are in Oklahoma), but other mineralized shales occur in the lower part of the Flowerpot and in the underlying San Angelo Sandstone. Precise correlation between the

Oklahoma and Texas ore bodies must await further field study and detailed stratigraphic analysis.

Copper in Sandstones

In addition to the important mineralization in shales, there are many known copper occurrences in alluvial and deltaic sandstones in the Permian of Texas, Oklahoma, and Kansas (Merritt, 1940; Hill, 1967; Stroud and others, 1970). Copper minerals are commonly associated with carbonized fossil wood and pyrite in the standstone channels.

Copper occurs not only in the San Angelo and Duncan Sandstones but also in the older Permian (Leonardian) standstones of the Wichita and Clear Fork Groups in Texas and equivalent sandstones in Oklahoma and Kansas. Sandstone bodies are commonly lenticular or channelized, and mineralization is difficult to trace laterally because of rapid facies changes. Although the grade of cupriferous sandstones might range up to 10 or 15 % copper in some samples, the erratic distribution of copper has prevented profitable mining of these deposits.

SUMMARY AND CONCLUSIONS

Six known copper-shale ore bodies crop out over a distance of some 200 km in the Permian of Oklahoma and Texas. Ore deposits are typically about 20 cm thick, are elongated north-south or northeast-southwest (subparallel to the inferred Permian shoreline), have dimensions of about 10 km by 3 km, and cover about 30 km^2. At all sites 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 Permian 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 (1972) 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 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 was emplaced in the host shales syngenetically or at an early stage of diagenesis.

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