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GEOLOGY AND MINERALIZATION OF THE CULBERSON SULFUR DEPOSIT

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Abstract—The Culberson sulfur deposit occurs as a replacement of Upper Permian evaporites (Salado and Castile Formations) by sulfur-bearing carbonates in the west-central Delaware basin. Structures derived from two major periods of tectonic activity control the location of sulfur mineralization. Pre-mineralization faults developed in response to Laramide compressional tectonics in the Late Cretaceous to early Tertiary, as indicated by breccia clast assemblages filling paleokarst features along the faults. Basin and Range extensional tectonics uplifted the western Delaware basin beginning in the middle to latest Miocene, resulting in a change in basin hydrodynamics conducive to bioepigenesis. Age of mineralization may be less than 5 Ma, based on mineralization crosscutting karst-related deposits thought to be of Ogallala (middle-late Miocene) age. Crude oil analyses and con-elation of anionic ground water constituents indicate the Guadalupian Cherry Canyon Formation is a probable source for hydrocarbons and oxygenated waters necessary for bioepigenetic sulfur deposition at Culberson. Sulfur occurs as microcrystalline disseminations in replacement limestone and as crystalline vug fillings associated with epigenetic barite, celestite and isotopically light carbonate minerals.

INTRODUCTION

The Culberson bioepigenetic sulfur deposit is a stratabound ore body located in the west-central Delaware basin, Culberson County, Texas (Fig. 1). Native sulfur occurs predominantly with carbonates as a replacement of calcium sulfate minerals in the Upper Permian (Ochoan) Castile, Salado and Rustler Formations (Fig. 2). The Salado and Castile Formations are the lithostratigraphic units that are volumetrically the most altered and most economically important. The ore that has been mined and for which the most information exists occurs as a subhorizontal layer in the Salado Formation.

The purpose of this paper is to provide an updated summary of salient geological characteristics of the deposit and to cite evidence to support a hypothesis of origin and timing of emplacement for the deposit. Although the Ochoan rocks within the Culberson and the greater Rustler Springs sulfur district have relatively simple stratigraphy, post-depositional geologic processes formed complex relationships. As with many economic mineral deposits, ore textures, structural features and associated lithologies provide important clues to determining origin and timing of mineralization. Lithologic and structural relationships indicate that sulfur mineralization and well-developed karst features within the deposit are related to specific hydrologic conditions.

Economic deposits of bioepigenetic native sulfur are rare. Unique conditions are required to bring reactants together in sufficient quantities and at the appropriate time while preserving products within the system. The most likely process for elemental sulfur formation in bedded evaporites involves biochemical reduction of anhydrite/gypsum by sulfate-reducing bacteria (Feely and Kulp, 1957; Davis and Kirkland, 1979). The bacteria oxidize hydrocarbons as a source of energy utilizing sulfate ions as the oxidant (Kirkland and Evans, 1980). As a result of the process, anhydrite/gypsum is replaced by calcite or fine-crystalline limestone and hydrogen sulfide is produced. if the hydrogen sulfide is trapped within the replacement (also termed secondary, diagenetic, biogenic or alteration) limestone long enough to be oxidized, deposition of elemental sulfur results. Low-temperature oxidation of hydrogen sulfide by oxygenated ground water is probably the mechanism for sulfur precipitation, as presented by Ivanov (1968), Davis and Kirkland (1970), Davis et al. (1970), Kirkland and Evans (1980) and Machel (1989, 1992), although other mechanisms of hydrogen sulfide oxidation have been suggested (Feely and Kulp, 1957; Ruckmick et al., 1979). In this paper, the term "alteration" refers to all mineral phases and rock textures that result from the chemical recombination and modification of host rock components. The term mineralization is intended to denote the process by which sulfur, as an ore mineral, is deposited. In this context, mineralization may be considered an aspect of alteration.

FIGURE 1. Locality map of the Culberson ore deposit.

Porch (1917) first reported on the surface occurrences and workings of sulfur deposits in the Rustler Springs district, including small-scale mining operations at the Michigan mine (Fig. 3). This near-surface deposit is located directly above deep-seated biogenic alteration in the southern part of the Culberson deposit area. Attempts to develop underground workings into a suspected larger deposit were unsuccessful. The most successful entrepreneur/operator of the Michigan mine was Mr. Thad Sanford of Carlsbad, New Mexico, who excavated sulfur-bearing soil for local agricultural use.

The 1967 discovery of the Culberson deposit is credited primarily to the efforts of Donn M. Clippenger, a geologist under the employment of Duval Corporation (now Pennzoil Sulphur Company). Pennzoil has operated the property continuously since 1969 using the Frasch method to mine from an original sulfur resource estimated to be about 76 million long tons (LT).

PREVIOUS INTERPRETATIONS

A general hydrogeologic mechanism involving flushing of hydrocarbons by ground-water movement from subjacent Bell Canyon Formation sandstones into the Castile Formation was proposed by Davis and Kirkland (1970) to account for native sulfur generation in the Pokorny bioepigenetic deposit. They also recognized the potential significance of karst features, through which oxygenated meteoric water descended deep into the Castile evaporites and thus was available to oxidize dissolved hydrogen sulfide or polysulfides to elemental sulfur. Their study essentially first established the primary requisites for bioepigenetic deposition of sulfur.

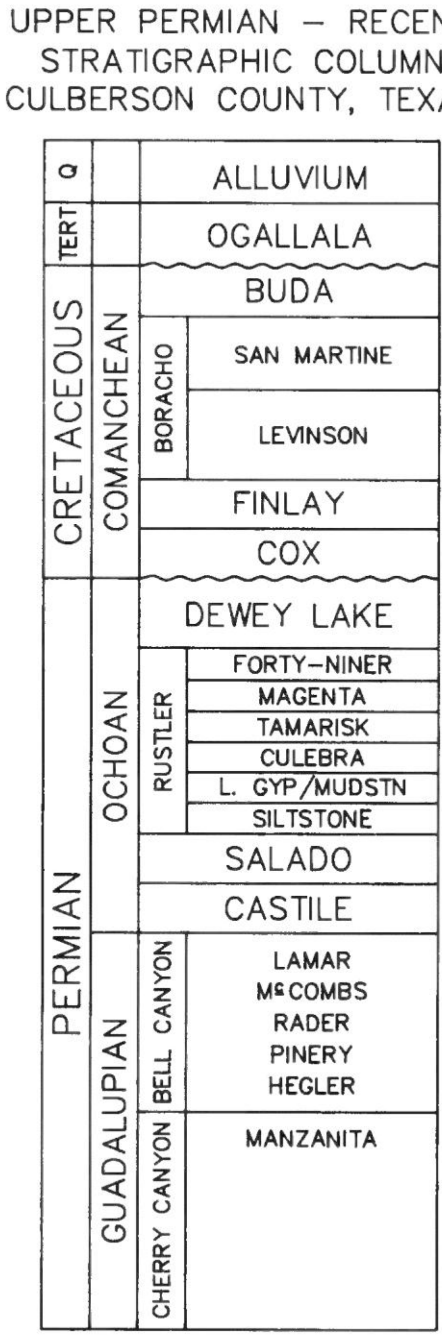

FIGURE 2. Stratigraphic column of Upper Permian and younger formations, Culberson County, Texas.

Smith (1978) first described the general geology of the Culberson deposit as part of an interpretive study that detailed the stratigraphic and structural features relating to sulfur deposits of the western Delaware basin. Most importantly, he noted that faults were associated with the larger deposits in the district and were likely pathways for hydrocarbons to come in contact with evaporites. A barrier to contain sulfur-forming reaction products, such as a clay layer or faults that die out upward, was also noted as a requisite to forming native sulfur. Smith viewed the Bell Canyon Formation as the source bed supplying hydrocarbons necessary for bioepigenesis.

The first generalized genetic model for all Delaware basin stratabound sulfur deposits was presented by Ruckmick et al. (1979), who suggested that hydrocarbons from petroliferous sandstones (Bell Canyon) underlying Ochoan evaporites came in contact with the evaporites by means of faults that acted both as leaky traps and as conduits for vertical hydrocarbon migration. Artesian meteoric water flow, also from below the evaporite sequence, was considered the agent responsible for providing the anaerobic sulfate-reducing bacteria, driving the hydrocarbons and dissociating calcium sulfate minerals. Once formed, the deposits were protected below an impermeable layer.

Hentz and Henry (1989) estimated that sporadic sulfur mineralization in Trans-Pecos Permian evaporites was initiated in the middle Miocene along northeast-trending faults and grabens in response to late Basin and Range northwest-oriented extension. Like Smith (1978) and Ruckmick et al. (1979), they too concluded that faults were essential in providing migration pathways necessary for reactants. They also viewed these faults, at least in conjunction with Castile Formation sulfur deposits, as traps at higher structural levels in the evaporite sequence where migrating formation waters hydrated anhydrite to gypsum, thereby effectively sealing the system.

General information on the Culberson ore body geology and a description of mining methods was summarized by Crawford (1990). Wallace and Crawford (1992) discussed the relationships between the structural, lithologic and stratigraphic features of the Culberson ore body mainly in the context of how mineralization may have been influenced by karst features.

Other mineral resource surveys relevant to Delaware basin native sulfur deposits were contributed by Bishop and Dixon (1968), Zimmerman and Thomas (1969), Hinds and Cunningham (1970), Ellison (1971) and Hentz et al. (1989).

GEOLOGIC SETTING

The Delaware basin is the westernmost structural subprovince of the Permian basin of west Texas and southeastern New Mexico. It is separated from the Midland basin subprovince by the Central Basin platform (Fig I). As the basin subsided during the late Paleozoic, it accumulated more than 24,000 ft of sediments and developed extensive fringing reefs on the basin margins and the Central Basin platform (Lang, 1937; Adams, 1944; Hills, 1942, 1984).

By the Late Permian, influx of seawater into the Delaware basin had become restricted, resulting in deposition of thick beds of evaporite minerals with minor carbonates and siliciclastics (Adams, 1944; King, 1947). These evaporites comprise the Castile, Salado and Rustler Formations (Fig. 2) and include more than 2000 ft of calcium sulfate in the vicinity of the Culberson deposit. Permian sedimentation ended with deposition of the Dewey Lake Formation red beds.

A major unconformity marks the boundary between Paleozoic and Mesozoic strata. Triassic Dockum Group red beds are found in other parts of the basin, but have not been recognized in the vicinity of the Culberson deposit. Here, Lower Cretaceous rocks (Fig. 2) directly overlie Permian strata and include a basal conglomerate overlain by marine carbonates and shales (Cox, Finlay, Boracho and Buda Formations).

Cenozoic deposits include local lake beds, terrace gravels and alluvial debris. Clasts derived from Permian and Cretaceous formations, as well as exotic metamorphic and igneous pebbles, are present in gravels, conglomerates and fine-grained alluvial materials, some of which have been tilted and displaced by dissolution of underlying evaporites.

In post-Permian time, the Delaware basin was slightly affected by the Laramide orogeny and by Basin and Range uplift and faulting. Laramide compressional forces resulted in uplift and eastward tilting of the basin (Hills, 1984). Basin and Range extensional tectonism resulted in normal faulting, observed in outcrop south and west of the Delaware basin and further uplifted the western part of the basin (Henry and Price, 1985). Within the interior of the basin, the effects of this tectonism are difficult to separate from older structures, and may be limited to reactivation of older structures. Most petroleum migration into stratigraphic traps within the upper Delaware Mountain Group sequence probably occurred during the Tertiary in response to uplift and eastward tilting of the western part of the Delaware basin (Grauten, 1965).

Evaporite dissolution and karst development probably was initiated shortly after or during deposition of the Permian strata and has signif-

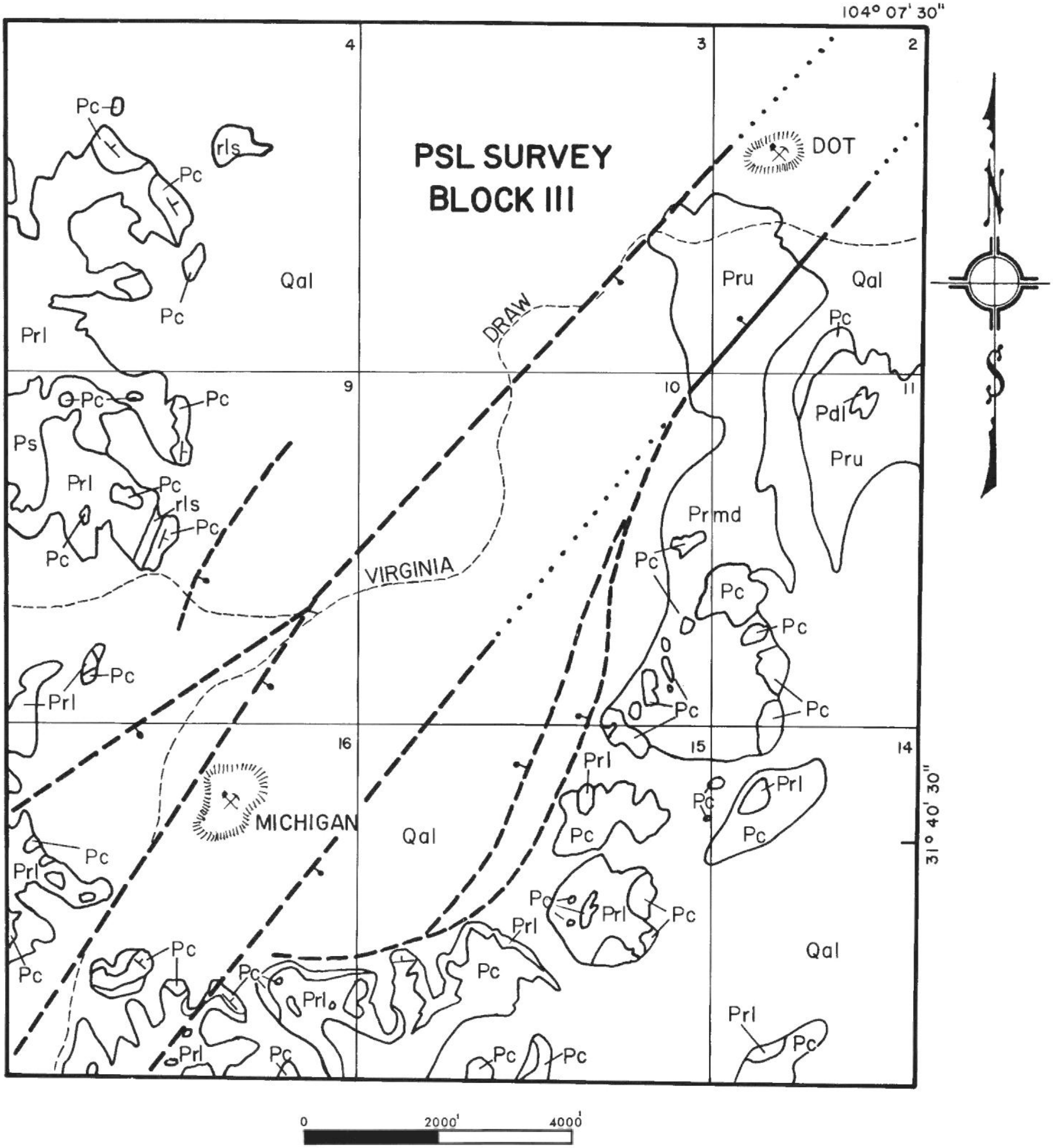

FIGURE 3. Generalized geologic map of the Culberson mine area. In ascending stratigraphic order: Ps = Salado Formation; Prl = siliciclastic and dolomitic facies, lower Rustler Formation; Prmd = mudstone and gypsum facies, lower Rustler Formation; Pc = Culebra Member, Rustler Formation; Pru = undifferentiated upper Rustler Formation composed of Tamarisk, Magenta and Forty-niner Members; Pdl = Dewey Lake Formation; Qal = undifferentiated alluvium; rls = biogenic limestone. Faults dashed where concealed, dotted where inferred.

icantly modified the evaporites and overlying rocks during several episodes (Adams, 1944; Bachman, 1984, 1987). Heterolithic breccia bodies within the Salado Formation containing fragments of Permian and younger formations suggest that extensive solution and collapse occurred during several lengthy episodes beginning as early as the Late Cretaceous (Crawford, 1990). Evidence for a Triassic-Jurassic period of extensive dissolution is difficult to establish. The presence of numerous sinkholes, solution-subsidence troughs (e.g., Olive, 1957) and other karst features (Horberg, 1949; Vine, 1963) indicate evaporite dissolution has remained active to the present. As stated by Borns (1987), "The presence of dissolution in the Delaware basin is not questioned, but the extent, timing and process of dissolution is a matter of debate."

DESCRIPTION OF THE DEPOSIT

Host rocks and local stratigraphy

Castile Formation

The Castile Formation is the oldest lithostratigraphic unit hosting sulfur mineralization and, where unaltered, consists mainly of anhydrite with thin, organic-rich calcite laminae. In the deposit area, as elsewhere in the district, the unit conformably overlies basinal elastics of the Guadalupian Delaware Mountain Group. This contact is fairly abrupt with underlying black calcareous shales of the Lamar Member of the Bell Canyon Formation. The Castile occurs only in the subsurface at Culberson and attains a local thickness of 1250 ft. Halite beds in the Castile may have extended as far west as the Culberson area, as indicated by zones of indurated breccia, but are missing due to dissolution (Anderson et al., 1978). The contact with the overlying Salado Formation appears to be transitional over a short vertical distance, with laminae becoming less distinct and less numerous upward. The general convention adopted by many workers is to pick the top of the Castile (in core) by first appearance of distinct brown calcite laminations, although Madsen and Raup (1988) maintained that anhydrite of the lowermost Salado in the western part of the Delaware basin may actually be Castile based on mineralogical and textural differences.

At Culberson, biogenic alteration of the Castile is expressed most commonly by vertical, chimney-like, sulfur-bearing replacement limestone bodies of limited lateral extent. Alteration and sulfur mineralization is locally continuous from the Castile level up into the Salado ore body.

Salado Formation

The Salado Formation overlies the Castile Formation and is, as far as presently known, the main sulfur host rock of the Culberson deposit. In other parts of the Delaware basin, the unit is up to 2450 ft thick and contains proportionately more bedded argillaceous halite with interbeds of anhydrite, polyhalite, fine-grained elastics and potash minerals (Schaller and Henderson, 1932; Vine, 1963; Adams, 1967). Although no halite beds are found in the immediate vicinity of the deposit, subsurface Salado halite outliers do exist 10 mi to the east. Salado halite beds probably existed in the Culberson area but were dissolved, leaving behind heterolithic, sulfate-dominant breccias and fine-grained elastics as insoluble residue. In the vicinity of the deposit, the subsurface unaltered unit has a thickness of 600 ft, consisting of gypsum, claystone, massive-to-brecciated aphanitic anhydrite and heterolithic breccias. Outcrops of Salado gypsum are locally exposed along the lower slopes of cuestas formed by the Rustler Formation immediately west of the deposit (Fig. 3). The lower third of the formation in the deposit area is generally massive, clay-free anhydrite with very faint zones of healed (diagenetic recrystallization) breccia. The upper part of the Salado, where brecciated, includes an interclastic matrix of gray to orange-red silty claystone. This interval characteristically contains scattered, millimeter-size euhedral pink quartz crystals. The claystone matrix associated with gypsum and anhydrite breccia increases upward in the unit, forming both matrix-supported and clast-supported breccias. In addition to occurring as breccia clasts, gypsum occurs as large (up to 1 cm) crystals in anhydrite, as reaction rims around anhydrite breccia clasts, and as displacive selenite veins in claystone and massive gypsum.

In the area of alteration and mineralization, the Salado is thinned to about 360 ft by extreme, but localized, solution-collapse of halite and sulfate beds. The Salado-level ore body lies mainly in the upper half of the Salado Formation. The contact of the mineralized zone with the surrounding, unaltered Salado is marked by a knife-edge zone of transition that contains a sporadic, centimeter-thick gray clay layer. The unaltered Salado is gypsum.

The contact of the Salado with the overlying Rustler Formation may be unconformable locally (Adams, 1944; Bachman, 1984). Accurate characterization of this contact is difficult in the deposit area because of a claystone unit that generally occurs as a single layer of highly variable thickness at the top of the Salado. The unit consists of blue-gray, pyritic, calcareous claystone with fragments of gypsum, replacement limestone and post-Salado formations. Minute, doubly terminated quartz crystals are common. Although analogous units occur locally in other parts of the basin (Adams, 1944), the extent to which this unit is developed at the Culberson deposit is unique. Vine (1963) noted a correlative layer in the northern part of the basin and suggested that it is a residual deposit resulting from dissolution of Salado halite by ground water. The residual claystone unit at Culberson attains thicknesses in excess of 100 ft and contains chert pebbles of much younger formations, suggesting that the unit had a connection with the surface.

In the western part of the Delaware basin, the Salado commonly contains post-depositional breccias. The breccias fall into three heterolithic assemblages designated here as Type 1, Type 2 and Type 3 (Fig. 4; Table 1). Type 1 is abundant, regionally widespread and contains only fragments derived from the Permian Rustler, Dewey Lake and Salado Formations. Type 2 includes fragments of Cretaceous Cox and Boracho(?) Formations, as well as older formations. Types I and 2 are usually in close spatial association and occur within similar-textured gypsum/anhydrite breccias. Type 3 is the least abundant and is, in part, conglomeratic. It includes igneous pebbles and older, locally derived and exotic fragmented lithologies. Type 3 breccias are exposed 3 mi north of Culberson in sec. 13 Block 113 PSL. All three types of post-depositional heterolithic breccias are major rock types within the Culberson deposit.

Rustler Formation

The Permian Rustler Formation is the youngest unit hosting sulfur mineralization. The contact between the Rustler and Salado generally is abrupt, although structurally irregular and is marked by the base of the lower Rustler siltstone and dolomite sequence. There is also a marked absence of sulfate minerals in the lower Rustler. In some areas, the contact is less distinct, apparently due to collapse of Rustler material into the upper part of the Salado Formation.

The Rustler Formation is typically about 500 ft thick and consists of six members (Eager, 1983), all of which are preserved in the subsurface

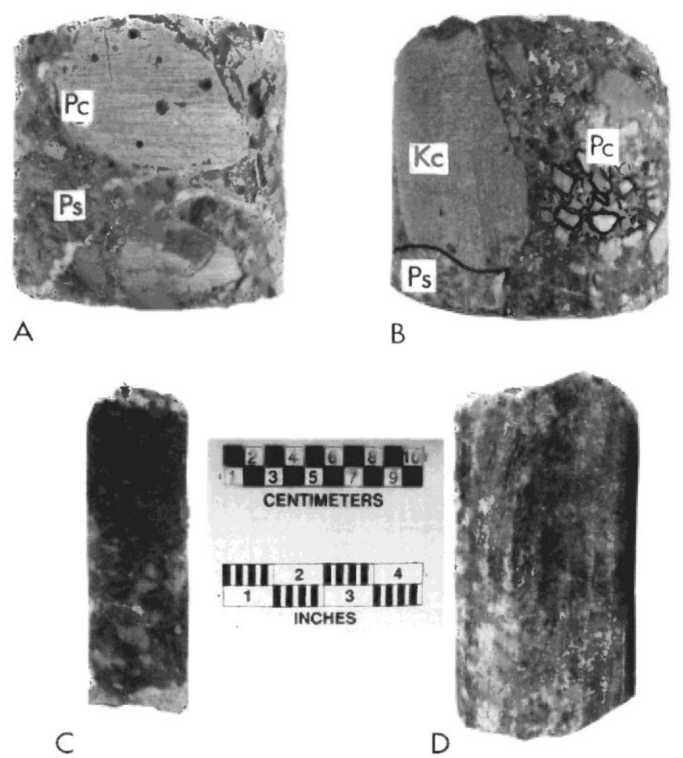

FIGURE 4. Subsurface heterolithic breccia assemblages within the Salado Formation. A, Type 1 breccia with clasts of Culebra Member (Pc) and Salado gypsum (Ps); B, Type 2 breccia with clasts of Cox Formation (Kc), Culebra Member (Pc) and Salado gypsum (Ps); C, Type 3 breccia with subangular clasts of Rustler Formation lithologies, shell fragments, volcanic pebbles and chert pebbles in clay matrix; D, massive gypsum, Salado Formation.

TABLE 1. Summary table of breccia characteristics and probable formational provenance of clasts. Abbreviations: an = anhydrite; gy = gypsum; do = dolomite; st = siltstone; ss = sandstone; cong = conglomerate.

	TYPE 1	TYPE 2	TYPE 3
Lithologies	an gy do st, red/gray	an ss gy cong do st, red/gray	an metaquartzite pebbles gy shell fragments do igneous pebbles ss chert pebbles cong st, red/gray
Texture/ Structure	rubble breccia, mosaic breccia	rubble breccia, mosaic breccia	rubble breccia-conglomerate; local graded bedding
Depth Strat. Occurrence	Salado Fm.	Salado Fm.	Castile Fm.
Mode of Occurrence	Blanket-like and irregular bodies, variable thickness; regional	Blanket-like and irregular bodies, variable thickness; regional	Vertical pipes or fissure fillings; crosscut older features
Formations Represented	Dewey Lake Rustler Salado	Boracho (?) Cox Dewey Lake Rustler Salado	Ogallala Boracho (?) Cox Dewey Lake Rustler Salado Castile

at the Culberson deposit. Because the Rustler Formation is severely eroded, brecciated and commonly altered in the mine area, it is useful to informally divide the Rustler into the upper Rustler, the Culebra Dolomite Member and the lower Rustler.

The upper Rustler consists of the Forty-niner, Magenta and Tamarisk Members, that conform to descriptions by Vine (1963). These members contain abundant anhydrite or gypsum with subordinate laminated dolomite and dolomitic clastics. Individual members can be distinguished locally, but commonly are truncated or brecciated and, therefore, cannot be mapped throughout the deposit area.

The Culebra Dolomite Member is typically 30 to 50 ft thick and consists of hard, brown micritic to silty dolomite. The dolomite is commonly fractured and is an aquifer used locally as a source of low-quality water. Characteristic spherical vugs up to 2 cm are common. The unit contains silty, sandy and oolitic facies.

The lower Rustler consists of an upper gypsum and mudstone unit and an underlying unit composed of varied lithologies (Eager, 1983). At Culberson, these units are mappable. The lowermost unit is typically 100 to 150 ft thick and is composed of calcareous to dolomitic siltstone, limestone and fine-grained carbonate-cemented sandstone. Claystone and other fine-grained clastics are common near the upper and basal contacts. A bed of anhydrite or gypsum occurs near the upper contact in many areas.

Dewey Lake Formation

Red beds of the Dewey Lake Formation are the uppermost Permian strata in the basin. They are commonly a distinctive dark orange-red but locally are reduced to pink-gray and gray-green where overlying alteration zones. The Dewey Lake consists of siltstone and fine-grained ferruginous sandstone. Micas and dark opaque minerals locally constitute about 5% of the rock. Gray-green reduction spots are characteristic of this unit. Gypsum and calcite veinlets occur more commonly toward the base of the formation. The contact between the upper Rustler sulfates and the overlying Dewey Lake red beds is distinct and easily identified in core and on geophysical logs. Surface exposures generally are poor because of the friable nature of the unit. Dewey Lake strata locally occur as beds dipping at high angles into depressions formed by collapse of underlying material. On the eastern margin of the deposit the Dewey Lake attains thicknesses up to 100 ft where preserved in down-faulted blocks.

Cox Formation

The Cretaceous Cox Formation overlies and truncates the Permian rocks, with clasts of Dewey Lake incorporated in basal conglomeratic zones. The unit consists of brown to white coarse-grained quartz sandstone containing conglomeratic zones. The conglomerates are mostly calcite-cemented but are commonly silica-cemented in outcrop. Conglomerates are composed of varicolored chert and metaquartzite pebbles, sandstone clasts and rare dark-gray oncolite limestone pebbles. Black shale and petrified wood are found within this unit locally. Near the Culberson deposit scattered Cox remnants are preserved, but the outcrops are too small to be shown at the scale of the geologic map. Breccia clasts of Cox are also preserved within the Salado Formation in the subsurface within the deposit. Outside the immediate vicinity of the deposit to the south, younger Cretaceous formations including Finlay, Boracho and Buda, are found in collapse features.

Surficial deposits

In the Culberson vicinity, older surficial deposits form a veneer mantling the higher elevations around the deposit and in depressions within the Rustler Hills to the west. These gravel deposits are composed of varicolored chert, metaquartzite, fossiliferous carbonate, fine-grained sandstone and lithologies derived from the Cox, Rustler and Castile Formations.

Younger gravels are preserved in the subsurface alluvial sequence conforming with the drainage of Virginia Draw, which transects the Culberson deposit. These are composed of gypsite, clays and pebbles of gypsum, limestone, dolomite and varicolored quartz cemented in a vadose carbonate matrix (calcite). Recent deposits include dolomite gravels and sands as outwash from the nearby Rustler Hills. Reworked Cox pebbles are scattered near outcrops in low-lying areas and are developed on soils derived from the Cox or older Permian rocks.

These lithologic units may correlate with some of the Pleistocene deposits of the Carlsbad area described by Horberg (1949). However, precise correlation of geomorphic surfaces and related deposits in the Delaware basin has not progressed to the point of projecting, with certainty, the stratigraphic nomenclature in use in New Mexico into this region.

Mineralized surficial deposits containing surface encrustations of sulfur, iron sulfates and selenite crystals occur in the abandoned Michigan mine area, located in sec. 16 Block I l I PSL and rarely in the Dot claim, sec. 3 Block 111 PSL (Fig. 3).

Structural and karst features

The structure of the Rustler Springs district is characterized as a homocline dipping eastward at a rate of 100 to 250 ft/mile with local structural noses that have an approximate east-west strike (Dunlap, contract report, 1970; Grauten, 1965). This interpretation is based largely on subsurface drill-hole data that include information on the Lamar Member markerbed of the Delaware Mountain Group. Outcrops in the deposit vicinity are not regarded as reliable for characterization of structural features because of later disruption by karst features.

The Culberson deposit lies within the Rustler Hills graben (Fig. 5), a fault- and steep flexure-bounded feature enhanced by extensive dissolution of sulfate- and halite-bearing strata. Offsets projected in Rustler and younger strata appear to die out with depth, being accommodated by extreme solution-thinning of the Salado and possibly of the Castile sequence. Local structural definition by close-spaced drilling indicates deeper crustal faults that trend N39°E and project through the deposit and mine vicinity, offsetting and fracturing the Delaware Mountain Group (Fig. 6). These normal faults propagate upward into the Ochoan sequence where they become difficult to trace into the brecciated overlying units. These structures are similar in aspect to northeast-trending faults noted by King (1949) within Guadalupian clastics farther west. Bentz and Henry (1989) related these faults to a northwest-directed Basin and Range extensional phase initiated during the middle Miocene. Structural definition by drilling and thickness projections from the top of the Castile indicate that these faults are of moderate displacement (50-100 ft) (Fig. 5) and have indicated relative net movement largely

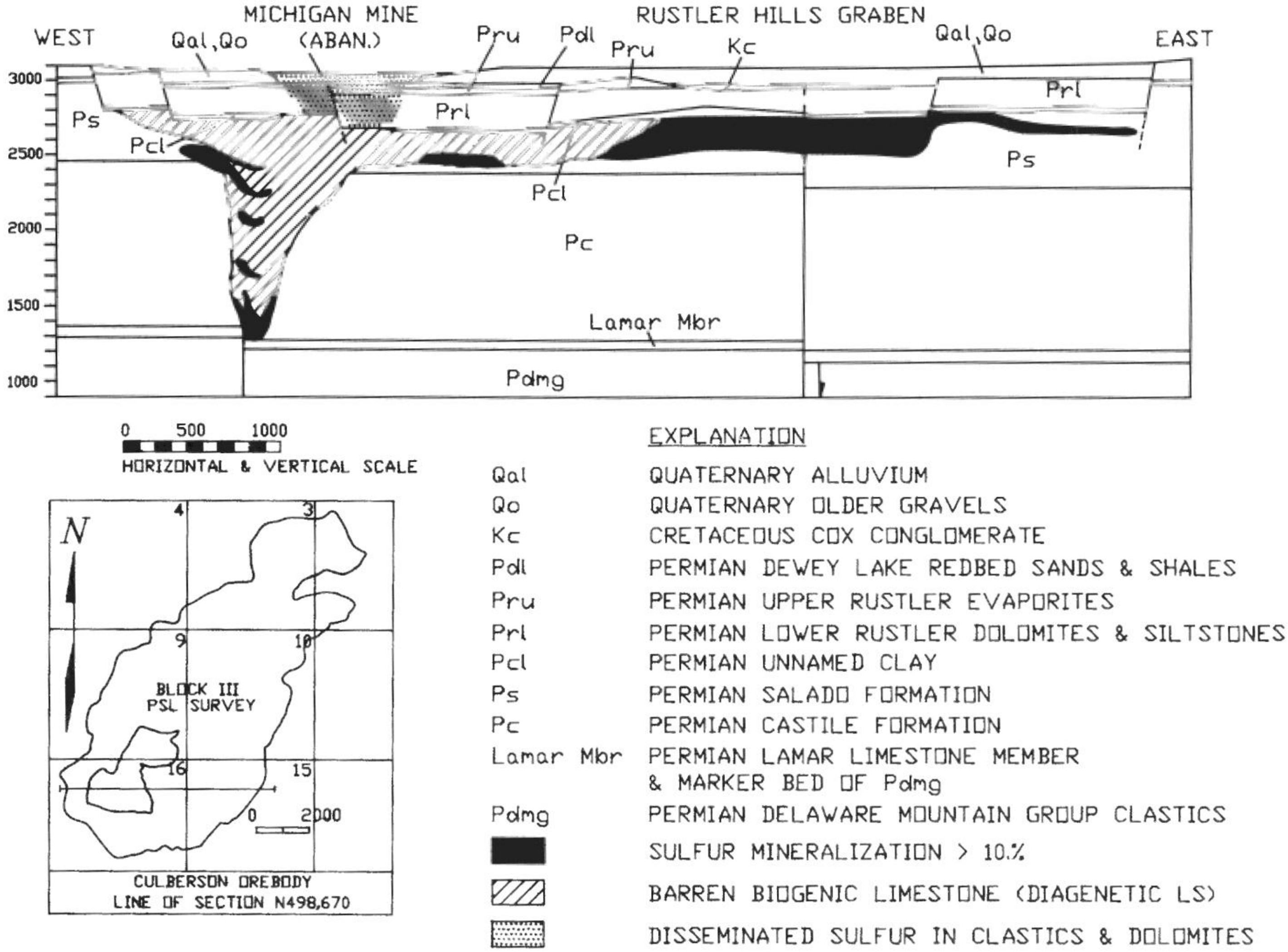

FIGURE 5. West-to-east generalized cross section of the Culberson deposit showing alteration root zone, high-grade sulfur mineralization and faults. Note location of Michigan mine over zone without claystone layer at base of the Rustler Formation.

FIGURE 6. Lamar Member of Bell Canyon Formation (Delaware Mountain Group) taken from the Culberson area. Core on left is fault breccia with coarse-crystalline calcite. Core on right is typical Lamar dark calcareous shale. Top of right core shows Lamar-Castile contact.

down to the east or southeast. The apparent attitude of dip along the fault planes is vertical. Apparent reversals of vertical offset along fault strike have been noted at Culberson (Crawford, 1990; Wallace and Crawford, 1992), which suggests a wrench-faulting or reverse faulting component. Cores from the Castile Formation contain horizontally slickensided surfaces, but this may result from local dissolution and block-rotational effects rather than wrench tectonics.

The trace of the eastern deposit-boundary fault (Fig. 3) has been mapped at the surface in sections 2 and 11 Block 1 1 1 PSL, in which the upper Rustler sequence has been downfaulted against the lower Rustler sequence. In this locality, relative indicated normal fault movement is down to the northwest into the geomorphic depression of the ore body. It is not clear if this fault is related to tectonic activity or is related to solution-thinning of the Salado.

In comparison, Guilinger and Nestlerode (1992, p. 128) have interpreted from very close-spaced drilling at the nearby Phillips Ranch deposit a clearly defined, narrow normal fault-bounded graben that trends N66°E. They also identified north- to northwest-trending vertical fault cross-structures with indicated offsets in the Lamar Member of up to 90 ft. These cross-structures are indicated to have relative movement down to the east and northeast. The graben boundary faults, which apparently control mineralization at Phillips Ranch, are generally subparallel to the deep crustal faults at Culberson, but they differ in strike azimuth by about 27°, possibly suggesting different timing of faulting or slightly different fault kinematics.

The magnitude of structural relief related to karst dissolution effects is shown by the thickness of alluvium over the deposit (Fig. 7) and by the extreme thinning of the Salado (Fig. 8). The thinning is due to depression of the top of the formation rather than by deposition of the Salado sequence around a structural feature (Fig. 9).

The structure and facies of breccias developed within the Rustler and Salado Formations (Fig. 10) are comparable to solution-triggered collapse breccias described by Laznicka (1988, p. 407) for the Prairie evaporites in the Devonian Elk Point Basin, Manitoba. Consequently, similar features such as breccia chimneys, stratiform heterolithic breccias and post-collapse, crosscutting breccia pipes are exhibited that are related to void-filling processes. Fig. 11 shows the thickness and distribution of Type **I** and Type 2 heterolithic karst breccias within the Salado. An outcrop of a breccia pipe analogous to those projected within the deposit is exposed along the edge of mineralization in the western part of sec. 16 Block 11l PSL. This exposure is in the highwall of a drill site.

Mineralization and alteration

Sulfur mineralization and associated alteration occur in the Rustler, Salado and Castile Formations (Fig. 12). The higher-grade mineralization lies generally between 350 and 600 ft below the mine surface and has an average grade of 25 weight percent sulfur. The upper limit ore grade, encountered in enriched zones, is about 50 weight percent. Leaching and remobilization of sulfur at Culberson account for barren and lower-grade zones (Fig. 5) and alteration textures in barren areas where orthorhombic casts after sulfur occur within drusy calcite.

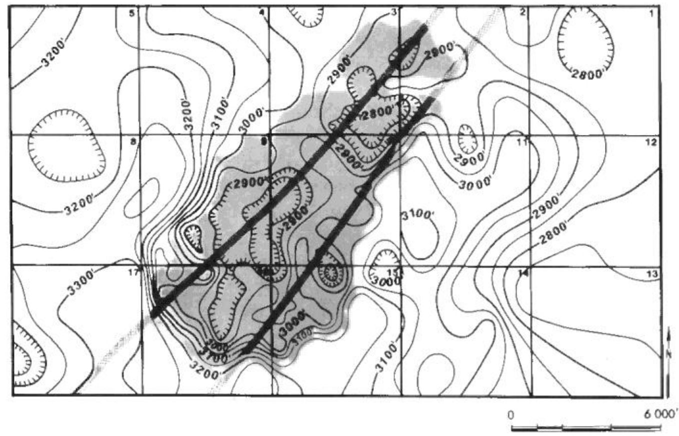

FIGURE 9. Structure of top of Salado Formation. Northeast-trending lines are major faults. Contour interval = 50 ft.

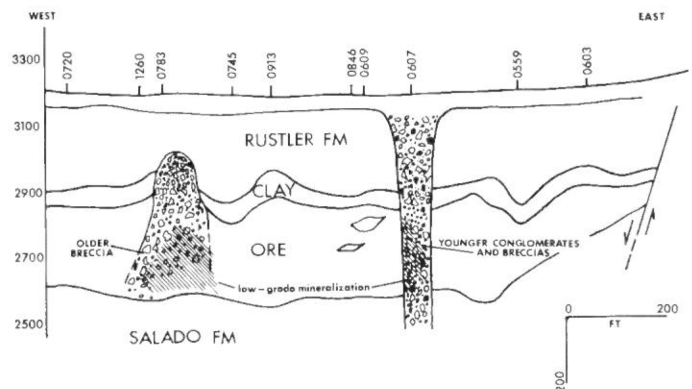

FIGURE 10. Cross section of deposit showing lithologic and structural relations among ore zone, claystone layer, and heterolithic breccia bodies. Note younger breccia/conglomerate feature penetrates through base of mineralization.

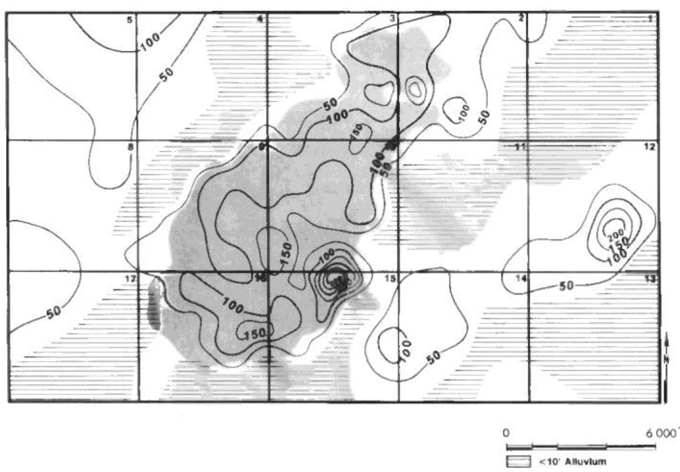

FIGURE 7. Isopach map of undifferentiated alluvium. Shading shows area of orebody. Contour interval = 50 ft.

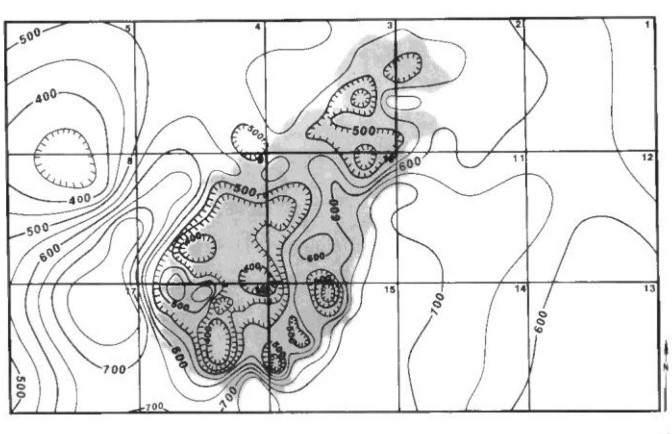

FIGURE 8. Isopach map of Salado Formation. Contour interval = 50 ft.

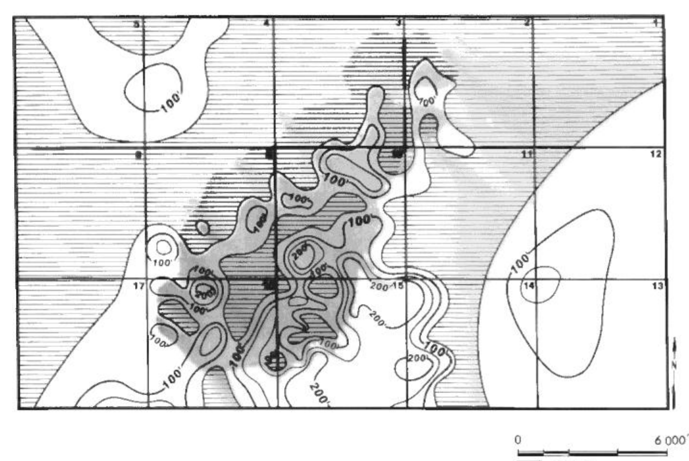

FIGURE 11. Isopach map of heterolithic breccias within Salado Formation. Contour interval = 50 ft.

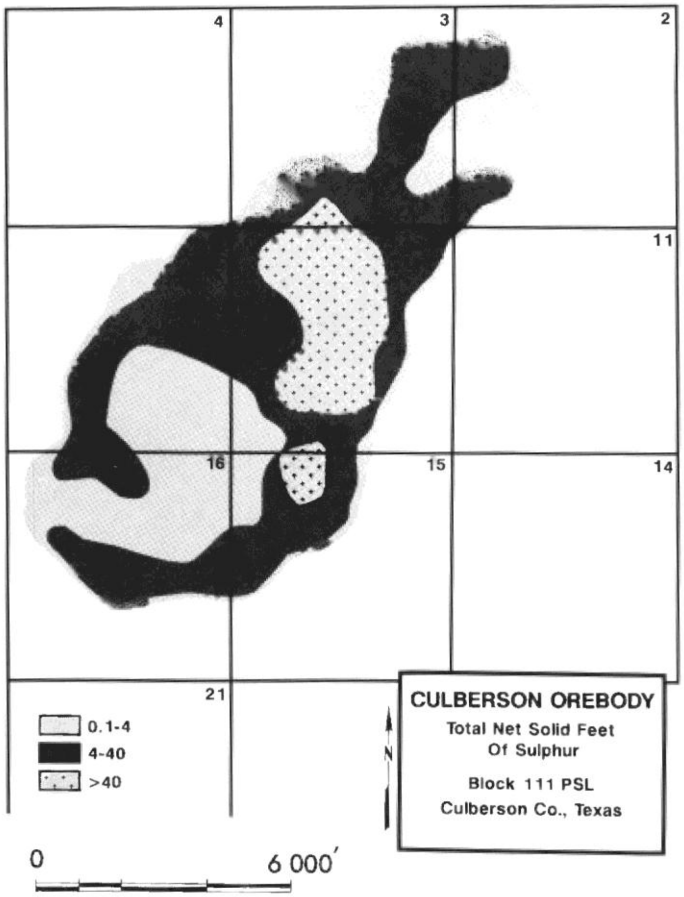

FIGURE 12. Areal distribution and grade-thickness zones of sulfur mineralization in the Salado-level orebody.

FIGURE 13. Salado ore showing preservation of original sulfate breccia texture by porosity development. Porous, tightly laminated patches are biogenically replaced individual clasts. Dark streak is clay fracture filling.

Native sulfur mineralization occurs in two general modes within the Salado altered zone. Where not affected by the mining process, the sulfur occurs as (1) microcrystalline disseminations in gray micritic replacement limestone or karst breccias containing replacement limestone matrix, and (2) open-space filling texture in which delicate orthorhombic crystals or encrustations line vugs developed within the replacement limestone. These two modes of occurrence generally are found together. Sulfur also occurs in a powdery, pale yellow cryptocrystalline form in more oxidized parts of the deposit and in the surficial deposits of the Michigan mine (Fig. 5). Sulfur mineralization textures associated with the Rustler and Castile Formations are similar to those for the Salado and will not be discussed here.

The alteration limestone in which the sulfur mainly occurs is a replacement of gypsum/anhydrite solution-collapse breccias. Original breccia textures are locally preserved in the limestone in the form of fenestral porosity or boxworks that outline ghost clasts (Fig. 13). The manifestation of rock fabric/depositional texture by porosity development may be due to the volume change induced by the gypsum-to-limestone alteration (Pawlowski et al., 1979). Further evidence for sulfate replacement is shown by nonreactive breccia clasts that appear to float (matrix-supported breccia) in replacement limestone matrix (Fig. 14). The porosity displays a penetrative fabric with respect to nonreactive clasts, clearly showing that the clasts were in place prior to alteration. Porosity of the Salado zone averages 15% but is locally as high as 40%. Insoluble residue in the limestone is composed of detrital and authigenic quartz, clays and iron sulfides.

Epigenetic alteration minerals associated with sulfur mineralization at Culberson are calcite, aragonite, barite, celestite, pyrite/marcasite and fluorite. This mineral assemblage is identical to that described by Goldman (1952) in biogenic caprock at Sulphur salt dome, Louisiana. Hauerite, a manganese sulfide, was identified by Thomsen (1992) in dry stream sediments near Culberson, suggesting that its occurrence is related to sulfur-forming processes. This mineral has not been identified within the Culberson deposit, although it may exist in small amounts. Occurrences of this mineral have been documented in association with bioepigenetic sulfur deposits in many other localities (Thomsen, 1992; Samuelson, 1992).

The arrangement of minerals in core samples indicates that replacement of sulfates by carbonates was an early stage of alteration accompanied by generation of hydrogen sulfide and possibly polysulfides (Davis and Kirkland, 1970, p. 115). These compounds were then oxidized to precipitate native sulfur. The microcrystalline disseminated sulfur (crystalline masses less than 0.1 m) in the alteration replacement limestone appears to have been first deposited contemporaneous with, or shortly after, crystallization of the replacement carbonate.

Later-stage crystalline sulfur occurs as open-space vug linings mainly in association with calcite. Crystalline sulfur also occurs as intergrowths and as paper-thin interlaminations with calcite, suggesting coprecipitation. Native sulfur isotope values for Culberson (Hill, personal comm. 1988; Hill, 1992) fall within the range of biologically fractionated sulfur (Thode et al., 1954; Feely and Kulp, 1957; Davis and Kirkland, 1970).

Calcite occurs as crystalline druse linings in the vuggy replacement limestone and also as veinlets in limestone and fractured breccia lithologies. Calcite and aragonite also form late, drusy overgrowths on sulfur. Calcite and aragonite carbon isotopes (8'3C) from within the deposit range from —21% to —49%, based on nine samples (Pennzoil, unpubl. data; Hill, personal comm. 1988). Carbon-isotope compositions of oil extracted from Castile Formation replacement limestone cores show 8"C values of —26.7% and —27.7% in saturated (paraffinic) and

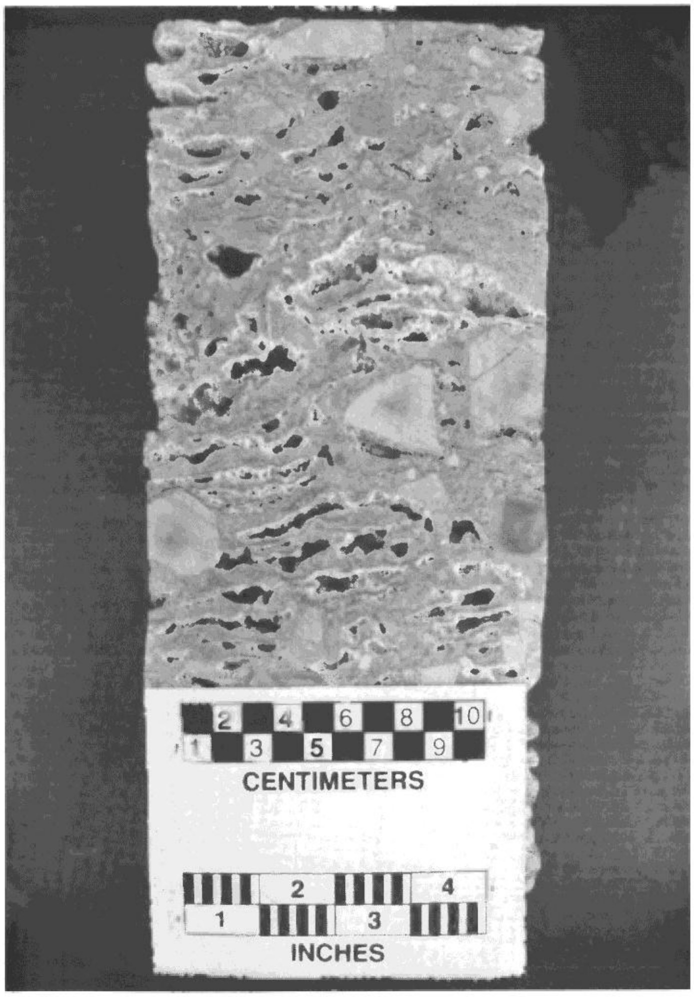

FIGURE 14. Salado ore showing porosity development in breccia-type ore. Rustler Formation clasts were emplaced prior to alteration. White lining in vugs is calcite with sulfur.

aromatic fractions (Talukdar, contract report, 1991). These isotopic ranges are compatible with data presented by Feely and Kulp (1957) for bioepigenetic carbonates in Gulf Coast salt dome sulfur deposits.

Barite and celestite commonly form radiating masses on a drusy calcite substrate, but also occur as complex intergrowths with calcite in core intercepts up to 5 ft thick. Replacement of calcite by barite is locally evident. This type of occurrence is porous and brittle and contains sulfur as irregular crystalline to colloform masses. Celestite appears to form later than most of the sulfur, as it commonly occurs as acicular individual crystals or radiating masses on both sulfur and calcite. The occurrence of barite and celestite is pervasive throughout the Castile and Salado zones at Culberson and rarely has been documented in fractures within overlying formations. In contrast, Davis and Kirkland (1970) noted that celestite was only associated with sulfur in the nearby Pokorny deposit.

Formation water analyses from the Salado altered zone have Sr concentrations ranging from 40.2 ppm to 45.4 ppm, whereas Ba concentrations are in trace amounts (<1 ppm). This suggests that celestite precipitation may be an ongoing process within the deposit, as is further indicated by strontianite scale inside mine high-temperature water-well pipelines. In this context, formation waters carrying barium and strontium will precipitate celestite and barite when introduced into an environment containing abundant aqueous sulfate.

The source of strontium may be migrating, chloride-rich oil-field-type connate waters or from release in small amounts from the host sulfates during aqueous dissociation and alteration of the sulfate to carbonate. Equilibrium studies by Saunders et al. (1988) suggest that precipitation of celestite is favored over strontianite by low-temperature solutions enriched in sulfate and strontium.

The source of Ba is probably from migrating oil-field-type connate brines and may have been transported as aqueous chloride complexes. Sulfur $\delta^{34}S$ isotope values up to $73^0/_{00}$ have been recorded for barite at Culberson (Kyle, personal comm. 1983), with celestite having a value of 48%0 (Hill, personal comm. 1988). Kyle (1990, p. 174) suggested that "a viable mechanism for the production of heavy sulfate is the complementary enrichment of ^{34}S in residual aqueous sulfate as a result of selective fractionation of 8^{34}5 during bacterial reduction of sulfate as a precursor to formation of the isotopically light elemental sulfur concentrations." Alternatively, a series of complex reactions involving thiosulfate in the precipitation of ^{34}5-rich barite is strongly suggested by the extreme isotopic fractionation of sulfur in barite at Culberson (Spirakis, 1991). Barite is volumetrically far more abundant in the Culberson deposit than celestite. We estimate the total barite content of the Culberson deposit to be between 3 and 5 million metric tons.

Pyrite is disseminated throughout the lower Rustler elastics as isolated euhedral cubes (commonly 1 mm or less) and framboids. Pyrite rarely occurs in the alteration limestone. Pyrite/marcasite is locally found within the uppermost Salado claystone bed as halos of disseminated crystals around biogenic limestone breccia clasts. This suggests that much of the iron-sulfide in the claystone as well as in the overlying Rustler elastics is derived from bacteriogenic hydrogen sulfide. Isotopic studies may verify this relationship.

Fluorite mineralization is rare. The mineral occurs as dark-purple, sub-millimeter size crystals usually within calcite veinlets. Direct contact of this mineral with sulfur has not been observed, but it does occur in all recorded instances within a few centimeters of sulfur, barite or celestite at the top of the altered zone and in the upper Salado claystone. Madsen (1984) reported rare fluorite in the Castile evaporite sequence. To our knowledge, fluorite has not been found elsewhere within the Salado Formation (Schaller and Henderson, 1932).

Hydration of anhydrite to secondary gypsum as part of the mineralization sequence is not clearly established at Culberson because this process is regionally pervasive, mainly occurring in the zone of weathering and along deep fractures. However, where the deposit contacts have been observed in core the host sulfates are invariably gypsum with abundant displacive selenite veins. This gypsum zone grades downward into anhydrite or anhydritic lithologies. The depth of the gypsum/anhydrite transition is difficult to estimate below the deposit and in surrounding areas because many borehole logs do not distinguish between gypsum and anhydrite and production wells are seldom completed more than 3 ft below the base of the ore as a cost consideration.

The siliceous alteration noted at some other deposits (Klemmick, 1992) has not been observed at the Culberson deposit. Nodular chert beds within the Culebra Member of the Rustler Formation are interpreted to be diagenetic and not related to sulfur forming processes.

Epigenetic alteration and sulfur mineralization in the Culberson deposit show a paragenetic sequence only in a general sense. That is, sulfur was deposited in an early stage with replacement alteration limestone and then in later stages in close temporal association with other epigenetic minerals as open-space fillings. It is quite possible that sulfur deposition occurred as a continuum and that the other epigenetic minerals precipitated as reaction kinetics and Eh-pH conditions allowed. The paragenesis proposed by Crawford (1990, p. 154) recognized a generalized sequence of mineral deposition that accommodated various observed complex mineral textures by overlapping temporal relationships. The potential for more than one protracted pulse of mineralization is recognized, but is not supported by the presented data.

DISCUSSION

Timing of faulting and mineralization

Karst breccia features at Culberson and elsewhere in the Delaware basin (Vine, 1963; Bachman, 1987) provide a unique opportunity to consider the regional distribution of lithologic units preserved in them for which few surface remnants exist. We may also infer the timing of their emplacement into karstic voids by identifying the lithostratigraphically youngest breccia or conglomeratic components. As such, cross-cutting relationships between deep karst fragmentites and sulfur mineralization can provide a relative timing of mineralization if the age of emplacement of infilling materials can be constrained. Timing and kinematics of fault development are evidently closely linked with the formation of some of these breccias.

Textures observed in cores show that alteration and mineralization generally post-date the emplacement of karst-infilling detrital material composed of Rustler and younger lithostratigraphic units. Based on observed breccia and conglomeratic clast assemblages, at least two major periods of intense karst development are recognized.

Late Cretaceous—early Tertiary

Breccia bodies containing Rustler, Dewey Lake and Cretaceous lithologies (Fig. 4A, B) probably developed in the Late Cretaceous or early Tertiary in response to Laramide regional uplift and tilting of the basin (Hills, 1984; Horak, 1985). These breccias have not been found below the base of the Salado, suggesting that they resulted from partial dissolution of halite and sulfate beds within this formation by infiltrating meteoric ground water. A general lowering or fluctuating of the water table, resulting from regional uplift, induced collapse of overlying strata into integrated sulfate cave systems. The breccia clasts were subsequently distributed by ground-water flow in the cave systems. Recent analogies to such cave development and water flows have been described for the Gypsum Plain by Olive (1957) and Sares and Wells (1987). This mechanism is invoked to explain highly indurated breccias composed of fragments of Permian and Lower Cretaceous units locally occurring below complete Upper Permian sequences, a feature observed in exploration cores throughout the district. Smith (1978) described dolomite beds within the Salado Formation. However, the fragmental aspect of dolomites in the Salado, their resemblance to Rustler lithologies and the fact that hole-to-hole correlation is nearly impossible suggest that dolomite beds were not deposited in the Trans-Pecos Salado sequence and that dolomite fragments occurring within it are from younger formations. We believe heterolithic breccias within the Salado represent detrital infilling of an integrated paleocavern system (Fig. II). The breccia clast assemblages indicate that these were probably emplaced during Late Cretaceous or early Tertiary time.

An earlier phase of karst development may have taken place during Triassic time (Bachman, 1984) and is suggested locally by Salado-level breccias containing only Permian breccia clasts. However, where observed within the Salado in association with brecciated gypsum, the dolomitic components (Rustler) are themselves highly indurated clast-supported breccias (Fig. 15). These clasts may represent dissolution of upper Rustler evaporites, possibly during the Triassic-Jurassic, which were not emplaced within the Salado until a later period such as Late Cretaceous. It is also possible that these clasts record diastems occurring within the Rustler during its deposition.

The possibility of a Triassic assemblage is suggested by the absence of all clasts identified as younger than the latest Permian. However, petrologic evidence suggests that these earlier(?) breccias (Type I) and Late Cretaceous breccias may actually be time-equivalent breccia facies (Laznicka, 1988, p. 406), emphasizing intense dissolution and breccia development in the Late Cretaceous or early Tertiary. Stratiform breccias composed of Permian carbonates, clastics and sulfates show similar clast size-ranges (up to 30 cm), as do similar breccias that contain fragments of Cox sandstones and conglomerates. These breccias also show the same degree of induration with respect to anhydrite, with crosscutting relationships generally lacking. Both assemblages also have generally small amounts of fine clastic materials as matrix. If these breccias represent the same dissolution episode, the relative paucity of Cox detritus can be explained by (1) the proportional thickness of Permian Rustler Formation to Cretaceous rocks exposed in the district being on the order of 6:1, with the Cox being the only identifiable residual component preserved from the basal Cretaceous in the Culberson vicinity, and (2), the Cox Formation as a siliceous unit is more resistant to chemical erosion than younger Cretaceous carbonates and may have been left as volumetrically smaller erosional remnants on

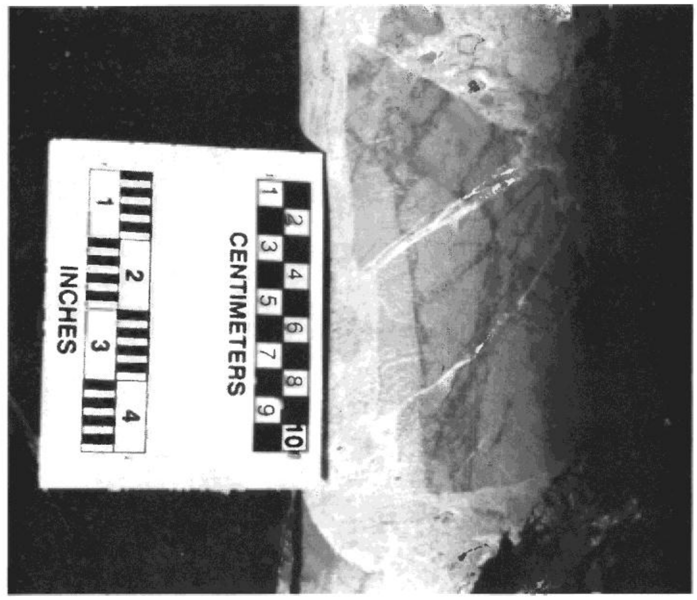

FIGURE 15. Salado breccia-type ore with fragments of Rustler Formation mosaic breccia. Rock fabric indicates multiple phases of brecciation. Veins along low-angle offsets are calcite.

Permian units that eventually foundered into karstic voids along with the older Permian units. The relative rarity of Cox fragments may be partially a function of borehole sampling.

Bachman (1987) described Triassic beds of the Dockum Group in collapse features located along the northern edge of the Delaware basin, Eddy County, New Mexico. Here, the Triassic is in contact with the Permian and incorporates clasts of Permian Dewey Lake in the basal strata. The relationship suggests that the timing of solution and collapse of materials into such features was evidently later than Triassic. Although continental Triassic strata cover large portions of west Texas and southeastern New Mexico, the difficulty in distinguishing uppermost Permian red beds from Triassic red beds suggests that erosion and karst were subdued geologic processes in this region during the Triassic (Sellards et al., 1932) and that the older breccia assemblage developed at Culberson and elsewhere in the district was probably developed during the more tectonically active Late Cretaceous and early Tertiary (Windley, 1977, p. 265).

We propose an alternate explanation for the observed textures and relationships of the older breccia clast assemblage, which relies on Laznicka's (1988) model involving upward stoping and collapse of younger strata into dissolving evaporites in which no local connection with the surface is required. Observed breccia clast assemblages may simply reflect the vertical magnitude of stoping into successively higher strata during a given time period. As such, a period of dissolution occurring during the Triassic-Jurassic would not be evident: the period of stoping that reached up into the Cretaceous units clearly post-dates the Triassic-Jurassic. In this mechanism, flowing, undersaturated ground-water drainage systems would be required to dissolve evaporites in the subsurface and to transport breccia fragments that foundered into voids short lateral distances. Evidence for such a process operating on a regional scale is shown by the present magnitude of halite dissolution in the Castile Formation (Smith, 1978). Because these older breccias do not extend below the Salado, ground water flow and evaporite dissolution were probably restricted to the Salado Formation during the Late Cretaceous and early Tertiary.

The structural trend of development of these older breccias closely conforms with the strike of interpreted northeast-trending fault zones (Fig. 9), indicating that the breccias developed along fault-controlled solution channels. The timing of faulting indicated by the occurrence of these breccias is Late Cretaceous or older, which is earlier than the timing of Basin and Range northeast-trending faults proposed by Hentz and Henry (1989).

The timing and kinematics of the Culberson and Phillips Ranch (Guilinger and Nestlerode, 1992) fault systems may be related to similar regional tectonic events, but locally different stress regimes, during the Late Cretaceous. The trend of these faults conforms to wrench fault tectonic features described by Bolden (1984) as part of a northwest-trending series of left-lateral faults that lie north of and subparallel to the Texas lineament. The locations of the Culberson and Phillips Ranch deposits are within a 6-mi-wide northwest-trending disturbed zone that Bolden named the Pecos lineament. According to Bolden (1984) and others, repeated movement along these faults occurred between the Mississippian and Tertiary. The fault trends identified at Culberson are parallel to a right-lateral conjugate shear stress regime within the disturbed zone. The fault trends at Phillips Ranch are compatible with a related tensional regime. A regional wrench fault mechanism is a possible explanation for the differences in the fault kinematics apparent at Phillips Ranch and Culberson, with the timing of fault development in general agreement with relative timing of breccia development along faults at Culberson. However, as noted above, horizontally slickensided surfaces may not be reliable indications of tectonic activity. The high-angle dips and local reversals of offset along the strike of the faults at Culberson suggest reverse faulting that was caused by a compressional regime. We recognize the possible existence of numerous normal faults that, based on limited borehole information, might suggest offset reversal along a single fault. However, we believe that the faults originally formed in a compressional regime, as suggested by high angles of dip, that were later reactivated by extensional tectonism.

In support of reactivated fault movement, correlation of thicker zones of Type 2 breccias with a thickened Salado in the deposit suggests a later period of sulfate dissolution around these breccias bodies and subsequent draping of strata over them. This relationship at Culberson requires the formation of these older breccias along zones of weakness, such as faults, before Basin and Range tectonics. Later localized, intensive dissolution involving thinning of the Salado at Culberson may have been caused by undersaturated waters migrating along these older fault zones. These fault zones may have been reactivated by a late Basin and Range extensional phase. As the earlier period of karst development may have occurred on a regional scale controlled by prevailing climatic conditions, the large difference in the thickness of the Salado at Culberson compared to the surrounding area is difficult to explain in terms of a widespread and uniformly active dissolutional process. This suggests that an alternate mechanism, possibly operating during a later period, is required to explain this structural feature.

We propose that the thinning of the Salado Formation in the area of the deposit is primarily due to pre-mineralization evaporite dissolution and not bioepigenetic alteration processes. The process of hydration of anhydrite to gypsum produces a 60% increase in rock volume. Upon bioepigenesis, if gypsum is completely converted to replacement limestone there is a 28% reduction in volume (Pawlowski et al., 1979). This reduced volume is comparable to the replacement limestone porosities observed within the Culberson deposit.

Late Tertiary—Quaternary

Conglomerates and breccias found within and below the deposit crosscut the Late Cretaceous—early Tertiary breccias and are likewise interpreted from textural relations in cores to have been emplaced before mineralization. These rocks, mainly conglomerates, were apparently deposited concurrently with a second period of intense karst development occurring in middle to later Miocene time, during late phase Basin and Range extension, as proposed by Hentz and Henry (1989). These conglomerates are composed of varicolored chert, metaquartzite, altered intermediate volcanics (or shallow intrusives), carbonized wood fragments, fossiliferous carbonates, rounded petrified wood clasts and shell fragments. Because a few remnants of this conglomeratic unit are found as high-level surficial deposits or in collapse features within the region, we propose that this unit was deposited within, or was collapsed into late Cenozoic (middle Miocene or later Tertiary) karst features before the more recent, ongoing phase of regional uplift of the western part of the Delaware Basin (Horak, 1985; Borns, 1987).

According to Bretz and Horberg (1949), the Ogallala Formation was deposited in an ancestral Pecos River valley by streams carrying sediments to the south and southeast. The extent of gravelly remnants of Ogallala they mapped indicate that the formation extended as far south as the Texas state line (Yeso Hills) (see discussion by Hawley, this volume). Based on petrologic similarity of mine core samples with outcrops in southern New Mexico identified as Ogallala (Bretz and Horberg, 1949), and the fact that they are at a high level with respect to the current Pecos drainage, we believe that this unit extended at least as far south as Culberson and was deposited initially in the middle Miocene as a fluvial tributary or outwash plain deposit representing detritus from the Delaware-Guadalupe-Sacramento-Capitan highlands and the reworking of basal Cretaceous Cox conglomerates. Age determinations of Ogallala deposits are made in areas outside this study area; therefore we tentatively infer an age of middle to late Miocene for these deposits (Hawley, this volume, 1993). Miller (1992) described lithologies similar to this unit within subsurface paleokarst systems in the Culberson vicinity, but assigned them to the Cox Formation, perhaps based on the dominance of Cox-derived materials.

It is possible that this unit is Gatuňa Formation (late Tertiary), based on descriptions by Lang (1938) and Kelley (1980) and may therefore represent deposits in a paleotributary of the Pecos River. However, these deposits are somewhat far removed from the distribution of Gatuňa mapped by Kelley (1980) and Maley and Huffington (1953), are generally more indurated and have a different clast assemblage. The high-level gravels near Culberson may be Gatuňa or younger unclassified deposits of probable Pleistocene age.

It is possible that the volcanic fragments within the cores at Culberson are derived from the Davis Mountains volcanic complex. Volcanism in the Davis Mountains occurred from 35.5 to 39.0 Ma (Henry and McDowell, 1986), suggesting that igneous fragments could be derived from the south at a time compatible with Ogallala deposition. Pending further research, we favor the concept that the volcanic clasts at Culberson were transported in a southerly direction during Miocene (Ogallala) time because of their association with lithologies known to occur to the north in the Sierra Blanca region of New Mexico.

Because these later stage karst deposits are crosscut by mineralization and were probably deposited in middle to late Miocene time, scattered surface remnants imply post-Ogallala uplift of the district. Only after this uplift could the hydrologic regime which formed Culberson and further removed halite beds from the Castile Formation, begin to develop. This is supported by the lack of sulfur deposits east of the updip edge of the halite dissolution front, as described by Hinds and Cunningham (1970) and Smith (1978). Alteration and mineralization at Culberson probably began within the last 5 Ma and continues to the present.

Hydrogeology

The fact that the entire Upper Permian sequence is preserved within the isolated depression at Culberson indicates that further dissolution of evaporites, primarily within the Salado, occurred at this site. This suggests relatively high-volume or prolonged upward flow of undersaturated waters through permeable structural features (faults) from aquifers below the evaporite sequence (Olive, 1957; Ruckmick et al., 1979), or infiltration down from the Rustler aquifer through discontinuities in the upper Salado claystone, as noted at the Michigan mine site (Fig. 5). Outflow from the system is thought to be from points stratigraphically above the evaporite sequence.

Two lines of evidence suggest substantial upward flow of both hydrocarbons and oxygenated waters from the Cherry Canyon Formation. First, analyses of oil extracted from altered Castile Formation core samples from a point very close to the line of section in Fig. 5 show a definite correlation with west Texas Cherry Canyon oil (Talukdar, contract report, 1991). Second, the solute components and original static levels of mine water-wells show probable maximum artesian flow into the Castile altered zone in the area of the Michigan mine. Also suggestive is the fact that the Culberson deposit in plan view appears as a plume of alteration/mineralization sweeping to the northeast away from the inflow area in sec. 16 Block 111 PSL. These relationships are explained in the following model.

In constructing a hydrogeologic model of the Culberson deposit we may view the porous, bioepigenetically altered Salado and Castile zones as confined (but interconnected) aquifers below an aquitard formed by the upper Salado residual claystone layer. The surrounding unaltered evaporite section has comparatively very low porosity and permeability. An unconfined water-table aquifer composed of fractured and brecciated Rustler members is situated above the aquitard having limited connection with the underlying deposit formation waters. The deepest litho-logic units considered reasonable sources of hydrocarbons and water are the regionally petroliferous, water-bearing siliciclastics of the Bell Canyon and Cherry Canyon Formations. Hydrodynamic conditions encountered in these units (Grauten, 1965; McNeal, 1965), and the fact

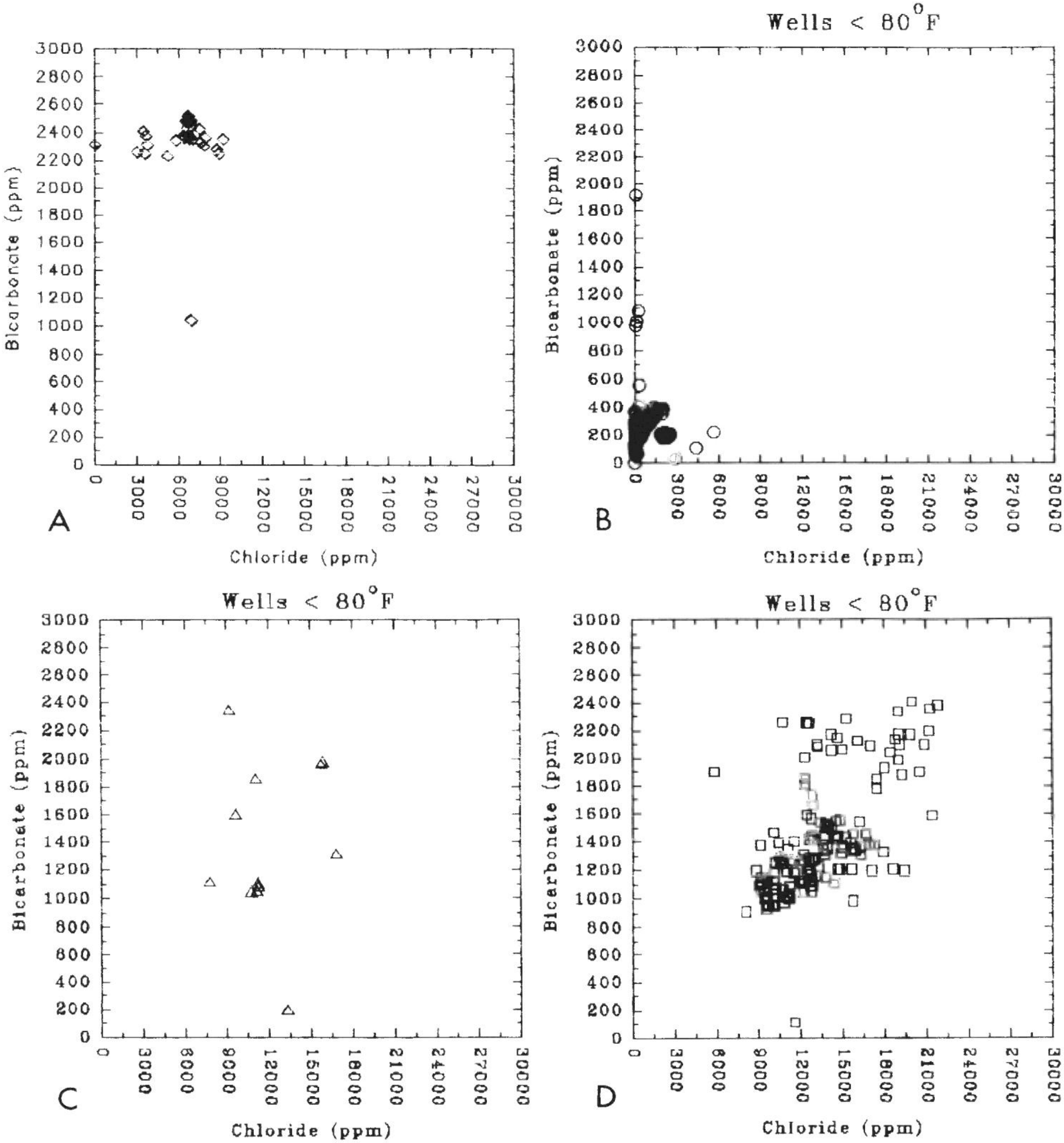

FIGURE 16. Bicarbonate vs. chloride concentrations in the Culberson vicinity. A, 30 analyses, Cherry Canyon well C-209; B, 868 analyses, Rustler Aquifer windmill samples; C, 13 analyses from deposit water wells near artesian-flow area; D, 111 analyses, all water wells penetrating the deposit.

that they are hydrocarbon-bearing within the district, indicates that they are important to the origin of the deposit. The aquitard separating the altered Ochoan aquifers from the Delaware Mountain Group are compact, thin-bedded limestones and clayey siltstones of the Lamar Member of the Bell Canyon Formation.

For comparative purposes, historical major cation/anion water analyses were utilized to help define which units should be considered aquifers and to determine chemical differences between aquifers. Water samples from the deposit were taken from mine water-pressure reduction wells and include analyses only from wells in which the water was found to be less than 80°F, to minimize the effects of mine production waters.

Well C-209 is located in sec. 2 Block 111 PSL and was drilled to a depth of 3548 ft directly below the northern part of the Culberson deposit. There is no alteration below the Salado at this site. Geophysical and sample logs indicate that the well penetrates at least 428 ft of Cherry Canyon, including the permeable sandstones of the Manzanita Member. Waters flowing from this well under artesian pressure are largely from the Manzanita and therefore the analyses are taken to be representative of this unit. Analyses of Rustler aquifer water were run on samples from seven windmills and other monitoring points that lie within a 5 mi radius of the Culberson deposit.

The bicarbonate vs. chloride plots of these units are different (Fig. 16) and were used as criteria in developing the hydrogeologic model. However, an evolution of water chemistries between the Cherry Canyon and the overlying deposit is indicated, and such an aquifer interconnection requires the presence of a fault or fracture zone. The bicarbonate concentrations within the deposit do not exceed the Cherry Canyon bicarbonate values from well C-209 (maximum 2500 ppm). Assuming that the Cherry Canyon analyses are representative, waters flowing upward into the deposit become depleted in bicarbonate and enriched in chloride content. The depletion in bicarbonate can be explained by calcite precipitation within the deposit. Water wells within the deposit that are farthest away from the apparent site of inflow (sec. 16 Block 1 1 1 PSL) have lower bicarbonate values, suggesting that the extent of calcite precipitation and activity of bicarbonate is related to the solution residence time within the deposit and to the distance of fluid migration away from the point of inflow. Vertical gradients in the concentrations of bicarbonate within the deposit as a function of distance are implied by plot C in Fig. 16. A study that compared the variation of bicarbonate concentrations over the time that the wells were pumped (months) showed an increase in bicarbonate and a decrease in chlorides. These wells are closer to the proposed point of inflow than any other wells used in this evaluation and were probably inducing upward flow from depth, as reflected in the analyses.

The relative increase in chlorides between the Cherry Canyon and the deposit may result from continued leaching of residual halite from remnant sulfate minerals in the altered zone and surrounding host formations, and higher chloride waters existing locally within the Cherry Canyon or overlying Bell Canyon sequences. Although adjacent intraformational permeability zones as channel fills within the Bell Canyon are known to contain quite different salinities (Grauten, 1965), the chlorides within the Culberson deposit appear to have been derived from local leaching of the Ochoan sequence (Fig. 17). The evolution of the chlorides from the Cherry Canyon up into the deposit appears to be a continuum, further supporting a fluid migration pathway such as a fault (Fig. I6A, D). Chlorides in C-209 range from 3000 ppm to about 9000 ppm. Chlorides from the deposit range from about 9000 ppm to a maximum of 21,000 ppm. Another well in the Culberson area encountering artesian water flow from the Cherry Canyon or the Bell Canyon was drilled by Chapman in sec. 15 Block 113 PSL. This suggests that the presence of waters of probable meteoric origin within the Delaware Mountain Group are not unique to the Culberson site.

The potentiometric surface at Culberson, as calculated from well C-209 wellhead pressures (100 psi) and the elevation of the Cherry Canyon recharge area (Dietrich et al., 1967), lies about 231 ft above the mine surface (100 psi @ 62°F= 231 ft head). The head loss from the recharge area to this point is about 1450 ft. Thus, sufficient hydrostatic pressure exists within the Cherry Canyon to force meteoric water and dispersed hydrocarbons upward through faults to come in contact with the Ochoan sequence, thereby initiating bioepigenesis and also supplying the oxygen necessary for native sulfur mineralization (Fig. 18). This model also implies that bicarbonates could be generated by oxidation of hydrocarbons below the Ochoan sequence as well as within the deposit, resulting in reaction of bicarbonates with Ca ions released from calcium sulfate dissociation to precipitate isotopically light calcite.

We believe that alteration and mineralization reactions generally take place contemporaneously where the evolution of various textures and mineralogic relationships within the ore ultimately reflect the limited availability of reactants. Mineralogic assemblages that include Sr and

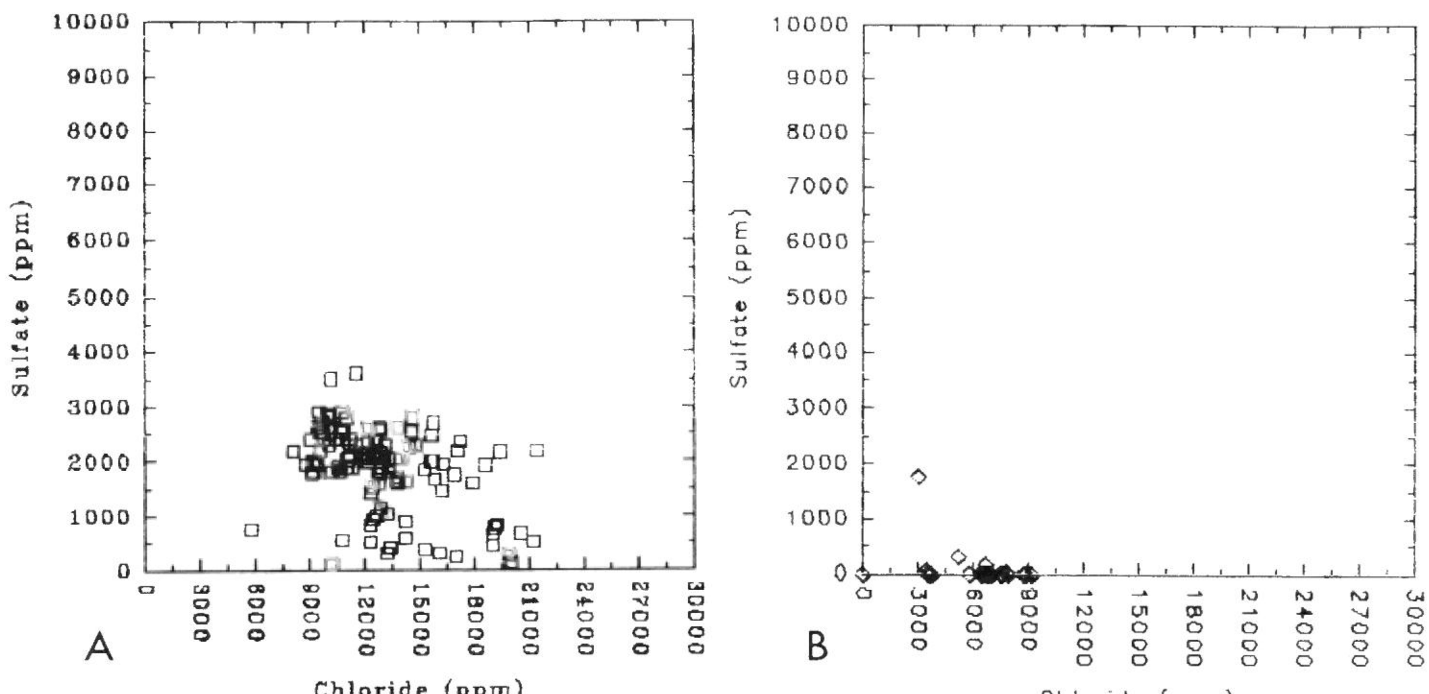

FIGURE 17. Sulfate vs. chloride. A, 111 analyses, water wells penetrating the deposit; B, 30 analyses, Cherry Canyon well C-209.

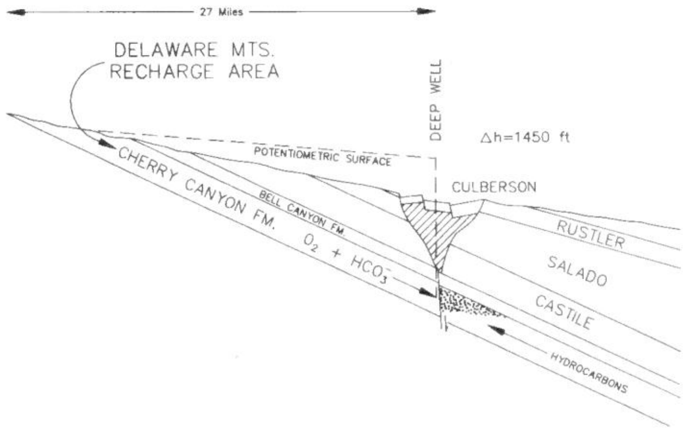

FIGURE 18. Schematic hydrogeologic regional model showing relationships of Cherry Canyon and Bell Canyon aquifers to Culberson artesian system. Adapted from Ruckmick et al. (1979).

Ba suggest influx of basinal waters (oil-field brines) admixed with fresh recharge waters in the Cherry Canyon. The influx of metalliferous brines carrying relatively high Sr values has been noted in other localities (Saunders, 1988) and explain anomalous quantities of celestite mineralization.

SUMMARY

Features derived from uplift during two major tectonic episodes created the controlling framework for native sulfur mineralization at Culberson. Although dissolution of evaporites in the Permian Ochoan sequence was probably initiated shortly after deposition, Laramide regional uplift of the western Delaware basin, on the order of several thousand feet, initiated extensive karst dissolution of Ochoan evaporites that extended at least as deep as the Salado Formation. Heterolithic breccias developed during this time within solution channels along syntectonic faults or older, reactivated zones of crustal weakness, constraining the timing of fault displacement in the Guadalupian clastics and Ochoan evaporites to Late Cretaceous or early Tertiary. During this episode, heterolithic breccias most likely formed by means of upward stoping and gravity collapse into voids created by evaporite dissolution. This dissolution was probably by infiltrating, undersaturated meteoric waters.

Basin and Range tectonism further uplifted the western Delaware basin several thousand feet. This uplift induced westward, updip hydrocarbon secondary migration and entrapment in Guadalupian siliciclastics. Further intensive down-dip dissolution retreat of halite beds took place in the remaining Salado sequence and probably in the Castile Formation. The Guadalupian basinal clastics and carbonates were unroofed on the high western margin of the basin concurrently with evaporite dissolution, which was propagating in a general easterly direction. Meteoric recharge waters in the Guadalupian Cherry Canyon and Bell Canyon Formations, mixed with basinal brines containing dispersed hydrocarbons, migrated upward by artesian flow along indicated faults at Culberson to come in contact with a large volume of evaporites in the Castile, Salado and Rustler Formations. Where the hydrocarbon-bearing artesian waters were innoculated with sulfate-reducing bacteria, bioepigenesis began. It is possible that bioepigenetic alteration may have occurred locally within the basin during an earlier time where hydrocarbons migrated along faults and fractures to meet the basal Ochoan sequence, but vertical migration was limited by very thick impermeable halite beds. In such cases, formation of replacement limestone may occur, but native sulfur deposition may be inhibited because of lack of a sufficiently oxidizing environment or lack of a point of outflow. Such may be the case for the castiles of the Gypsum Plain.

The hydrologic regime necessary to induce bioepigenesis has been active probably since the late Miocene. Downward infiltration of meteoric water is clearly an ongoing process regionally, but the extreme thinning of the Salado Formation at Culberson suggests that dissolution of evaporites by upward-flowing undersaturated waters is (or was) a dominant process, as indicated by aquifer chemistries and mineral assemblages that indicate influx of connate brines.

The fact that Culberson and Phillips Ranch are the largest deposits in the district may relate to the coincidence of faulting along the Pecos lineament that breached previously entrapped hydrocarbons, or provided a permeability fairway through which a tremendous volume of hydrocarbons migrated.

CONCLUSIONS

1. Mineralization at Culberson probably occurred within the last 5 Ma and may be an ongoing process.
2. The timing of mineralization is constrained by mineralization that crosscuts karst detritus of probable Ogallala Formation age and affinity. This places the timing of Culberson mineralization later than that proposed by Hentz and Henry (1989) for Delaware basin evaporite-hosted sulfur deposits.
3. High-angle reverse faulting is indicated at Culberson but not at the nearby Phillips Ranch deposit. Different structural kinematics of these deposits suggest different local stress regimes, although they may have formed from a common regional state of stress.
4. The source of hydrocarbons and meteoric waters at Culberson appears to be the Guadalupian Cherry Canyon Formation. Previous authors specified the Bell Canyon as the hydrocarbon source for bioepigenesis of Ochoan evaporites. Our data appear to substantiate the general hypothesis on the hydrodynamics of Delaware basin sulfur deposits illustrated by Ruckmick et al. (1979).
5. The regional tectonic events establishing the structural framework for the formation of the Culberson deposit are recorded by dissolution breccias developed during the Late Cretaceous—early Tertiary and late Tertiary—present.

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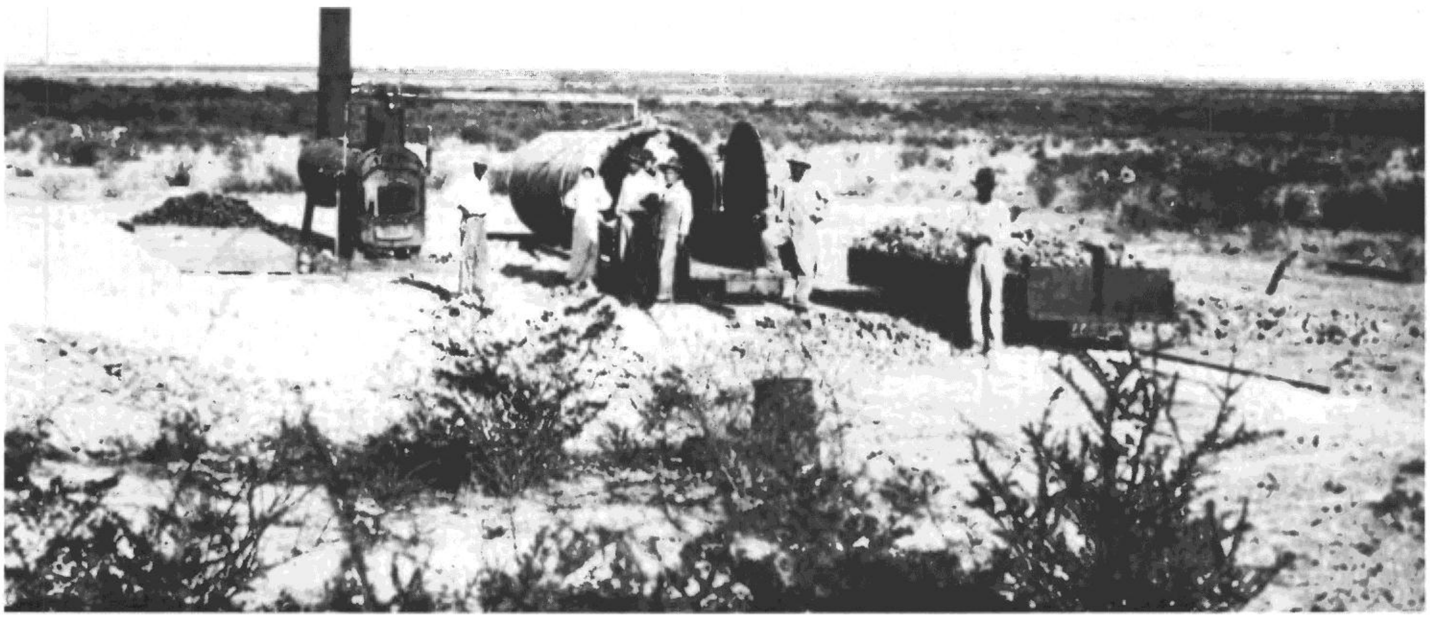

Drying unit for the early American Sulphur Company operation west of Orla, Texas (near Day 1, Stop 4). Photograph by George Adams, c. 1912. Courtesy of Southeastern New Mexico Historical Society of Carlsbad.