GEOLOGICAL SURVEY CIRCULAR 628

Elemental Sulfur in Eddy County, New Mexico

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By Jim S. Hinds and Richard R. Cunningham

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A compilation of sulfur occurrences reported from wells and outcrops in Eddy County, N. Mex., with observations on their geologic setting

Washington 1970

United States Department of the Interior
WALTER J. HICKEL, *Secretary*

Geological Survey
William T. Pecora, *Director*

Free on application to the U.S. Geological Survey, Washington, D.C. 20242

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By JIM S. HINDS and RICHARD R. CUNNINGHAM

ABSTRACT

Sulfur has been reported in Eddy County, N. Mex., in rocks ranging from Silurian to Holocene in age at depths of 0–15,020 feet. Targets of present exploration are Permian formations in the Delaware Basin and northwest shelf areas at depths of less than 4,000 feet. Most of the reported sulfur occurrences in the shelf area are in the "Abo" (as used by some subsurface geologists), Yeso, and San Andres Formations and the Artesia Group. Sulfur deposition in the dense dolomites of the "Abo," Yeso, and San Andres Formations is attributed to the reduction of ionic sulfate by hydrogen sulfide in formation waters in zones of preexisting porosity and permeability. A similar origin accounts for most of the sulfur deposits in the formations of the Artesia Group, but some of the sulfur in these formations may have originated in place through the alteration of anhydrite to carbonate and sulfur by the metabolic processes of bacteria in the presence of hydrocarbons.

Exploration in the Delaware Basin area is directed primarily toward the Castile Formation. Sulfur deposits in the Castile Formation are found in irregular masses of cavernous brecciated secondary carbonate rock enveloped by impermeable anhydrite. The carbonate masses, or "castiles," probably originated as collapse features resulting from subsurface solution and upward stoping. Formation of carbonate rock and sulfur in the castiles is attributed to the reduction of brecciated anhydrite by bacteria and hydrocarbons in the same process ascribed to the formation of carbonate and sulfur in the caprocks of salt domes.

INTRODUCTION

A worldwide shortage of sulfur accompanied by rising sulfur prices from 1964 to 1968 resulted in renewed interest in long-known sulfur deposits in the Delaware Basin area of west Texas and southeast New Mexico (fig. 1). Early attempts, dating from 1896 to 1918, to exploit the surface sulfur deposits of the area by open-pit mining methods had failed owing to high extraction and transportation costs and generally low sulfur prices. The surface deposits and early mining operations were described in detail by Richardson (1905) and Porch (1917). Sporadic exploratory drilling and development efforts between the years 1918 and 1966 were made with generally discouraging results. The most noteworthy mining effort 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; in 1968, he sold most of his holdings to a major company.

In 1966 the Duval Corp. announced plans to build a Frasch sulfur plant to exploit sulfur deposits on the southwest flank of the central basin platform, near the town of Fort Stockton in Pecos County, Tex. (fig. 2). The Duval plant began production in 1967, and construction of another plant in the same area was begun in 1967 by Sinclair Oil Corp. (Atlantic Richfield Co.) (fig. 2). The success of these plants demonstrated that the Delaware Basin sulfur deposits are amenable to exploitation by the Frasch process, and the search for sulfur in west Texas and southeast New Mexico accelerated to boom proportions. Lease sales on University of Texas lands near the Fort Stockton plants brought as much as $300,000 for a 640-acre lease, and a 555-acre tract in Culberson County sold for more than $1 million. Thousands of acres of New Mexico State lands were leased, and hundreds of prospecting-permit applications were filed on Federal lands in Eddy County. Early in 1968 the Duval Corp. announced plans to build a $65 million Frasch facility to mine 2.5 million long tons of sulfur per year near the old Sanford workings in the eastern part of Culberson County, Tex., near the central part of the Delaware Basin and only 23 miles south of the south boundary of

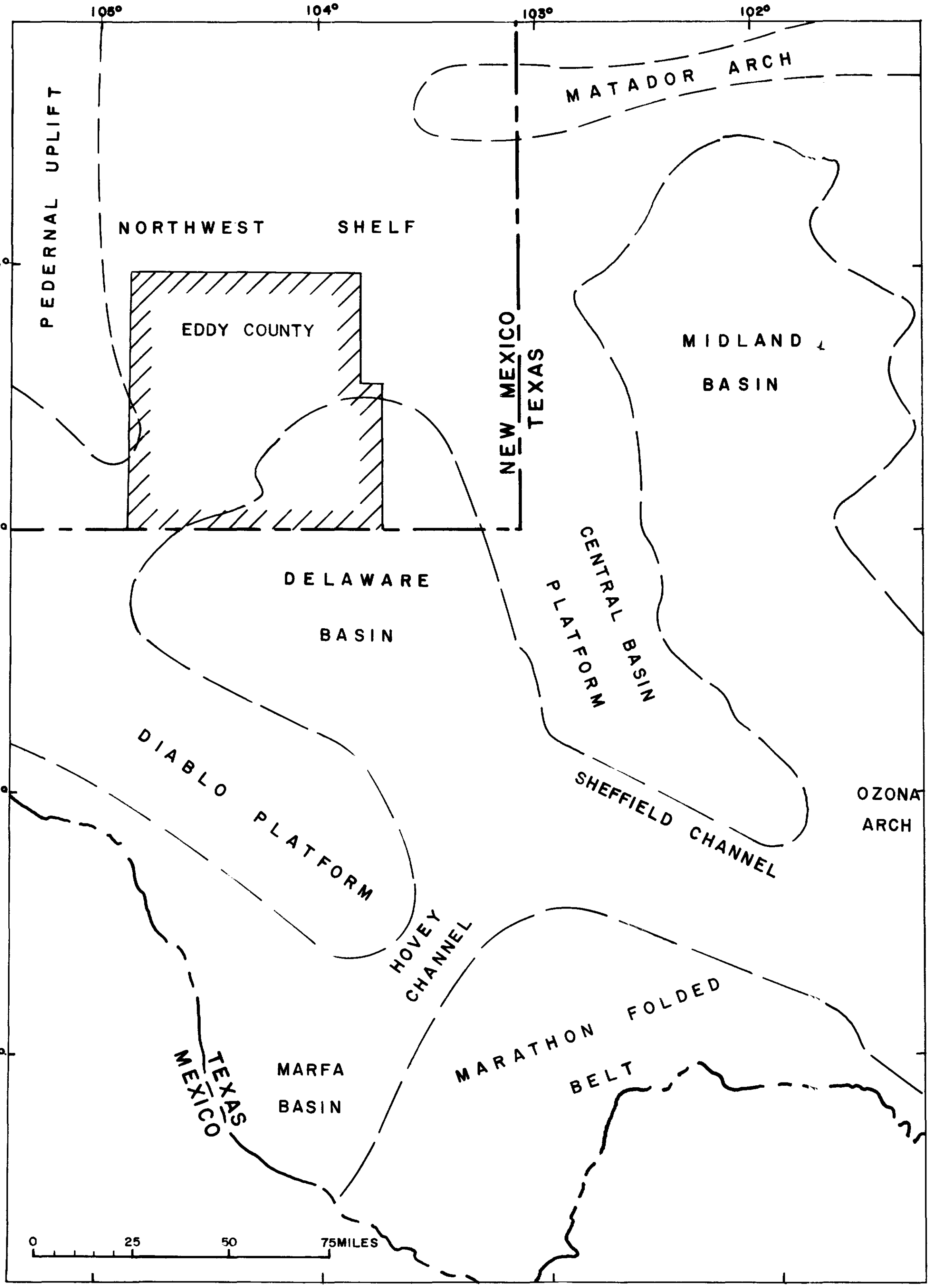


FIGURE 1.—Location of Eddy County and major tectonic features that affected Permian deposition in the Delaware Basin area.

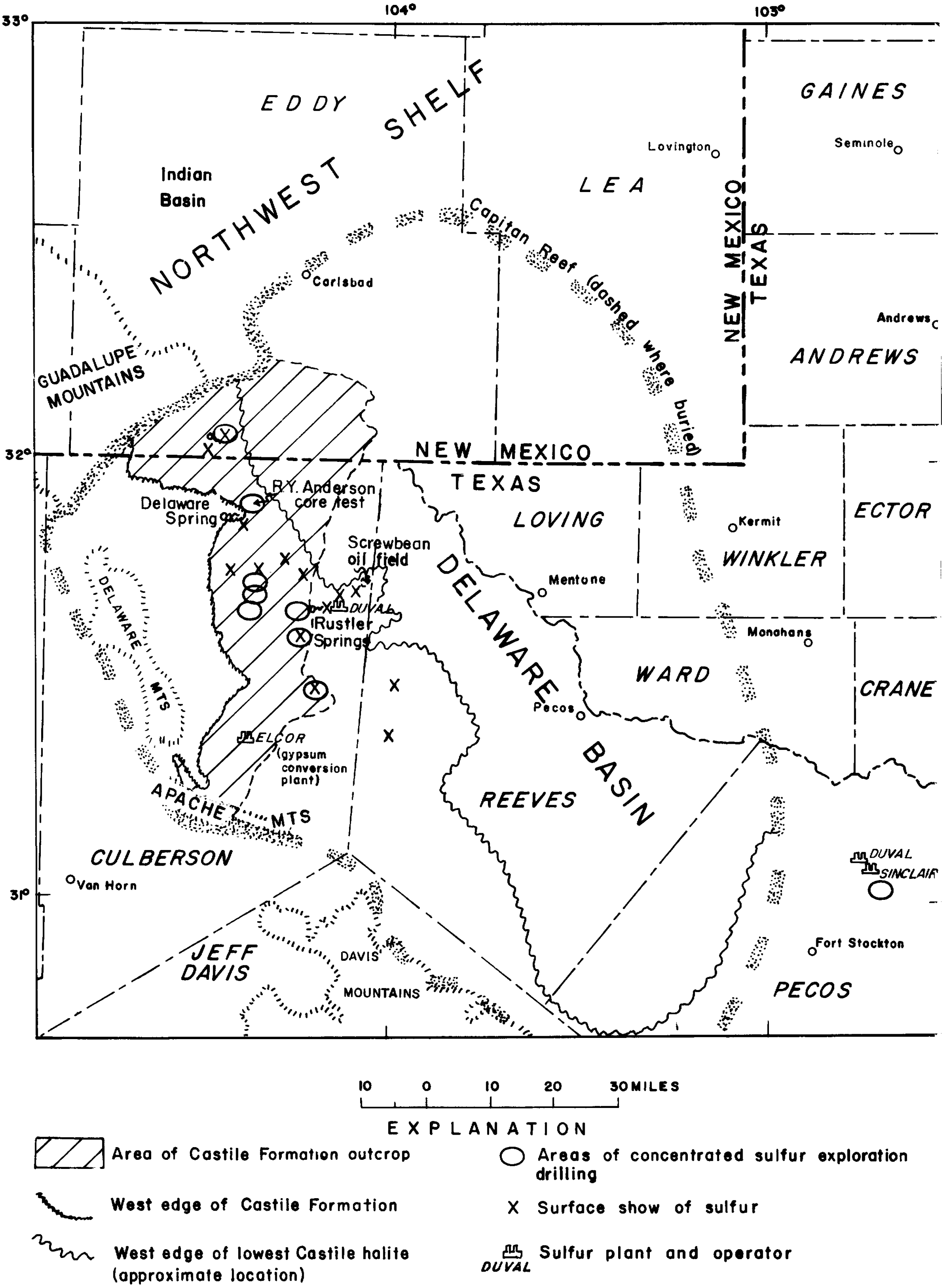


FIGURE 2.—Location of sulfur recovery plants, surface sulfur occurrences, areas of concentrated exploratory drilling, Castile Formation outcrop, and approximate position of the edge of the Castile halite.

Eddy County, N. Mex. (fig. 2). As of 1969, the sulfur boom is continuing, encouraged by high sulfur prices and the speculation fever common to all mineral booms.

PURPOSE AND SCOPE

Many articles and reports have been written concerning the sulfur deposits in Pecos, Reeves, and Culberson Counties, Tex. However, only a small amount of data is available on the occurrence of sulfur in the extreme northwestern part of the Delaware Basin and the adjacent shelf area in New Mexico. The purpose of this report is to present available information on sulfur occurrences and to discuss the geologic framework of the sulfur deposits in Eddy County, N. Mex., where most of the federally owned lands involved in the present exploration activity are located. Sulfur deposits in west Texas are discussed because the sulfur in the Permian beds of west Texas and southeast New Mexico is genetically related.

ACKNOWLEDGMENTS

We express our appreciation to the following people and organizations: Personnel of the New Mexico Bureau of Mines and Mineral Resources, particularly Mr. Robert Bieberman, for allowing free access to, and providing assistance with, the Bureau's extensive library of well-cuttings samples; Mr. Roger Anderson, Geology Department, University of New Mexico, for permission to examine cores collected by him; personnel of the University of Texas Lands Geology Department for their many helpful suggestions and hours spent in informative discussions of the west Texas sulfur deposits; and the many sulfur, oil, and mining company personnel who have contributed through many hours of discussion on sulfur in the Delaware Basin area and the problems of finding it.

HISTORY OF ACTIVITY IN EDDY COUNTY

Sulfur has been reported from scattered drill holes in Eddy County since the early 1900's. The earliest known reference to sulfur in the county is on the driller's log of a water well drilled in the town of Artesia in 1909. The log, from the files of the U.S. Geological Survey, is reproduced below:

It should be noted that many of the early drillers in Eddy County reported "sulphur water" and "black sulphur rock" in numerous wells. Water saturated with hydrogen sulfide is common in wells throughout much of the county. It is probable, however, that the reference in the Western College Well log to "sulphur and lime" at 1,172 feet indicates elemental sulfur because the standard terms "sulphur water" and "black sulphur rock" were not used.

Driller's Log
Western College Well
Sperry and Lunkins, Drillers
NW¼SE¼ sec. 17, T. 17 S., R 26 E.
Commenced: 9-1-1909

Lithology	Depth (feet)
Concrete	40
Clay and fine gravel	200
Clay	500
Rock	660
Shale	681
Hard rock	710
Hard rock	721
Shale	735
Water rock	741
Shale rock	781
Red sand rock	800
Hard lime rock	848
Very hard lime	871
Hard white lime	1,165
Sulphur and lime	1,172
Bottom of hole	1,172

Sulfur occurrences reported from drill cuttings since 1909 range from thin coatings on bedding planes to 20 percent sulfur through a 20-foot interval (reported on a sample log prepared from oil-well cuttings). The reports of sulfur in well cuttings have resulted in several surges of prospecting activity. In 1931, sulfur was discovered between 940 and 960 feet in a water well drilled by Oliver Pearson and Sons in the NW¼NE¼ sec. 8, T. 16 S., R. 25 E. Following this discovery, Union Sulfur Co. drilled five core-hole tests in sec. 8 and surrounding sections. Some sulfur was found in one of the core holes, in the NE¼NW¼ sec. 8, between 900 and 950 feet, but the holes were abandoned, and there has been no activity in the immediate area since 1932.

In 1952, the National Farmers Union drilled a well in the NE¼NW¼ sec. 13, T. 20 S., R. 26 E., on a Federal prospecting permit belonging to S. P. Yates of Artesia, N. Mex. This test was probably based on shows of sulfur reported on logs from U.S. Army Corps of Engineers and

U.S. Bureau of Reclamation damsite test holes nearby. Several shows of sulfur were found, the best of which contained 4.7 percent sulfur from a 0.9-foot interval between 1,044.8 and 1,045.7 feet. The hole was abandoned, and the permit subsequently expired.

In 1954, more than a dozen prospecting permits were issued on Federal lands in T. 16 S., R. 27 E., but no wells were drilled. In April 1964, sulfur was found between 2,580 and 2, 640 feet and between 3,010 and 3,030 feet in a well drilled for gas in sec. 6, T. 22 S., R. 24 E. On the basis of the reported sulfur shows in this well, The Atlantic Refining Co. drilled a well in the NW¼NW¼ sec. 6 in November 1966 but reported only traces of sulfur at depths of 3,015 and 3,048 feet.

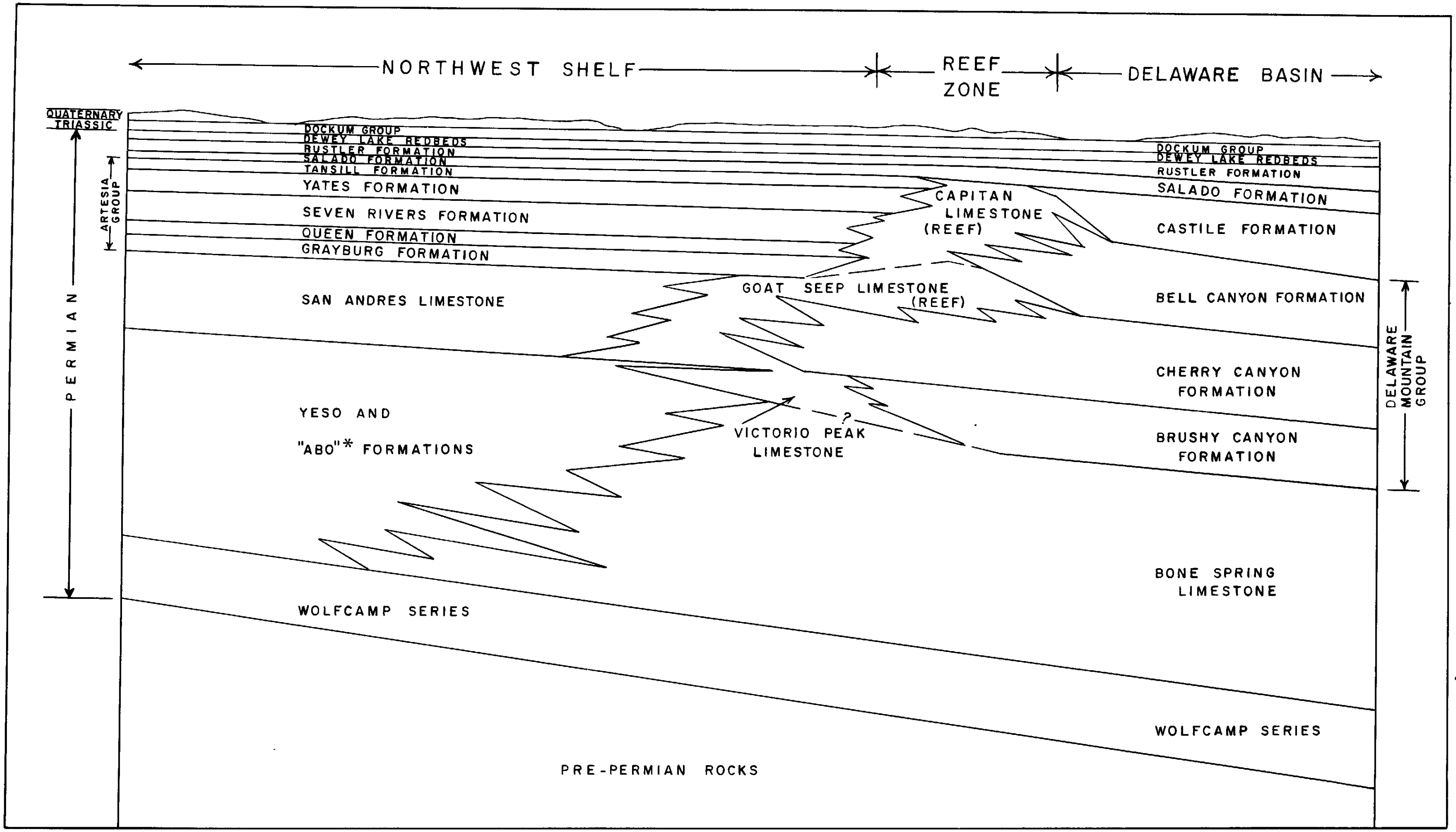
Sulfur-exploration activity in Eddy County increased rapidly after 1966 subsequent to the announcements of discoveries and plant construction in Pecos and Culberson Counties, Tex. At least 30 wells were drilled in the county from 1966 through June 1969 to test for sulfur. As of 1969, exploration activity is continuing at a moderate pace; from one to three sulfur tests are drilled monthly.

GENERAL GEOLOGY

Eddy County encompasses the northwestern part of the Permian Delaware Basin and a large part of the adjacent northwest shelf area (figs. 1, 2). Sulfur occurrences have been reported in the county at depths of 0–15,020 feet in rocks ranging in age from Silurian to Holocene. Areas of known occurrences are shown in figures 2 and 4. The only sulfur shows of present economic concern, however, are those which are found in rocks of Permian age at depths of less than 4,000 feet. Figure 3 shows the relationship between the Permian formations of the northwest shelf and the formations of the Delaware Basin. Shows of sulfur have been reported in each of the Permian formations shown in figure 3 except for the shelf-margin reefs, the Delaware Mountain Group, and the Dewey Lake Redbeds. Most of the shows reported in Eddy County are in the "Abo" (as used by some geologists), Yeso, and San Andres Formations and the Artesia Group in the shelf area and in the Castile Formation in the Delaware Basin area. The name Abo Formation has been applied by some geologists to rocks on the shelf that lie above the Wolfcamp and beneath the Yeso (fig. 3). However, these rocks are 'clearly separated from and" are "stratigraphically higher than the type Abo" (McKee and others, 1967, p. 39). Sulfur is found in the Castile, Salado, and Rustler Formations in eastern Culberson County, Tex., and in surface "acidic earth" deposits in younger rocks in western Reeves County, Tex. The deposits near Fort Stockton, in Pecos County, Tex., are reported to be in the Seven Rivers, Yates, and Tansill Formations of the Artesia Group and the overlying residuum from the Salado and Rustler Formations (Zimmerman and Thomas, 1969). Discussion in this report is limited to the Permian rock units named above, which contain the majority of the reported sulfur occurrences and are presently the prime exploration targets in the search for sulfur.

The "Abo," Yeso, and San Andres Formations and the Artesia Group are restricted to the shelf areas. They grade basinward into the Bone Spring Limestone and the shelf-margin reefs (fig. 3). In Eddy County, the "Abo," Yeso, and San Andres Formations are composed mostly of dolomite, dolomitic limestone, and a few thin beds of sandstone, shale, and anhydrite. The formations of the Artesia Group each consist of a carbonate facies adjacent to the shelf-margin-reef transition zone and an evaporite facies farther shelfward. Thus, the dominant lithology of each formation in the group grades from dolomite and dolomitic limestone and interbedded red shale and sandstone near the reefs to anhydrite, red shale, and sandstone shelfward. The Tansill Formation, the uppermost formation of the Artesia Group, also contains halite deposits in the shelfward facies (Jones, 1954).

The Castile Formation is present only in the Delaware Basin and is encircled by the Capitan Reef (fig. 2). The Castile is composed of anhydrite, calcite-banded anhydrite, halite, and limestone. The calcite-banded anhydrite, together with two massive halite intervals, composes the lower two-thirds, or about 1,200 feet, of the formation. Toward the western margins of the Delaware Basin, the lower part of the banded anhydrite unit grades reefward into a laminated limestone. The upper third, or



*As used by some geologists

FIGURE 3.—Diagrammatic section of Permian formations in Eddy County.

about 600 feet, of the formation consists of massive white anhydrite intercalated with numerous halite tongues. The halite tongues of the upper part of the formation thicken reefward and coalesce into the basal halite strata of the overlying Salado Formation (Jones, 1954). Throughout a broad area in the western and southern parts of the Delaware Basin, the halite of the Castile Formation is absent owing either to nondeposition or to subsequent removal by subsurface solution. The formation has been eroded from the extreme western part of the basin (fig. 2).

In the Delaware Basin, the Castile Formation is overlain successively by the Salado and Rustler Formations. These formations extend across the reef formed by the Capitan Limestone and, in the shelf areas, directly overlie the formations of the Artesia Group. The Salado and Rustler Formations are present only in the eastern half of Eddy County, having been truncated by erosion in the western half. The Salado Formation is composed of as much as 2,000 feet of massive halite beds and includes interbeds of anhydrite and potash salts as much as 20 feet thick and thinner beds of red shale and sandstone. The Rustler Formation consists of anhydrite, dolomite, halite, and minor amounts of limestone, siltstone, and sandstone. The soluble salts in both of these formations have been removed by solution near their areas of outcrop. In areas of extensive solution, only a thin zone of residual material from the Salado Formation separates the more-resistant dolomites and gypsum of the Rustler Formation from the Casetile Formation or the Artesia Group.

SULFUR OCCURRENCES

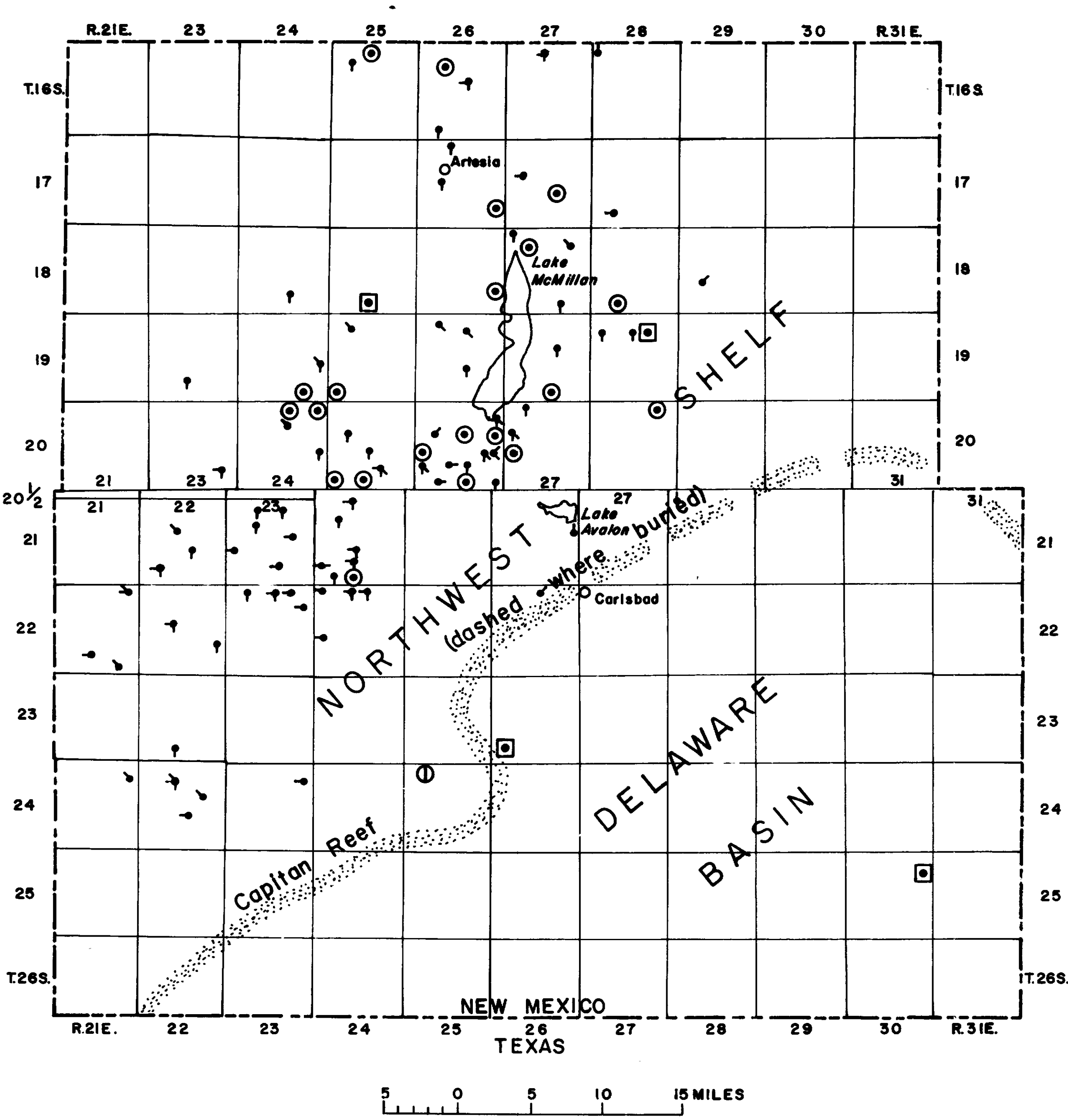
NORTHWEST SHELF AREA

"ABO," YESO, AND SAN ANDRES FORMATIONS

Areas of sulfur occurrences reported from the "Abo," Yeso, and San Andres Formations in Eddy County are shown in figure 4. Sulfur occurrences in these formations account for the majority of the reported sulfur shows in the northwest shelf area. Most of the reported shows are in the San Andres Limestone in the west-central part of the county (fig. 4). The sulfur occurs mostly in dolomite and dolomitic limestone as thin coatings on fractures and bedding planes and as small crystals in vugs and fractures. Reported amounts range from traces to more than 10 percent. Apparently, the sulfur has been deposited as a secondary mineral in zones of preexisting porosity in the dolomite. The most probable origin of the sulfur in these formations is the reduction of sulfate ions in formation waters by hydrogen sulfide, according to the following reaction: $SO_4^{-2} + 3H_2S \rightarrow 4S + 2H_2O + 2OH^{-1}$ (Feely and Kulp, 1957, p. 1846). If this is the origin of the sulfur, the sulfur deposition in the dolomites of the "Abo," Yeso, and San Andres Formations is dependent on the following factors:

1. Preexisting porosity, or the amount of void space in the rock available for sulfur deposition.
2. Permeability, or the transmissibility potential of the rock for formation waters transporting sulfate ions and hydrogen sulfide to the sites of deposition.
3. Availability of ionic sulfate.
4. Availiability of hydrogen sulfide.
5. The presence of a suitable trap, either structural or stratigraphic, which would allow the local concentration of hydrogen sulfide and ionic sulfate to reach saturation levels favorable to the progression of the reaction and the deposition of sulfur.
6. Continuing replenishment of ionic sulfate and hydrogen sulfide within the trap through the hydraulic system of the host rock.

Ionic sulfate and hydrogen sulfide are commonly found in formation waters throughout most of Eddy County. The origin of the hydrogen sulfide in the northwest shelf area is not known, but it is probably related to the action of bacteria on the widespread hydrocarbon accumulations of the area. Numerous zones of vuggy porosity with excellent permeability are found in the dense dolomites of the formations under discussion. The coincidence of these factors accounts for the widespread reports of traces of sulfur in the "Abo," Yeso, and San Andres Formations in Eddy County. Large deposits of sulfur in these formations may be expected only where conditions 5 and 6, above, are fulfilled in addition to conditions 1 through



EXPLANATION

- Yates Formation
- Seven Rivers Formation
- Queen Formation
- Grayburg Formation
- Artesia Group (formation unknown)
- San Andres Limestone
- Yeso Formation
- "Abo" Formation, as used by some geologists
- Bone Spring Limestone
- Pre-Permian formations

FIGURE 4.—Subsurface occurrences of sulfur in Eddy County.

4. The size of a potential deposit is limited only by the size of the original trap (condition 5). The grade of the deposit is limited by the original porosity within the trap (condition 1), the continuance of a supply of ionic sulfate and hydrogen sulfide (conditions 2, 3, 4, and 6), the amount of pore space filled by secondary minerals other than sulfur (mainly calcite), and the amount of pore space remaining after permeability channels have been sealed or deposition has been otherwise interrupted.

The amount of sulfur in the dolomites of the "Abo," Yeso, and San Andres Formations is not likely to be much more than 10 or 15 percent, owing to the conditions of deposition as set forth above. Even an initial porosity of as much as 32 percent, filled to three-fourths capacity with sulfur and calcite in a ratio of 3 to 1, would result in a sulfur deposit of only 18 percent. Such deposits may exist in favorable structural or stratigraphic traps in the "Abo," Yeso, and San Andres Formations in the northwest shelf area of Eddy County. The "Abo" and Yeso Formations are presently unattractive targets because of their depth of burial. The San Andres lies at moderate depths and has showings of sulfur over a broad area. The reported depths of sulfur shows in these formations range from about 600 feet in the upper part of the San Andres in T. 20 S., R. 24 E., to more than 4,000 feet in the "Abo" Formation throughout most of the area.

ARTESIA GROUP

All the formations of the Artesia Group (fig. 3) contain reported sulfur occurrences. The Seven Rivers, Yates, and Tansill Formations are reported to contain part of the ore bodies northeast of Fort Stockton, Tex. (Zimmerman and Thomas, 1969). In Eddy County there is a concentration of sulfur shows in the Grayburg, Queen, Seven Rivers, and Yates Formations around and southwest of Lake McMillan (fig. 4). The shows range from traces to more than 10 percent sulfur as reported, and they occur at depths of about 200–1,500 feet. Several samples of weathered surface material containing sulfur crystals have been brought to the Carlsbad office of the U.S. Geological Survey by individuals who reportedly obtained the samples from areas of Artesia Group outcrops. Definite locations for the source of the surface sulfur samples are not available.

The origin of most of the reported sulfur occurrences in rocks of the Artesia Group is probably the same as that proposed for the sulfur occurrences in the "Abo," Yeso, and San Andres Formations—local reduction of ionic sulfate by hydrogen sulfide in zones of previously existing porosity and permeability. Some of the sulfur in the Artesia Group, however, may have originated in place through the alteration of anhydrite to carbonate and sulfur by the metabolic processes of bacteria in the presence of hydrocarbons. This reaction apparently occurs in the caprocks of salt domes and has been discussed in detail by Feely and Kulp (1957). The sulfate-reducing bacteria, utilizing hydrocarbons as an energy source, reduce calcium sulfate to calcium carbonate and hydrogen sulfide. The hydrogen sulfide thus formed reacts further with additional sulfate ions to produce sulfur, which may be deposited in the void spaces of the carbonate rock formed by the initial reaction. The sulfur deposits of the Fort Stockton area appear to have been formed in this manner. They are found in carbonate lenses within the anhydrite beds of the Artesia Group and overlying Salado and Rustler Formations (Zimmerman and Thomas, 1969). The Fort Stockton deposits overlie structural highs in the Yates Formation. The structures provided sites for the accumulation of hydrocarbons and bacteria and subsequently for the hydrogen sulfide and sulfur. Similar sulfur deposits may occur in the shelfward facies of the formations of the Artesia Group in Eddy County.

One area which warrants further testing of the shallow Artesia Group is the vicinity of the Bluebird 2 Hackberry oil test in the SW¼NE¼ sec. 3, T. 22 S., R. 26 E. An old log of this test from the files of the U.S. Geological Survey is reproduced below:

Sample Log
Bluebird No. 2 Hackberry
SW¼NE¼ sec. 3, T. 22 S., R. 26 E.
Elevation: 3325 feet
Completed: 8–28–1926

Lithology	Depth (feet)
White limestone	32
White limestone, hard	35
Sandy yellow limestone	50
Hard dark limestone	60
Flint limestone, hard	62
Open cavern	65

Lithology	Depth (feet)
White limestone, first water at 146 feet, just enough for drilling	160
White limestone, streaks of magnesia	170
White limestone	180
Blue shale—showing of oil	188
Blue limestone	195
Blue shale, showing oil	217
White limestone	255
Blue shale, turning hard and darker	267
Oil sand, some free oil	278
Hard limestone, water at 288 feet	320
Open flowing river of water, tools dropped entire distance	345
Close yellow sandstone	355
White limestone and blue shale alternating	400
Shale	402
White limestone	409
Blue shale	411
Soft white limestone	429
Blue shale	431
White limestone	480
Blue shale	482
Broken limestone, shale water	500
White limestone	531
Cave, strong sulphur water	535
White limestone	642
Brown limestone	695
Blue shale, black sulphur above it	697
White limestone	799
Blue shale	801
Open cave, black sulphur coating tools	807
White limestone, sulphur streaks	915
Limestone, showing trace of oil	955
White limestone, streaks of sulphur and bands of shale	1,258
Total depth 1,258 feet.	
Log kept by Scott Etter, Mgr.	

This well was drilled on the south edge of a domal structure near Carlsbad, N. Mex. The association of oil shows in cavernous limestones with "streaks" of sulfur reported at 1,258 feet ii noteworthy. The well was spudded in the Tansill Formation, and its bottom at a depth of 1,258 feet is probably within the Seven Rivers Formation.

DELAWARE BASIN AREA

CASTILE FORMATION

The Castile Formation is presently the prime target of sulfur exploration in the Delaware Basin area. The formation is limited to the Delaware Basin as outlined by the trace of the Capitan Reef. The Castile has been eroded in western Culberson County, Tex., and is covered by younger rocks throughout the eastern two-thirds of the basin. The general area where the Castile is exposed in outcrop is shown in figure 2.

Most of the known surface occurrences of sulfur in the Delaware Basin are within the outcrop area of the Castile Formation. A few of the surface sulfur occurrences are east of the outcrop of the Castile in rocks of Rustler Formation age near Rustler Springs and of Cretaceous age in western Reeves County (fig. 2). The deposits near Rustler Springs apparently extend at depth into the Castile Formation. Referring to this area, Zimmerman and Thomas (1969, p. 17) stated: "There are 400 to 600 feet of massive gypsum and anhydrite beneath the Rustler Formation which is probably Salado in age. The limestone equivalent of this zone contains the most sulfur. Banded anhydrite of the Castile Formation underlies the massive gypsum and anhydrite." We believe that the "massive gypsum and anhydrite" constitute the upper massive part of the Castile Formation which overlies the banded anhydrite that makes up the lower approximate two-thirds of the formation. A thin zone of Salado residuum is probably present at the top of this interval in the Rustler Springs area; however, it appears that the major part of the ore body is within the Castile and not the Salado Formation. The sulfur in western Reeves County may also extend downward into rocks of Rustler and Castile age.

The surface occurrences of sulfur in the Delaware Basin form a general northwest trend extending from western Reeves County through eastern Culberson County, Tex., and into the southwestern part of Eddy County, N. Mex. Numerous exploratory core holes have been and are being drilled along the trend. Some of the areas of concentrated drilling activity are shown in figure 2. Zimmerman and Thomas (1969) reported that, in addition to Duval's deposit in Culberson County, Sinclair Oil Corp. (Atlantic Richfield Co.) has announced a nearby discovery (an extension of the Duval deposit); three small deposits have been delineated that have combined in-place reserves of about 800,00 long tons; and two other promising areas are being evaluated that have likely potentials of at least 1 million long tons of recoverable sulfur each. Reserve figures have not yet been released for the Sinclair strike. The latest published reserve figures for the Duval Rustler Springs deposit are 57 million long tons (Zimmerman and Thomas, 1969). Unpublished reserve estimates of 81 million tons were submitted to the Texas Land Commissioner in 1969 for the combined Duval-Sinclair deposits for the purpose of unitizing operations.

The sites of sulfur deposits in the Castile Formation are cavernous masses of brecciated secondary carbonate rock which locally replace the massive and laminated anhydrite typical of the formation. The secondary carbonate buildups are usually roughly circular in plan view although their shapes vary greatly. They extend vertically, in some places, to the base of the Castile Formation where they rest on apparently normal and undisturbed beds of the Delaware Mountain Group. These carbonate masses, appropriately named "castiles" (Adams, 1944, p. 1606), form resistant topographic features in areas where they have been exposed by erosion. Several dozen castiles were mapped in surface exposures by King (1949). Several others, which do not crop out, have been discovered in the subsurface by drilling operations. The following are examples of these castiles:

1. The Screwbean oil field (fig. 2), reported to produce from a reservoir in a subsurface castile (West Texas Geological Society, 1960, p. 23).
2. A sulfur deposit in the southern part of block 61, township 1, Texas and Pacific Survey, Culberson County, Tex., discovered by R. Y. Anderson of the University of New Mexico in a well drilled in connection with a study of the laminations of the Castile anhydrite. The approximate location of Anderson's core hole is shown in figure 2. Normal gypsum and anhydrite of the Castile Formation were penetrated in the first several hundred feet of the Anderson hole. At a depth of about 666 feet, this hole penetrated cavernous carbonate rock typical of the castile masses. Sulfur is present in the Anderson hole at depths of 666–735 feet. The interval between 725 and 735 feet contains more than 20 percent sulfur. This deposit has been extensively drilled by Texaco and other companies with adjacent leases.
3. The main ore zones at the Duval mine site near Rustler Springs are evidently in a castile-carbonate buildup underlying and extending into the Rustler Formation.
4. The sulfur deposits northeast of Fort Stockton. Although the deposits occur in evaporites of the Artesia Group and the Rustler Formation, they are in castilelike masses of cavernous carbonate enveloped by anhydrite. Their origin is probably the same as that of the castiles in the Castile Formation.

Several origins have been proposed to account for the castiles. The West Texas Geological Society (1960, p. 23–24) stated:

> The unusual physical appearance of the masses, the lack of bedding and the presence of random fragments of banded lower Castile imbedded in the limestone matrix, all contribute to the difficulty in explaining their origin. Metasomatism (replacement) has been suggested by several geologists who have given them considerable study. This is the process of practically simultaneous capillary solution and deposition by which a new mineral of partly or wholly differing chemical composition may grow in the body of an old mineral or mineral aggregate. This process seems a logical explanation because of the numerous small faults and jointings found in the rocks of the Delaware basin. Water for the replacement process could come up through these breaks.

Another explanation is that the castiles are the cores of collapse features (sinkholes). The highly brecciated nature of the bodies and the considerable clay filling found in some of the castiles support this hypothesis. However, it is difficult to explain the subsurface castiles that are overlain by several hundred feet of undisturbed and unaltered anhydrite and other rocks. The origin of these castiles may be explained by collapse from below, or natural stoping, due to subterranean solution below the undisturbed strata. The collapsed debris could be altered subsequently by metasomatism.

We believe that an adequate explanation of the origin of the castiles must take into account the close association of the carbonate masses with hydrocarbons, sulfur, and hydrogen sulfide gas. Although not all the castile-carbonate mounds examined by us in the field contain elemental sulfur, nearly all the carbonate rock has a characteristic odor of hydrogen sulfide when freshly broken. Our tentative hypothesis is that the brecciated castile masses are formed by collapse due to solution from below. If collapse continues long enough, the stope reaches the surface and results in an ordinary sinkhole which permits the entrance of surface waters carrying sand, clay, and colloids into the collapse chimney. During the course of its formation by upward stoping, but before it is vented by fractures to the surface, the collapse chimney may become a trap for upward migrating hydrocarbons and hydrogen sulfide gas. The anhydrite breccia in the chimney may be converted in part to carbonate by reduction by bacteria and hydrocarbons in the same process ascribed to the forming of carbonate and sulfur in the caprocks of salt domes (Feely and Kulp, 1957). Reduction of the anhydrite yields carbonate and hydrogen sulfide. If the chimney vents, most of the hydrogen sulfide escapes into the atmosphere. If the chimney does not vent, the hydrogen sulfide may be trapped and oxidized by reaction with sulfate ions to yield elemental sulfur, which is deposited in the fractures and vugs of the previously formed carbonate. Recrystallization of the limestone in laminae and metasomatic replacement of anhydrite between limestone laminae are also evidently part of the castile-forming process.

Whatever their origin, the porous carbonate masses enveloped by impermeable Castile anhydrite are the sought-after traps in which elemental sulfur in some places fills voids and solution channels. Several of these carbonate bodies are present in southwestern Eddy County within the area of the Castile Formation outcrop. Most of them are unmapped. We have found traces of sulfur associated with the castile carbonates at the surface in three separate areas in New Mexico, and, as previously stated, the odor of hydrogen sulfide gas is common from freshly broken surfaces of the carbonate rock. The chances are good that unexposed castile masses are present in the vicinity and may be the sites of sulfur deposition. It is possible that some of the exposed castiles contain sulfur mineralization at depth or in isolated pockets.

It is worth emphasizing here one feature related to, or coincident with, the location of all the castile-carbonate bodies of which we are aware. In the central parts of the Delaware Basin, the Castile Formation contains several thick beds of crystalline halite. Along the west and south sides of the basin, the halite beds either were never deposited or have been removed by subsurface solution. All the limestone castiles and all the surface and subsurface sulfur deposits of which we are aware lie beyond the present edge of the lowest Castile halite. The approximate position of the edge of the Castile salt, as determined by Henry Snider (1965), is shown in figure 2. The spatial relation of the salt edge and the castiles and sulfur areas is obvious. It appears that the most promising area to look for host rocks and sulfur-ore bodies is in the zone between the eroded edge of the Castile Formation and the edge of the Castile halite (fig. 2). This is the zone of most pronounced subsurface solution, and if the origin of the castile-carbonate buildups is due to solution and collapse, then it is in this zone that the most and largest subsurface castiles are likely to be found. We do not mean to imply, however that they cannot exist in areas where salt is still present or within the anhydrite of other formations. All that appears essential to their formation is: (1) a thick section of anhydrite, (2) extensive subsurface solution and collapse, (3) availability of hydrocarbons and sulfate-reducing bacteria to reduce the brecciated anhydrite to carbonate and hydrogen sulfide, and (4) maintenance of a seal over the trap to prevent the escape of the hydrogen sulfide, assuring its further reaction with ionic sulfate to produce sulfur, and to protect the sulfur deposit from further reaction and removal.

One location near the present salt edge which we believe warrants testing is a hill in sec. 5, T. 26 S., R. 25 E., New Mexico principal meridian, New Mexico. This hill known as C. P. Hill, is capped by remnants of bedded dolomite of the Rustler Formation. The hill is not unique in this respect, because there are numerous topographic remnants capped by Rustler dolomite 10 miles to the east near the main Rustler outcrop. What appears unusual is the preservation of these Rustler rocks in an isolated hill (actually a cluster of small hills) so far west in an area of considerable erosion of the Castile Formation. We believe that the preservation of this Rustler outlier may be due to local subsidence prior to the erosion of the Rustler Formation in this area. Its existence may be an indication of solution and subsidence at depth in the Castile Formation, which, in turn, would be a favorable indication of the possible presence of a subsurface castile. The area is presently untested. Several other anomalous areas in the southwestern part of Eddy County have equal possibilities.

SALADO AND RUSTLER FORMATIONS

Sulfur in the Rustler Formation and in residuum from the solution of Salado beds forms part of the ore bodies northeast of Fort Stockton and at the Rustler Springs site in Texas. The sulfur in the Rustler and Salado at these localities appears to represent the upward extension of castile-type carbonate-ore zones, most of which are in the underlying anhydrite of the Artesia Group (at Fort Stockton) and the Castile Formation (at Rustler Springs). We believe that favorable conditions for sulfur deposition may occur elsewhere in the Salado and Rustler Formations in areas of extensive subsurface solution. We think, however, that all the prerequisite conditions necessary for sulfur accumulation occur less commonly in the Rustler and Salado Formations than in the massive anhydrites of the Castile Formation and the Artesia Group. The critical factors limiting possibilities in the Rustler and Salado are probably the lack of available hydrocarbons within prospective traps and the lack of effective seals over the traps.

REFERENCES CITED

Adams, J. E., 1944, Upper Permian Ochoa series of Delaware Basin, west Texas and southeastern New Mexico: Am. Assoc. Petroleum Geologists Bull., v. 28, no. 11, p. 1596–1625.

Feely, H. W., and Kulp, J. L., 1957, Origin of Gulf Coast salt-dome sulphur deposits: Am. Assoc. Petroleum Geologists Bull., v. 41, no. 8, p. 1802–1853.

Jones, C. L., 1954, The occurrence and distribution of potassium minerals in southeastern New Mexico, *in* New Mexico Geol. Soc. Guidebook, 5th Field Conf., Oct. 1954: p. 107–112.

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

McKee, E. D., Oriel, S. S., and others, 1967, Paleotectonic investigations of the Permian System in the United States: U.S. Geol. Survey Prof. Paper 515, 271 p.

Porch, E. L., Jr., 1917, The Rustler Springs sulphur deposits: Texas Univ. Bull. 1722, 71 p.

Richardson, G. B., 1905, Native sulphur in El Paso County, Texas, *in* Contributions to economic geology, 1904: U.S. Geol. Survey Bull. 260, p. 589–592.

Snider, H. L., 1965, Stratigraphy and associated tectonics of the Upper Permian Castile-Salado-Rustler evaporite complex, Delaware Basin, west Texas and southeast New Mexico: N. Mex. Univ., unpub. doctoral dissert., 196 p.

West Texas Geological Society, 1960, Geology of the Delaware basin and field trip guidebook, Sept. 29–Oct. 1, 1960: Midland, Tex., 97 p.

Zimmerman, J. B., and Thomas, Eugene, 1969, Sulfur in West Texas—its geology and economics: Texas Univ. Bur. Econ. Geology, Geol. Circ. 69–2, 35 p.

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