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SULFUR DEPOSITS IN OCHOAN ROCKS OF THE GYPSUM PLAIN, SOUTHEAST NEW MEXICO AND WEST TEXAS

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INTRODUCTION

The Culberson sulfur mine (Rustler Hills deposit) near Orla, Texas, is the world's largest producer of sulfur by the Frasch method. Duval Corporation, a subsidiary of Pennzoil Corporation, began mining there on September 30, 1969, and had mined 17,299,521 mT through December 31, 1979; production continues at rates of 2 million mT per year. Reserves in place were originally estimated to be about 55 million mT, and subsequent drilling has confirmed and increased the reserve tonnage. Duval recently purchased the Phillips Ranch deposit a few miles west of the Culberson mine and expects to bring it into production about August 1980 at a low rate.

At least nine other sulfur deposits have been discovered in this area and, like the Rustler Hills deposit, they are associated with Ochoan evaporitic rocks in the Delaware Basin. All these others are much smaller. Several questions arise from our knowledge of the area and its deposits: Is there thus only one very large sulfur deposit in the Delaware Basin? Why is the Rustler Hills deposit so large and in its particular location? How and why does it differ from the smaller deposits? And, how did these sulfur deposits form? These questions, none of which can be answered now with certainty, are the topic of this paper. The speculations and conclusions contained here are my own, based on field work, on the literature, and on enjoyable discussions of Delaware Basin geology in its broadest sense with friends and colleagues.

STRATIGRAPHY

The Ochoan rocks of the Delaware Basin have been capably described in two recent publications (Anderson and others, 1972; Payne, 1976). Figure 1 shows the approximate outline of the constricted ocean basin as it probably existed at the beginning of Ochoan time. Presumably, the basin was then everywhere floored with clastic sediments of the Bell Canyon Formation, and water depth was probably a few hundred meters.

The lowermost Ochoan rock unit in the basin is the Castile Formation, consisting mainly of anhydrite with thin highly organic calcite laminae; massive halite is interbedded with the laminated anhydrite. Anderson and others (1972) have shown that many of the individual laminae in the Castile and overlying Salado can be correlated over most of the basin.

Anderson and others (1972) subdivide the Castile (Table 1) into the following informal members: Basal Limestone, up to 1 m thick; Anhydrite I, ranging from 52 to 107 m thick; Halite I, pure halite, up to 150 m thick; Anhydrite II, 27 to 45 m thick; Halite II, Halite with five thin anhydrite beds, up to 70 m thick; Anhydrite III, 85 to 92 m thick; Halite III, interbedded halite and anhydrite, 60 to 120 m thick; Anhydrite IV, anhydrite with some interbedded halite, 90 to more than 180 m thick. The basis of the subdivision is the presence of the major halite beds; where they are absent, it is difficult to separate the anhydrite units. The Halite III and Anhydrite IV members are present only in the deepest part of the basin, well east of the sulfur-bearing area.

In the western part of the basin Halite I and Halite II are absent, and in their place is a much thinner anhydrite breccia bed. Anderson and others (1972) believe that the breccia consists of the undissolved anhydrite laminae remaining after solution of the salt in the halite members. Figure 2 shows the western and southern limits of Halite I and Halite II in Culberson County and part of Reeves County.

Within the Castile Formation are masses of secondary limestone, apparently the result of local replacement of Castile gypsum by calcite. Outcrops of these masses form circular to elliptical hills ranging from a few meters high to buttes rising 30 m above the plain. Adams (1944, p. 1606) refers to the limestone hills as "castiles," a confusing term but one which remains in use. Kirkland and Evans (1976 and this volume) have good evidence to show that they are related to a part of the sulfur-forming process. In the subsurface, secondary limestone occurs in the Castile and Salado, and some of the limestone contains sulfur.

Overlying the Castile is the Salado Formation, predominantly halite in the subsurface with lesser amounts of anhydrite and, locally, potash salts. In the outcrop and shallow subsurface the salt

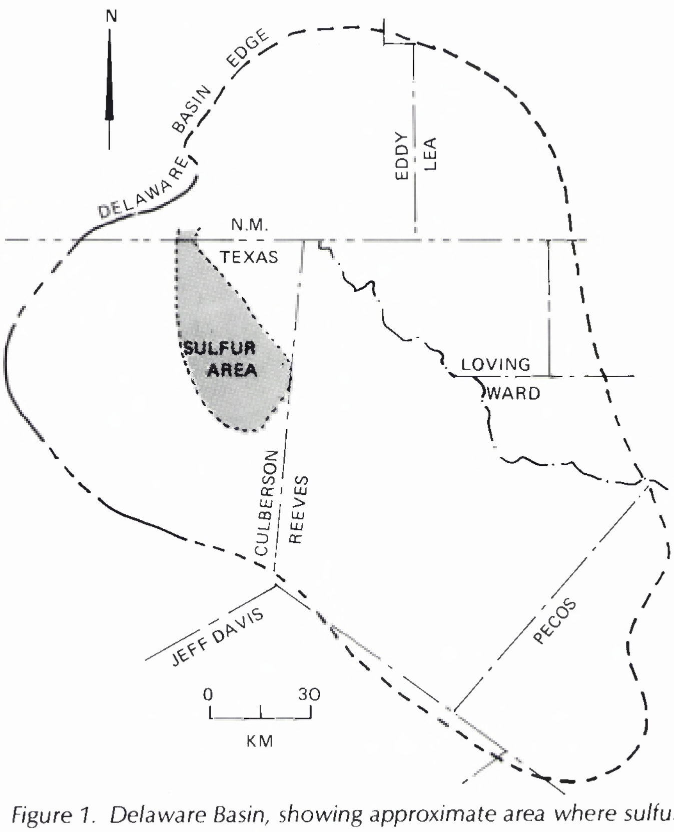

Figure 1. Delaware Basin, showing approximate area where sulfur occurs in Ochoan rocks.

Table 1. Stratigraphic table of Permian rocks of the Delaware Basin, West Texas and southeast New Mexico (from Snider, 1965).

SERIES	FORMATIONS	INFORMAL MEMBERS
Ochoa	Dewey Lake Redbeds	Anhydrite IV
	Rustler	Halite III
	Salado	Anhydrite III
	Castile ←	Halite II
Guadalupe	Bell Canyon	Anhydrite II
	Cherry Canyon	Halite I
	Brushy Canyon	Anhydrite I
		Basal Limestone
Leonard	Bone Spring Limestone	
Wolfcamp	undifferentiated	

is absent, presumably removed by solution, and the Salado consists mainly of anhydrite or gypsum breccia, commonly red-orange. In the Rustler Hills this zone is visible as red gypsum underlying Rustler dolomite. Some of the medium-bedded unbrecciated anhydrite and gypsum west of the Rustler Hills may be lower Salado (Snider, 1965).

Clastic rocks, including quartzite, chert, and older Permian limestone pebbles, green silty shale, and banded anhydrite fragments, occur irregularly in the Salado interval and in the upper Castile. They may represent: 1) fall-in of overlying rocks through sinkholes in the Rustler (some of the rocks could then be Cretaceous or younger) (Udden, 1922); 2) clastic sediments deposited on top of the Castile and in the Salado, perhaps as a tongue from back-reef areas; or 3) pre-Rustler or early Rustler clastic sediments filling lows formed by pre-Rustler post-Salado erosion or solution. A possible southward trend from the reef for these clastics suggests that the second possibility is likely. In the vicinity of the Rustler Hills sulfur deposit, the clastic unit may be several to 90 m thick.

Interbedded dolomite, anhydrite, redbeds, and salt of the Rustler Formation overlie the Salado in the deep subsurface on the east side of the basin. In outcrop, notably in the Rustler Hills, the Rustler is dolomite with subsidiary clay beds. Collapse and solution brecciation are abundantly evident in outcrops.

Cretaceous rocks occur in a few collapse areas and distinct sinkholes. Quaternary sediments partially fill valleys and sinkholes; they are anomalously thick in the Black River Valley along the Guadalupe Mountain front and in other large troughlike areas, such as the Pecos Trough, in the eastern part of the basin where salt has been dissolved at depth (Maley and Huffington, 1953; Hiss, 1976).

LOCAL STRUCTURE

Faults of small displacement have been mapped or inferred in the Castile. The most obvious are the boundary fractures of solution-subsidence troughs (Olive, 1957); these faults are described by King (1949) in the map explanation as "Linear features in Castile anhydrite (Possible fracture zones, in places forming low scarps . . .)." Several of these faults are shown on Figure 2 to indicate their almost uniform east-west trend. The eastern limit of the faults is west or south of the area where halite remains in the subsurface Castile.

Origin of the "solution-subsidence" faults is still not clear, but their downdip trend and their restriction to present salt-free areas of the Castile suggest that they are somehow related to solution of Halite I and Halite II. Logs of sulfur exploration tests drilled along

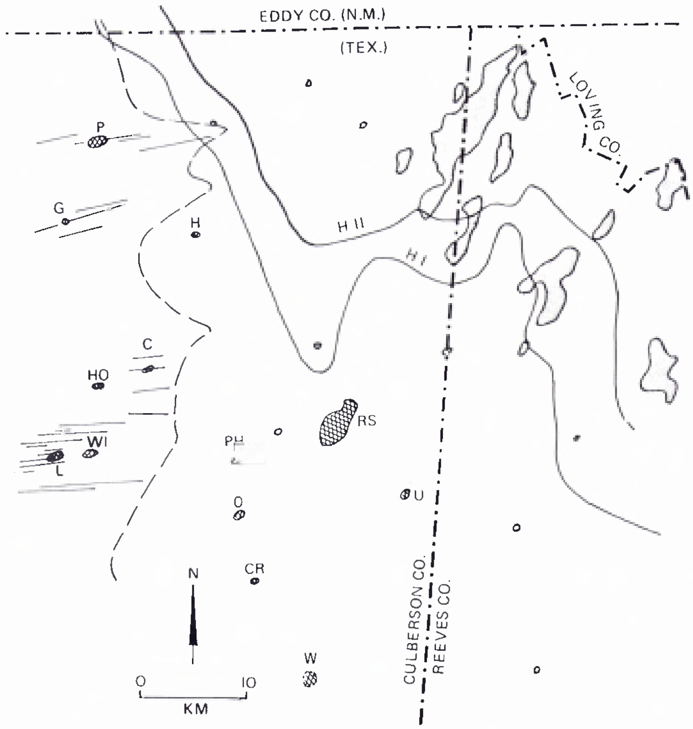

Figure 2. Larger scale map of sulfur area shown in Figure 1. HI and HII are southwest limits of Halite I and Halite II in Castile Formation; dashed line is eastward limit of solution-subsidence troughs shown by fine east-west lines; oil fields are screened but unlabeled. Sulfur deposits, from northwest to southeast, are: P, Pokorny; G, Grant; H, Hoss; C, Covington; HO, Hopi; L, Luna; WI, Windy; PH, Phillips Ranch; O, Olga; RH, Rustler Hills; U, Union-Kewanee; CR, Cricket; W, Weigel.

these fractures would shed light on this problem if they were released.

A second group of faults has been delineated only by sulfur test drilling, as far as I know. These faults, with displacements on the order of 8 to 25 m, are nearly vertical and trend about N 65°E. Good examples are the graben-boundary faults shown in Figure 3. Clearly, the displacement affects the upper Bell Canyon and the lowermost Castile—at least Anhydrite I—but well-log data have not been released that would show more details. It is possible that these faults are in the same system mapped by King (1949) in the Bell Canyon along the west edge of the Castile. Most of those that he mapped are in the Bell Canyon, but a few continue eastward into the lower Castile outcrop.

Photogeologic studies suggest two possible faults at depth trending northeast near the Eddy-Reeves-Culberson Counties junction and one probable fault at depth trending about N 25° E. The latter fault lies only about 3 km east of the Rustler Hills sulfur deposit. One other possible major fault zone could extend from just east of the Rustler Hills deposit, east-northeastward across Reeves, Loving, and Winkler Counties.

SULFUR DEPOSITS

Native sulfur has been known in the western Delaware Basin at least since the mid-1800's. Richardson (1904, 1905), Porch (1917), Evans (1946), Zimmerman and Thomas (1969), and others have described and discussed the surface and near-surface deposits in the region. Practically all the surface and subsurface deposits

Table 2. Sulfur exploration wells, Delaware Basin, 1967-1970.

	1967	1968	1969	1970
Culberson Co., Tex.	14	334	409	211
Reeves Co., Tex.		11	23	33
Eddy Co., N.M.		12	16	6
Totals	14	357	448	250

associated with Ochoan rocks in the basin are in the Sulfur Area marked on Figure 1.

Castile Formation Deposits

At least eight subsurface sulfur deposits are known in the Castile. All apparently occur at or near the base of the formation in Anhydrites I and II and in the Halite I breccia zone. Each of the deposits consists of brown, laminated to unlaminated to brecciated limestone containing crystalline sulfur, often reported as "secondary" or "brown" limestone on drillers' logs. (Sulfur companies rarely mention sulfur in any drillers' logs released into the public domain.) The brown limestone interfingers laterally with laminated gypsum that then grades into laminated anhydrite, which also overlies the limestone.

In the deposits for which information is available—Phillips Ranch, Pokorny, Covington—and probably in the others in the Castile, the sulfur-bearing rocks are oily, or there are oil-bearing zones within the secondary limestone. The oil composition in the Pokorny deposit, about 75% naphthenes and 16% aromatics, is "strikingly similar to the oil produced from the Castile Formation (Rustler Hills Field). . ." (Davis and Kirkland, 1970, p. 115-116). Oil from the upper Bell Canyon Formation is usually more than 50 percent paraffins.

The faults of moderate displacement in the upper Bell Canyon-lower Castile trending about N 65° E probably localized the basal Castile deposits. Because of lack of well data it is hard to be sure of this, but drilling patterns in most deposits indicate such a trend.

The Phillips Ranch deposit, discovered by Texasgulf Inc. (formerly Texas Gulf Sulphur Company), is an excellent example of the sulfur deposits in the basal Castile. The probable relationship between the sulfur-bearing secondary limestone and the Castile, as well as to the graben-bounding faults, is shown in Figure 3. In places between the faults the Castile is unreplaced but is surrounded by secondary limestone. The maximum thickness of the sulfur-bearing limestone is about 72 m (fig. 4).

Top of the Castile, picked from drillers' logs as "top of banded anhydrite" (fig. 3), is arched over the deposit. It is possible that this structural anomaly is a result of volume increase from replacement of anhydrite by limestone and gypsum, but it may have some other cause such as conversion of anhydrite at the top of the Castile to gypsum by groundwater.

The deposit is aligned along and between two faults forming a graben about 245 m wide (figs. 4, 5). Displacement on the faults is about 15 m. Close-spaced drilling has permitted delineation of the graben for more than a mile and a half along its N 65° E trend, and the faults probably continue farther.

Of the basal Castile deposits, the Phillips Ranch is probably the largest with reserves in excess of 6 million mT. The other deposits range from 100,000 to perhaps 3 million mT (depending upon who's talking), although exploration is not complete.

The Grant deposit, if indeed much sulfur is in the subsurface, is (or was) remarkable. According to Porch (1917) a natural shaft on one of the two adjacent limestone buttes, or castiles, was

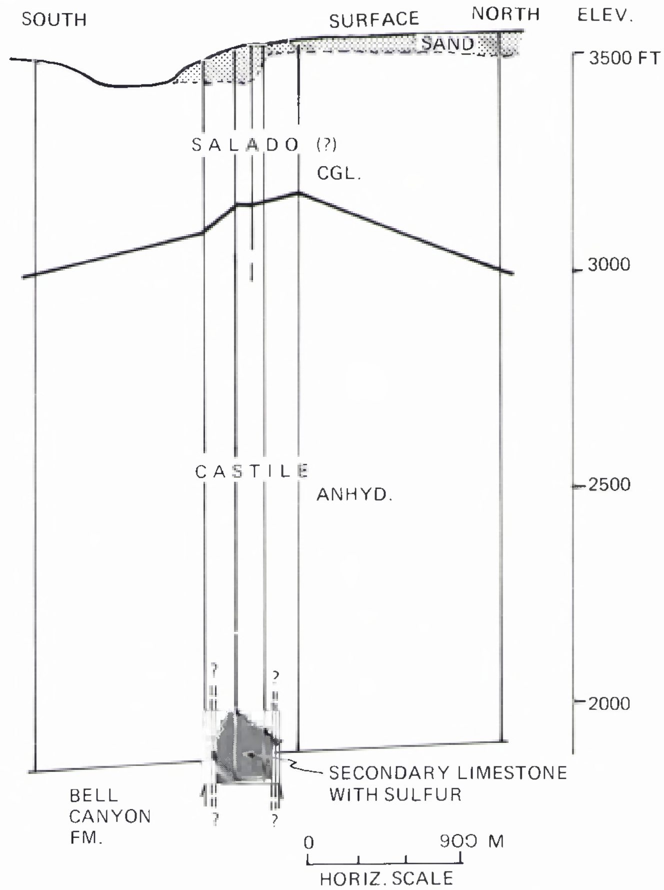

Figure 3. North-south cross-section, Phillips Ranch deposit; vertical lines represent selected sulfur tests drilled by Texas Gulf Sulphur Co. (Line of section is shown on Figure 4.)

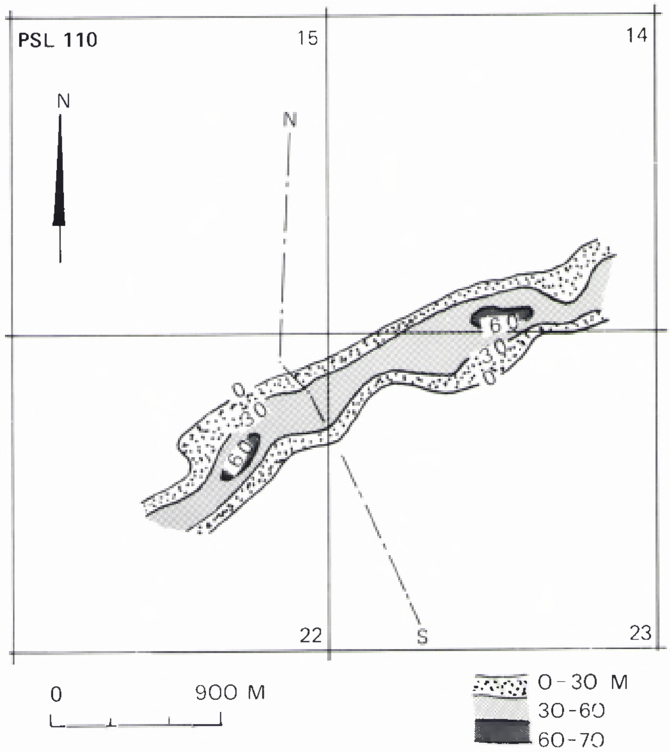

Figure 4. Isopachous map of secondary, sulfur-bearing limestone, Phillips Ranch deposit; contour interval is 30 m.

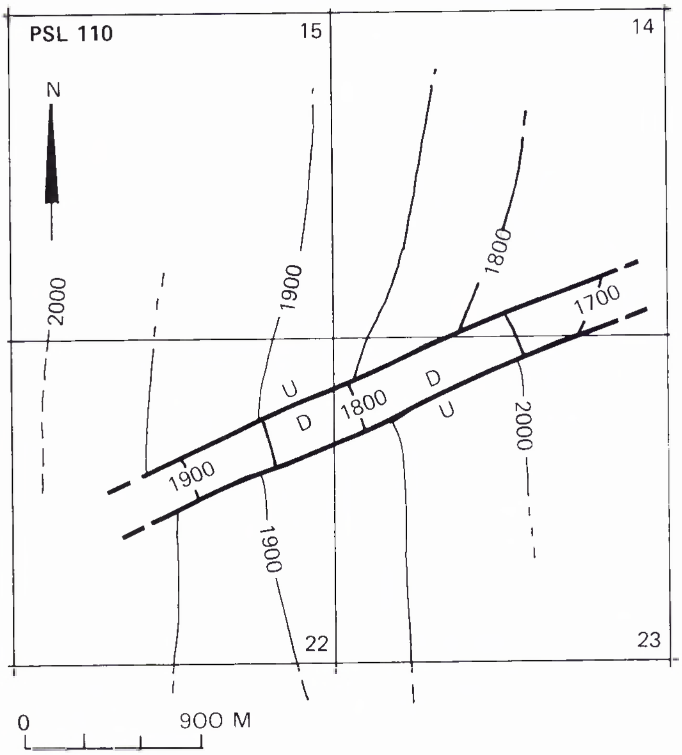

Figure 5. Structure contour map of base of Castile Formation, Phillips Ranch deposit; contour interval is 50 m.

reported to be 30 m deep and lined with a 10-cm layer of crystalline sulfur. The shaft is still there, most of the sulfur having been mined, but hydrogen sulfide issues from it in copious quantities. Texaco investigated the area with geophysical methods and several drill-holes, but there have been no reports of any subsurface deposit.

Salado Formation Deposits

Two sulfur deposits have been found in the Salado Formation in the Delaware Basin, the Rustler Hills deposit and the small Union–Kewanee deposit explored by Minerals Exploration Company. The latter probably contains about a half-million mT of sulfur, and not much information about it is public.

The Rustler Hills deposit (called the Culberson Mine by Duval) is more or less bowl-shaped with the center much thicker than the edges (fig. 6). The ore zone, like that in the basal Castile deposits, consists of vuggy secondary limestone; sulfur occurs as vug linings, as vug and fracture fillings, and as pore fillings. The deposit lies along the east side of the Rustler Hills and beneath Virginia Draw, a major valley cutting through the Rustler Hills. Underlying rocks are mostly masked by Quaternary and Recent alluvium, but Rustler carbonates are exposed on the west side in the edge of the Rustler Hills. Duval filed the following log for its sulfur test C-37 with the Texas Railroad Commission:

Depth, m	(ft)	Reported rock type
0- 99	(0-325)	Sandstone, conglomerate
99-121	(325-395)	Anhydrite
121-124	(395-405)	Clay
124-157	(405-515)	Dolomite
157-171	(515-560)	Sandstone, dolomite
171-247	(560-810)	Anhydrite with sandstone stringers
247-305	(810-1000)	Banded anhydrite

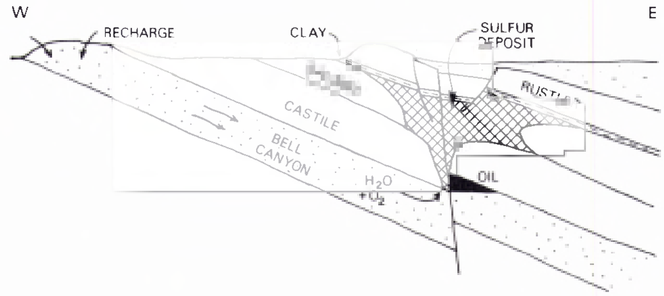

Figure 6. Highly diagrammatic cross-section of the Rustler Hills sulfur deposit (modified from Ruckmick and others, 1979).

The upper 99 m may be Cretaceous to Quaternary, and the banded anhydrite below 247 m is Castile. The remaining interval, 99 to 247 m, probably includes lower Rustler and Salado or Salado residuum. The interval between the clay bed and the banded anhydrite is the principal sulfur-bearing section in the Rustler Hills deposit. Correlations of lithic units above the top of the Castile (banded anhydrite) are difficult using the drillers' logs which have been filed. The extremely poor quality of the correlations enhances the interpretation that the interval represents material that slumped badly as salt (and possibly gypsum) in the Salado and Rustler was dissolved.

The clay bed shown in the drillers' log is important. Ranging from several cm to 30 m thick, it overlies the entire deposit. Clearly, the clay acted as an upward limit of mineralization. No data are available to determine whether or not the clay is absent beyond the edges of the deposit.

In the southwest part of the deposit, secondary limestone extends downward through the Castile to the top of the Bell Canyon. The "pipe" apparently contains very little sulfur, but nearby the secondary limestone extending down into the upper banded anhydrite is heavily mineralized.

Figure 7 shows the general shape of the deposit and the variation in the amount of sulfur in the orebody. The usual measure of the sulfur in drill holes among sulfur geologists is the "equivalent foot of solid sulfur" or E.F.S.S. (Sulfur geologists have not yet converted to meters!). For example, a fifty-foot section of rock with 15 percent sulfur would contain 7.5 E.F.S.S. One of the better wells in the Rustler Hills deposit was estimated to contain 48 E.F.S.S.; if the mineralized interval averaged 25 percent sulfur, the interval was at least 192 feet (58.6 m) thick.

Although the basal Castile deposits are oily or have oil-bearing zones, the Rustler Hills deposit is practically oil-free. Only a little asphaltic material and minor amounts of oil have been found. Another notable characteristic of the deposit is a thick mass of barite, up to several meters thick, overlying part of the sulfur section. Relationship of the barite to the sulfur is not clear from the public well logs. (*See also* Noel McAnulty, this guidebook, on barite in Castile at Seven Heart Gap.)

Structure of the rocks in and around the deposit appears from very limited control to be an east-dipping regional homocline. An obscure structural terrace or monocline might be present, superimposed on the regional dip, but it is not obvious. No evidence is available to indicate that a structural high in the evaporites predated the deposit and controlled its location.

Faulting, on the other hand, is strongly suggested, but mostly by inference. The graben-bounding faults described in the Phillips Ranch deposit trend N 65° E and, if extended, would intersect the northern part of the Rustler Hills deposit. A possible major fault

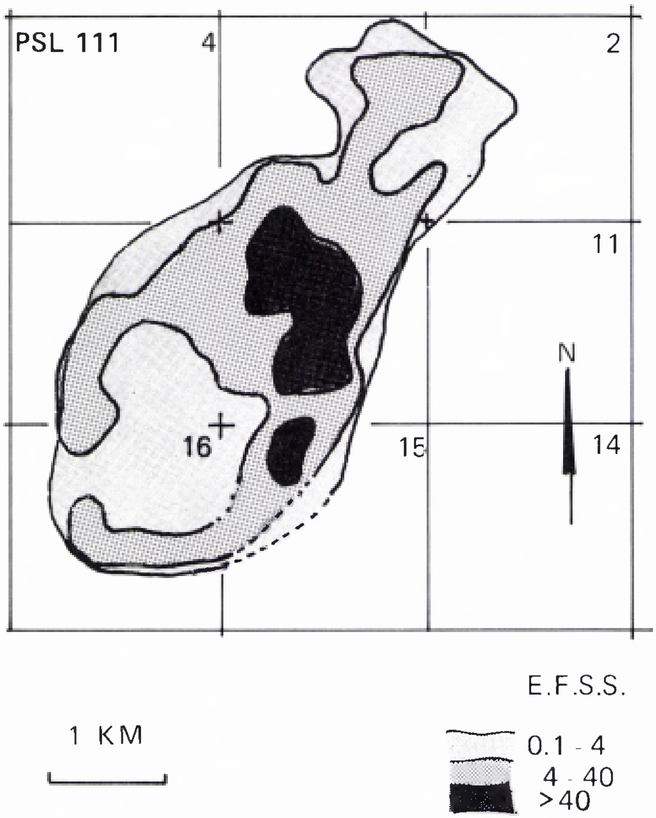

Figure 7. Generalized sulfur mineralization (sulfur isopach) map, Rustler Hills deposit; E.F.S.S. is the abbreviation for effective feet of solid sulfur (see text).

zone interpreted from aerial photography extends from the Rustler Hills deposit east to Winkler County, and a probable fault, trending N 25° E, lies about 3 km east of the deposit, as previously mentioned.

The Rustler Hills deposit is approximately in line with two prominent trends of upper Bell Canyon oil fields. One is the Screwbean north-northeast trend, and the other is the Sabre/Olds northeast trend. Grauten (1965) shows that oil in these upper Bell Canyon fields occurs in clean sandstone stratigraphic traps bounded above and below by shale and siltstone, and laterally by shaly or carbonate-cemented sandstone. William F. Grauten (personal correspondence) thinks that the clean sandstone trends continue into the Rustler Hills deposit area, but oil is generally absent in the trends west and south of the updip limits of Halite I (fig. 2).

Deposition and Localization

Davis and Kirkland (1970) discuss the origin and deposition of native sulfur in the Delaware Basin. They use as an example the Pokorny deposit in the basal Castile, but their ideas apply generally to all the deposits. According to their hypotheses, oil migrated into porous parts of the Castile sulfate rocks where sulfate-reducing bacteria generated hydrogen sulfide and carbon dioxide. Calcite was precipitated, and ultimately the hydrogen sulfide, if not lost to the surface or carried away, was oxidized by oxygenated groundwater to elemental sulfur. Sulfur and carbon isotope values from a core through the Pokorny deposit support the hypothesized origin of the sulfur and secondary calcite (Davis and Kirkland, 1979). Kirkland and Evans (1976) think that natural gas, rather than oil was used by sulfate-reducing bacteria as an energy source. Ruckmick and others (1979) generally concur in these ideas.

Based on the ideas of Kirkland and Davis (1970) and on other work, we can select six factors which are important in the origins and localization of sulfur deposits in the Castile and Salado Formations: 1) presence of sulfate rocks, 2) presence of hydrocarbons; 3) fracturing or brecciation of rocks to permit fluid flow; 4) oxygenated groundwater or other agents capable of oxidizing hydrogen sulfide; 5) sealing bed to prevent loss of H_2S to surface; and 6) absence of salt. Some geologists have suggested that as many as twelve factors must coincide for sulfur deposition. Figure 6 from Ruckmick and others (1979) summarizes several of the factors.

1) Sulfate rocks make up most of the Castile and Salado in the western part of the Delaware Basin. On the surface the Castile is gypsum, and drilling shows the gypsum normally to grade downward into anhydrite 15 to 30 m below the surface. In the vicinity of the basal Castile sulfur deposits, especially adjacent to the secondary limestone, the Castile is gypsum, apparently altered from anhydrite, far below the surface.

2) Oil is locally abundant in the upper Bell Canyon Formation; outlines of the major fields near the sulfur area are shown on Figure 2. Minor amounts of oil have been found in the Castile and Salado. Gas is much less common than oil in the upper Bell Canyon, Castile, and Salado.

Oil in the upper Bell Canyon fields is generally reported to be sweet but that in the Castile and Salado is sour. Small volumes of very sour gas ranging to almost pure hydrogen sulfide have been reported by drilling crews. This sour gas is a severe hazard during drilling and encounters with it have resulted in a few deaths.

Sulfur geologists now seem inclined to think that natural gas, probably from the Bell Canyon, was the hydrocarbon devoured by anaerobic bacteria to generate hydrogen sulfide which ultimately became the sulfur deposits. That hypothesis explains the general lack of hydrocarbon gases in the area. Whether oil or gas, an enormous volume of hydrocarbons was required for deposition of the Rustler Spring sulfur deposit, equivalent to more than 32 million m^3 (200 million barrels) of oil!

3) In order for hydrocarbons, whether oil or gas, to migrate into the sulfate rocks and for the metabolic products of sulfate-reducing bacteria to move to appropriate sites of calcite precipitation and sulfur deposition, permeable zones must have existed in the Castile Formation. Likewise, if oxygenated meteoric groundwater was required to oxidize the hydrogen sulfide, there must have been permeable zones in the Bell Canyon, Castile, and Salado. In the discussion of stratigraphy I have pointed out the possibly permeable breccia beds in the Castile, which remained after solution removal of the salt; these breccias do not appear to be very permeable in outcrop exposures. The Salado residuum overlying the Castile is certainly permeable. Faulting and fracturing in the Castile probably post-dated removal of the salt, especially in the Rustler Hills deposit area. Fractures through the salt probably would have healed by flowage and recrystallization unless fluid flow through them was great.

4) Sulfur in the deposits is presumed to have formed by oxidation of hydrogen sulfide. Davis and Kirkland (1970, p. 120) state, "Oxygenated ground waters may well have had a role in the oxidation of hydrogen sulfide to sulfur in salt-dome caprocks . . . This is very likely the oxidative mechanism in the West Texas area where porosity and permeability of the Castile Formation are evident." In a later paper Kirkland and Evans (1976) concur with the earlier statements. It is not yet clear if the hydrogen sulfide was oxidized

by oxygenated meteoric water moving downward through the Castile and the Salado residuum or upward from the underlying but poorly permeable Bell Canyon sandstone, or if the hydrogen sulfide might have been oxidized by other kinds of reactions not yet known, observed, or suspected.

5) Hydrogen sulfide generated in the subsurface by sulfate-reducing bacteria has a tendency to rise, to the surface if possible. If it does go to, or near, the surface, then it will be lost to the atmosphere or be dispersed by groundwaters perhaps depositing small amounts of sulfur, which is later destroyed by sulfur-oxidizing bacteria. To prevent the loss of hydrogen sulfide, to provide an upper limit on sulfur deposition, and possibly to prevent loss of sulfur by bacterial action, a seal or barrier must be present. In the Rustler Hills deposit the seal is a clay bed as previously described. In the basal Castile deposits along faults, the seal might be upward termination of the fractures or of fracture permeability. The former would be an important indicator of the age of faulting in the upper Bell Canyon and lower Castile.

6) Finally, all the subsurface sulfur deposits now known lie west and south of Halite I. This may be coincidental, or it may indicate that the requisite migrations of hydrocarbons, hydrogen sulfide, and/or oxygenated groundwater are prevented by the salt and its sealing action. This fact also leads me to doubt that salt was the seal above the basal Castile deposits.

I would not be surprised, nor would most active sulfur exploration geologists, to find that other factors are necessary for deposition of large sulfur deposits. When the Delaware Basin sulfur area is satisfactorily explored, we can hope that the sulfur companies will be free to publish their opinions on sulfur deposition along with their supporting data.

SULFUR EXPLORATION AND DEVELOPMENT

Early development of sulfur resources in the Delaware Basin was limited to shallow strip mining of sulfur occurring in gypsite and the sulfur lining of the natural shaft in the Grant deposit. Richardson (1905) and Porch (1917) describe the early mining operations in detail. According to Hinds and Cunningham (1970, p. 1).

> The most noteworthy mining effort between 1918 and 1966 was an open pit operated for 12 years as a one-man venture near Rustler Springs, Tex., by Mr. Thad Sanford of Carlsbad, N. Mex. Sanford recovered 800-900 tons per year of "sulfur soil" which he shipped by rail from Orla, Tex., and sold as a soil conditioner . . .

Exploration for subsurface sulfur deposits was not very active until the last half of the 1960's. Freeport Sulphur Company drilled several test-holes in the late 1940's, and a few other sulfur tests were drilled before 1965 with no promising results. With sulfur in short supply beginning about 1964, sulfur companies began active exploration in West Texas. Frasch sulfur mining in bedded evaporates was proven by Duval and Sinclair Oil Corporation in Pecos County, Texas, southeast of the Delaware Basin sulfur area. Exploration by Duval in the vicinity of the old Michigan surface mine revealed the Rustler Hills deposit, and research drilling by University of New Mexico geologists resulted in the inadvertent discovery of the Pokorny deposit. All the sulfur companies and several major and independent oil companies joined the search. Table 2 shows the numbers of reported sulfur exploration wells drilled in the Delaware Basin for the period 1967-1970; the totals shown include only the wells reported to regulatory agencies as sulfur tests. By 1971 drilling had practically ceased. Drilling was renewed by at least four companies in 1973, and several tests were drilled by Duval, Leonard Resources, and Texasgulf between 1973 and 1977. Little activity has taken place since 1977.

Several exploration methods were used in the Delaware Basin, based on a variety of hypotheses about sulfur deposition and localizing factors. The most obvious geophysical method was gravity, presuming a density contrast between the limestone-sulfur orebody and the surrounding Castile anhydrite. This method, although supported by the marked gravity low over the Rustler Hills deposit, yielded poor results because most of the basal Castile deposits were too deep, other features—caverns, gypsum—also produced gravity lows, and the detailed gravity coverage needed for success was generally too expensive. Also used were aeromagnetic, electrical, and seismic surveys, soil and soil-gas chemistry, groundwater chemistry, and color infrared photography, but to date none of these has provided more than a guide to drilling targets and, unfortunately, apparently none has led directly to discovery of a deposit.

Although exploration of the sulfur area in the Delaware Basin has been locally thorough, areas remain that have not been drilled at all or that have not been drilled to the base of the Castile. Continuing modest-scale exploration and occasional bursts of leasing activity indicate that some of the sulfur companies still hope to find economic deposits in the area. The current high price and demand for sulfur will perhaps encourage exploration.

REFERENCES

Adams, J. E., 1940, Structural development, Yates area, Texas: American Association of Petroleum Geologists Bulletin, v. 24, no. 1, p. 134-142.

———, 1944, Upper Permian Ochoa Series of Delaware Basin, West Texas and southeastern New Mexico: American Association of Petroleum Geologists Bulletin, v. 28, no. 11, p. 1596-1625.

Anderson. R. Y., Dean, W. E., Jr., Kirkland, D. W. and Snider, H. I., 1972, Permian Castile varved evaporite sequence, West Texas and New Mexico: Geological Society of America Bulletin, v. 83,. no. 1, p. 59-86.

Davis, J. B. and Kirkland, D. W., 1970, Native sulfur deposition in the Castile Formation, Culberson County, Texas: Economic Geology, v. 65, p. 107-121.

———, 1979, Bioepigenetic sulfur deposits: Economic Geology, v. 74, no. 2, p. 462-468.

Evans, G. L., 1946, The Rustler Springs sulphur deposits as a source of fertilizer: Texas Bureau of Economic Geology, Report of Investigations 1, 13 p.

Grauten, W. F., 1965, Fluid relationships in Delaware Mountain sandstone: Fluids in subsurface environments: American Association of Petroleum Geologists Memoir 4, p. 294-307.

Hayes, P. T., 1964, Geology of the Guadalupe Mountains, New Mexico: U.S. Geological Survey, Professional Paper 446, 69 p.

Hinds, J. S. and Cunningham, R. R., 1970, Elemental sulfur in Eddy County, New Mexico: U.S. Geological Survey Circular 628, 13 p.

Hiss, W. L., 1976, Structure of the Permian Ochoan Rustler Formation, southeast New Mexico and West Texas: New Mexico Bureau of Mines & Mineral Resources, Resource Map 7.

Jones, T. S. and Smith, H. M., 1965, Relationships of oil composition and stratigraphy in the Permian Basin of West Texas and New Mexico, *in* Fluids in subsurface environments: American Association of Petroleum Geologists, Memoir 4, p. 101-224.

King, P. B., 1949, Regional geologic map of parts of Culberson and Hudspeth Counties, Texas: U.S. Geological Survey, Oil and Gas Investigations, Preliminary Map 90.

Kirkland, D. W. and Evans, R., 1976, Origin of limestone buttes, Gypsum Plain, Culberson County, Texas: Geological Society of America Bulletin, v. 60, no. 11, p. 2005-2018.

———, 1980, Origin of castiles on the Gypsum Plain of Texas and New Mexico *in* Dickerson, P. W., Hoffer, J. M. and Callender, J. F., The Trans-Pecos Region: New Mexico Geological Society Guidebook, 31, p. 183.

Maley, V. C. and Huffington, R. M., 1953, Cenozoic fill and evaporate [sic] solution in the Delaware Basin, Texas and New Mexico: Geological Society of America Bulletin, v. 64, no. 5, p. 539-546.

Olive, W. W., 1957, Solution-subsidence troughs, Castile Formation of Gypsum Plain, Texas and New Mexico: Geological Society of America Bulletin, v. 68, no. 3, p. 351-358.

Payne, M. W., 1976, Basinal sandstone facies, Delaware Basin, West Texas and southeast New Mexico: American Association of Petroleum Geologists Bulletin, v. 60, no. 4, p. 517-527.

Porch. E. L., Jr., 1917, The Rustler Springs sulphur deposits: University of Texas Bulletin 1722, p. 1-71.

Richardson, G. B., 1904, Report of reconnaissance in Trans-Pecos Texas north of the Texas and Pacific Railway: University of Texas Bulletin 24 (Minerals Survey Series 9), p. 1-119.

———, 1905, Native sulphur in El Paso County, Texas: U.S. Geological Survey Bulletin 260, p. 589-592.

Ruckmick, J. C., Wimberly, B. H. and Edwards, A. F., 1979, Classification and genesis of biogenic sulfur deposits: Economic Geology, v. 74, no. 2, p. 469-474.

Smith, A. R., 1978, Sulfur deposits in Ochoan rocks of southeast New Mexico and West Texas: New Mexico Bureau of Mines & Mineral Resources Circular 159, p. 71-77.

Snider, H. I., 1965, Stratigraphy and associated tectonics of the Upper Permian Castile-Salado-Rustler evaporite complex, Delaware Basin, West Texas and southeast New Mexico (Ph.D. dissertation): University of New Mexico, 196 p.

Udden, J. A., 1922, Some cavern deposits in the Permian in West Texas: Geological Society of America Bulletin, v. 33, no. 1, p. 153-155.

Zimmerman, J. B. and Thomas, E., 1969, Sulfur in West Texas: Texas Bureau of Economic Geology, Circular 69-2, 35 p.

Beaver, *Castor canadensis*.

Nimblewill plant and spikelet, *Muhlenbergia schreberi.*