BUREAU OF ECONOMIC GEOLOGY

Geological Circular 69-2

Sulfur in West Texas: Its Geology and Economics

By

J. B. ZIMMERMAN and EUGENE THOMAS

The University of Texas at Austin

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James B. Zimmerman[1/] and Eugene Thomas[2/]

INTRODUCTION

Sulfur, along with salt, coal, and limestone, is one of the basic raw materials of the chemical industry. A nation's per capita sulfur consumption is a reliable index to its chemical production and a rough index to its standard of living. Sulfur, with its many properties, has literally hundreds of uses; most is used in the manufacture of fertilizers, fibers, papers, pigments, pharmaceuticals, and explosives.

Sulfur or brimstone is one of the oldest elements known to man. It was used more than 4,000 years ago in rituals of sacrifice and as a bleaching agent for cotton. The Chinese, around 500 B.C., used sulfur as an ingredient in gunpowder. Arabian alchemists are thought to have discovered sulfuric acid in the 8th Century while trying to convert sulfur to gold.

Sulfur became commercially important in 1791 with the development of the Leblanc soda ash process in France (Ambrose, 1965, p. 901). The sulfuric acid industry, which began in the United States near the end of the 18th Century, now uses about 87 percent of the total production.

Sulfur plays an increasingly vital role in American industry and agriculture. The 1966 sulfur shortage motivated a re-evaluation of West Texas' geologic and economic potential for sulfur production and a re-examination of its lengthy but spasmodic sulfur history.

The occurrence of sulfur in West Texas was first reported in Culberson County in 1854 by William P. Blake, a geologist attached to the War Department (Evans, 1946, p. 5). The first detailed investigation of the surface occurrences in Culberson County was made by G. B. Richardson about 1903. According to Richardson (1905, p. 590), a furnace was constructed in Culberson County about 1900 for extracting sulfur from surface deposits. Two or three carloads of refined sulfur were shipped before the operations were discontinued.

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E. L. Porch (1917) made an extensive study of the surface sulfur occurrences in Culberson and Reeves counties in 1916. He visited and described eighteen locations in detail and discussed eight others (fig. 4, p. 15). He stated that the surface deposits were being mined once again (1917) and that 40 tons of native sulfur had been shipped to market from the Michigan mine. This project was abandoned soon afterwards, probably due to the abrupt drop in market prices following World War I.

In 1900, a deposit of native[3/] sulfur was discovered in Pecos County in the Turney well (Adkins, 1927, pp. 102, 103; Richardson, 1904, p. 65; Udden, 1917, pp. 2-3). A lack of the necessary fuel and water for Frasch mining caused abandonment of the project. It is rumored that Frasch mining was tried in this well, but the rumor could not be substantiated.

Glen L. Evans, in his study of the Rustler Springs district, described some of the acidic sulfur earth deposits and discussed their use as a source of mineral fertilizer (Evans, 1946).

A brief drilling program was conducted by Freeport Sulphur Company in Culberson and Reeves counties during 1948 and 1949 without promising results.

In 1967, large scale sulfur exploration began in West Texas after Duval Corporation's Frasch pilot operation near Fort Stockton proved successful.

In August of 1967 Elcor Chemical Corporation and its subsidiary, National Sulphur Company, announced plans to construct a facility in Culberson County to extract sulfur from gypsum. Although gypsum-based sulfur plants have been constructed in foreign areas where sulfur is a high-cost, high-producing commodity, the Elcor facility is the first domestic operation to undertake commercial extraction of sulfur from gypsum. The plant, known as the Rock House Facility, was scheduled to start operation early in 1969 at a production rate of 1,000 tons of sulfur per day (p. 31).

Traditionally, sulfur exploration has come to West Texas only during times of short supply and higher prices. Attractive prices more than any other factor cause exploration. Nothing seems to fire the prospecting zeal of the explorationist more quickly than a price increase. Conversely, nothing will stop exploration any faster than a decline in market prices.

Acknowledgments.--The writers wish to thank the many individual employees of the oil and mining companies in Midland for their time and assistance

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3/ Industry refers to sulfur as "elemental" when it is used in a pure form even though it may have been separated from compounds (Hazleton, MS., p. 2). Due to this corruption of the word, the writers have used the term native sulfur when referring to sulfur in the natural state.

both in the office and field, and especially to thank: Sinclair Oil and Gas Company for the sample logs from their Fort Stockton property; Allied Chemical Corporation and Roden Oil Company for information about their Christoval area pilot project; F. Alan Ferguson and M. C. Manderson for so kindly furnishing copies of their discussions; John M. Hills and John Emery Adams for their comments on the stratigraphy of the Ochoa Series in eastern Culberson County; and Jared E. Hazleton for a copy of his manuscript to be published soon by Johns Hopkins Press.

REVIEW OF SULFUR PRODUCTION, DEMAND, AND ECONOMICS

Free World supplies.--Sources of sulfur in the Free World are enormous; 0.06 percent of the earth's crust is sulfur. For example, it is estimated that coal in minable deposits in the United States alone contains 5,000 million tons of sulfur (Ambrose, 1965, p. 909), but most sulfur in the earth's crust is not economically recoverable. The major current sources of Free World sulfur are native sulfur produced by the Frasch process, sulfur recovered from natural gases, and sulfur recovered from sulfide ores. Free World production for 1968 was 27.4 million long tons. Of this total, about 36 percent was Frasch sulfur, about 27 percent came from sulfide ores, about 25 percent was recovered from sour gas and oil, and the remaining minor amounts came from native sulfur, gypsum, industrial gases, and industrial processes such as desulfurization of residual fuels.

About 25 countries in the Free World produce sulfur. The United States as leader produces about 35 percent of the Free World total. Other leading producers are Canada, Mexico, and France.

Canada, which used to import sulfur, is now an exporter and will probably increase its exports to the Free World significantly. Canadian total output increased from 2.2 million long tons in 1967 to 3.1 million long tons in 1968, a 40 percent increase (Oil & Gas Journal, Jan. 27, 1969, p. 97). Recovered sulfur plant capacity in Canada is over 5 million long tons per year (Grekel et al., 1968, p. 88). In 1967 the United States imported 750,000 long tons of sulfur from Canada; 820,000 long tons were imported in 1968. These imports could easily double in a few years.

The Canadian reserves are located in western Canada far from water. The sulfur must be shipped by rail to the West Coast at a cost of $8 per long ton. Shell Canada is making a feasibility study on transporting sulfur by pipeline in a slurry of crude oil or condensate, which may reduce transportation costs by one-third (Daily Oil Bulletin, 1968). If feasible, the pipeline will run from the gas fields in western Alberta to Vancouver. The reserves of sulfur in the Athabasca tar sands in Alberta, which are quite large, will also be a future competitive factor.

Mexico produced about 1.6 million long tons of sulfur in 1968, down from 1.8 in 1967. However, prospects for new discoveries of sulfur in that country are good; 724,000 long tons were imported from Mexico in 1967 and about 750,000 long tons in 1968. These imports are also expected to grow.

France currently produces about 1.6 million long tons annually. France is an exporter of sulfur but will probably not increase its exports significantly. French production has risen very gradually from 1.3 million long tons in 1962.

African and Middle East countries are expected to add an additional 1 million tons to their total sulfur output by the end of 1971 (Manderson, 1968, p. 10). Other countries of the Free World which are expected to increase their combined outputs of sulfur during 1969 and 1970 by about 1.2 million long tons are Italy, Spain, Venezuela, Japan, India, and the Philippines.

In 1968, the Free World imported 600,000 long tons of sulfur from Communist countries (Oil & Gas Journal, 1969). These imports may increase due to enlarged capacities in Poland.

Most of the above-listed areas and countries, unless otherwise noted, are expected to continue increasing their outputs.

In addition to these future expansions, large deposits of native sulfur in Iraq and in the Andes Mountains of South America are regarded as excellent prospects for exploitation. The Iraqi reserves are estimated at more than 200 million long tons. Estimates of recoverable reserves from the Andes Mountains are as high as 100 million long tons (Eng. & Min. Jour., 1968).

Frasch sulfur.--Dr. Herman Frasch invented the process bearing his name and supervised an experiment in 1894 which proved that molten sulfur could be pumped from deep underground formations. Eight years later, his process was recognized as a commercial success. In theory the process is a simple one wherein water heated to about 330° F. is injected into the sulfur-bearing rock and the temperature of the formation is raised above the melting point of sulfur. Melted sulfur, being heavier than water, separates from the water and flows to the base of the well where it is lifted to the surface by air.

Three strings of pipe inside the casing are used in one well to accomplish the entire process. Normally, the three strings of pipe measure about 8 inches, 4 inches, and 1 inch, respectively, in diameter. The smaller inside string carries compressed air. Super-heated hot water is injected down the space between the 8-inch and 4-inch pipes and the sulfur is returned to the surface between the 1-inch and 4-inch pipes. Bleedwater wells are used either to remove excess water from the formation or to reduce excessive pressures. Since the viscosity of melted sulfur rises with temperature, the temperature of the injected water must be closely controlled in Frasch mining.

Commonly, in order to prevent water loss by channeling and to keep the hot water in contact with the sulfur, it is necessary to seal cavities and fractures with mud. The molten sulfur also helps seal lost circulation zones around the production well. As sulfur moves away from the well and heat source, it cools and returns to the solid state.

Before 1900, Sicily, with its large deposits of native sulfur, held a virtual monopoly in world trade (Ambrose, 1965, p. 901). The extraction of sulfur from sulfide ores (pyrites) began in the 1880s when the Sicilian combine raised prices 300 percent. The invention of the Frasch process revolutionized sulfur mining and resulted in the United States becoming the world's leading sulfur producer in 1913, a position which it still enjoys. Prior to Frasch mining, all sulfur consumed in this country was either produced domestically from pyrites or imported. By 1904, Frasch had captured 50 percent of the total domestic market, and since the early 1920s it has provided from 70 to 90 percent of the total output. Prior to the West Texas Frasch production, all Frasch sulfur was produced from salt domes along the Gulf Coast. As of January 1, 1968, the United States salt domes had yielded more than 180 million long tons of native sulfur. Frasch sulfur accounted for about 35 percent of the total Free World production of 27.4 million long tons in 1968. The total output of sulfur in the United States in 1968 was 9.8[4/] million long tons, composed of 77 percent Frasch (fig. 1).

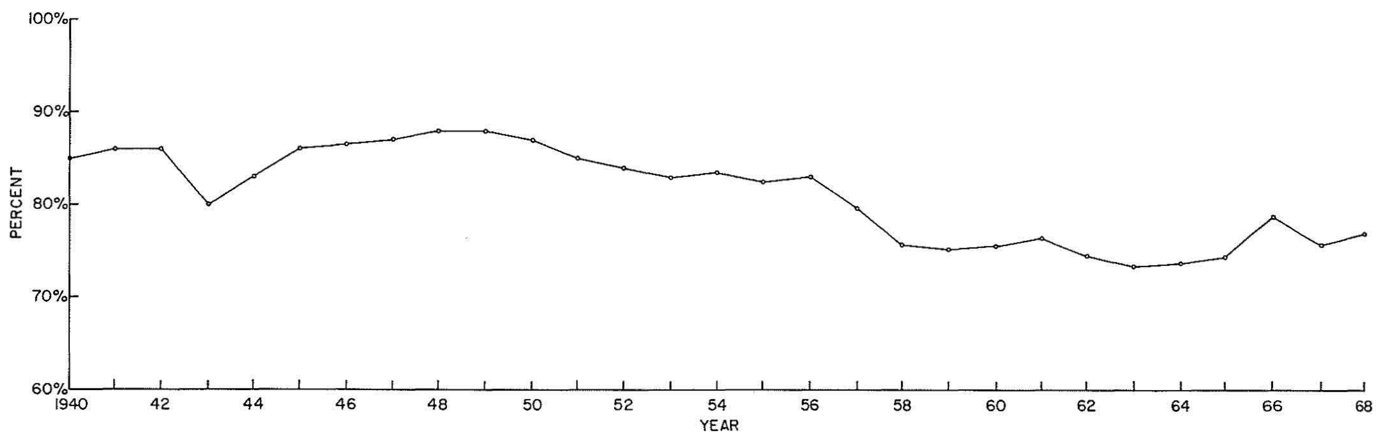

Fig. 1. Production of Frasch sulfur in the United States, 1940-1968.

The recoverable reserves from domestic salt domes are estimated to be about 70 to 80 million long tons based on present prices. Annual Frasch production for the last three years has leveled off at about 7 million tons. Based on a projected production rate for 1975 of about 14 million long tons total output, Frasch production will have to increase from about 7 million to over 10 million long tons annually by that time in order to retain its share of the market (fig.2).

Mexico produced about 1.6 million long tons of Frasch sulfur in 1968. The Mexican reserves are unknown but are thought to be less than 65 million long tons. New Frasch discoveries will probably be made in Mexico.

New discoveries of Frasch reserves may come from the off-shore salt domes in the United States but at increased costs. One sulfur company spent nearly 15 million dollars in 1966 and 1967 searching for sulfur on off-shore salt domes without finding any commercial amounts (Oil & Gas Journal, 1967).

4/ All 1968 production figures for the United States are estimates based on the first eleven months of actual production as released by the U. S. Bureau of Mines.

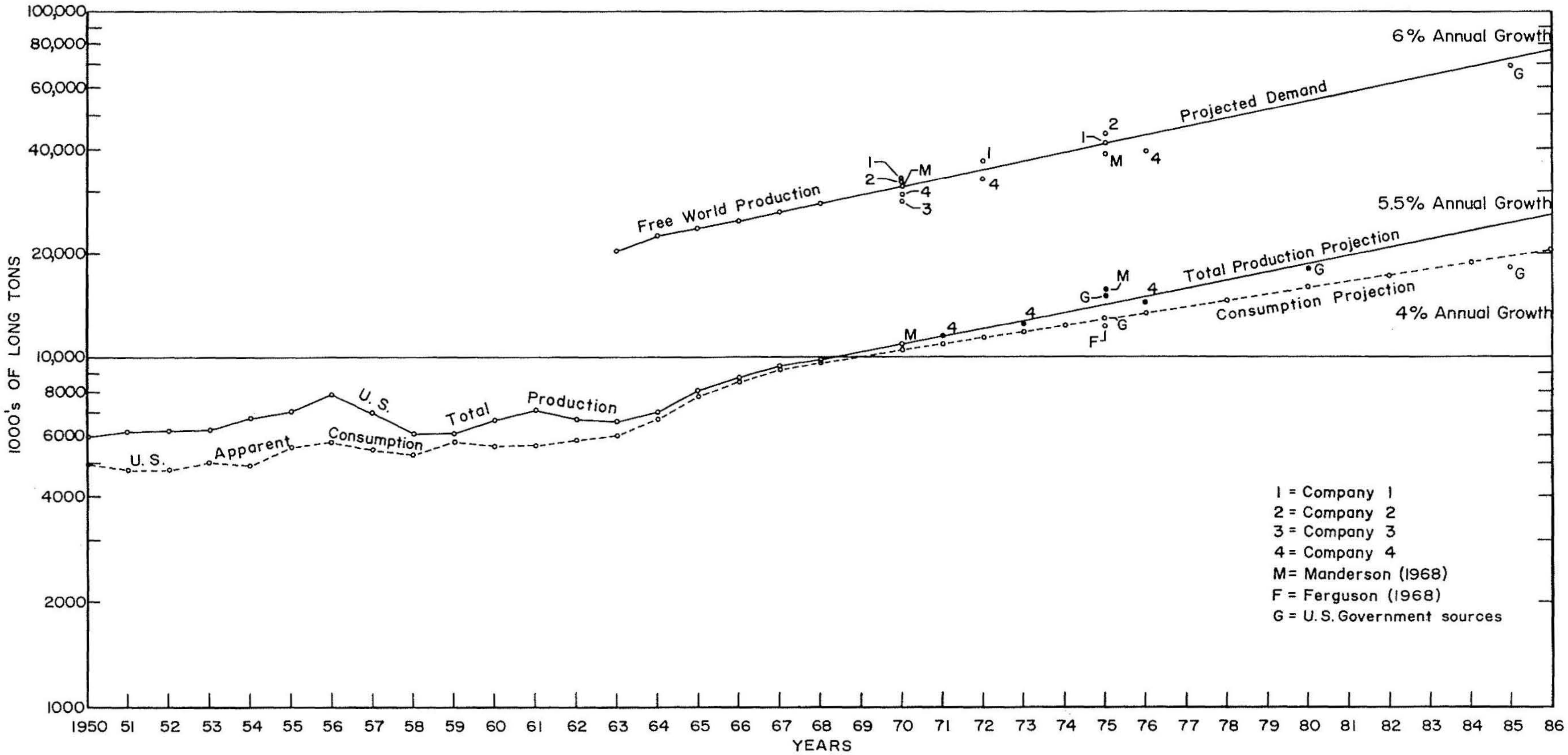

Fig. 2. United States and Free World sulfur production and consumption, with projected demands through 1986. Production figures from U. S. Bureau of Mines, Blue (1968), and Hazleton (MS.).

Experimental Frasch mining was commenced in Poland about two years ago. Although still labeled experimental, it is apparently successful, because Frasch production is now reported as more than 2,000 tons per day (Sulphur, 1968, p. 10).

Original doubts as to whether the Frasch method would be successful in the West Texas area were dispelled when the process was tried at the Duval and Sinclair mines in Pecos County near Fort Stockton. In addition, in 1968 Duval operated a pilot plant successfully at their Culberson County mine west of Orla, and Allied Chemical recovered sulfur in a small pilot operation in Tom Green County near Christoval. The newly discovered West Texas reserves will enable Frasch production to maintain its position as a leading source of sulfur in the Free World.

Announced Frasch reserves in West Texas are about 61 million long tons based on present prices. In addition, Sinclair Oil Corporation has announced a discovery just south of Duval's strike in Culberson County on which no reserve figures have been released. Two other areas have promising potential and are being evaluated at present; each of these locations is likely to contain at least 1 million long tons of recoverable reserves. Drilling has also revealed some smaller deposits of less than 1 million long tons recoverable sulfur. Three small deposits have been delineated in Culberson County with combined in-place reserves of about 800,000 long tons. These additional reserves should raise the total domestic Frasch reserves to about 140 million long tons, or a ratio of reserves to annual production of about 14 to 1. Barring new discoveries of reserves which can be mined by the Frasch process and assuming an increase in demand, any surplus capacity created by the West Texas discoveries should be relatively short lived.

Recovered sulfur.--West Texas is also a leading producer of sulfur recovered from sour gas. It is only in recent years that recovered sulfur has become important in the United States. The first commercial operation in West Texas commenced at Odessa in 1952 (Hazleton, MS.). Domestic production of recovered sulfur reached 1 million long tons in 1964 and rose gradually to 1.4 million long tons in 1968. Texas produces more than one-half of the recovered sulfur, with 390,000 long tons coming from West Texas alone. Estimated reserves of sulfur in sour gas in the United States are about 25 million long tons. Annual production is expected to be about 2.1 million long tons by 1975 (Manderson, 1968).

Sulfur recovered from sour gas is normally thought of as a by-product. However, some of the Canadian gas contains very high percentages of hydrogen sulfide. Sulfur is a by-product when the hydrogen sulfide is less than 10 percent; at 10 to 20 percent hydrogen sulfide, gas and sulfur are co-products; and when gas contains more than 20 percent hydrogen sulfide, the gas becomes a by-product (Hazleton, MS.).

Canada and France are the other major producers of recovered gas. Canadian reserves of sour gas are estimated at 60 to 80 million long tons.

Future demand.--Figure 2 shows projections for future Free World demand, United States total output, and United States demand for sulfur through 1986. They are based on some government projections and predictions by four sulfur companies and two research concerns.

The projections show 4 percent per year for annual growth of United States demand, 5.5 percent per year for United States total output, and 6 percent per year for Free World demand. These projections show United States production doubling by 1981 and Free World production doubling by 1980. The projections for the United States may prove conservative, since production grew at an annual rate of 5.3 percent between 1969 and 1967 and at an annual rate of 8 percent between 1963 and 1967.

Consumption of sulfur in the United States is impossible to determine exactly because of the difficulty in obtaining complete information pertaining to changes in stock, changes to liquid deliveries, sulfur equivalent reconstituted from acid sludge, and amounts recovered from smelter gases and other pollutant sources (Hazleton, MS.). However, it is felt that U. S. consumption and total output have been about equal since 1965 (Blue, 1968).

During the recent shortage, the domestic sulfur companies voluntarily curtailed exports. Future projected production is higher than projected consumption because the industry is expected to regain its export position. Most forecasters feel that Free World demand is the better guide to future United States output, since the industry is a net exporter and competes throughout the Free World. Freeport Sulphur Company, Texas Gulf Sulphur, Jefferson Lake Sulphur, and Elcor Chemical Corporation are members of Sulphur Export Corporation (Sulexco).

Most forecasters used a spread rather than one figure in their predictions. Only the median was posted on figure 2. Manderson (1968) expects United States demand to grow at 3.5 percent annually through 1975 but feels the rate could vary from 2.25 to 4.75 percent. Ferguson (1968) estimates U. S. consumption in 1975 from 11.5 to 13 million long tons. A Government forecast estimates that domestic demand will grow annually from 3.85 to 5 percent.

Most forecasters expect fertilizer demand to grow rapidly and base their predictions upon annual growth rates in phosphatic fertilizer of 6 to 10 percent in the Free World. Since about 50 percent of the domestic consumption is used as fertilizer, demand for sulfur is heavily dependent upon this one industry. Any event which prohibits the expected growth in fertilizer demand will upset all predictions, because growth rates in other uses are expected to remain low. A future increase in the direct application of sulfur to the soil may increase fertilizer consumption to an even greater extent (Hazleton, MS.).

The recent shortage was not too well anticipated by most producers and seemed to be somewhat of a surprise to the users. The intricate relationships between supply and demand throughout the world are difficult to predict. Obviously, most predictions are based on an extrapolation of past production history rather than on a detailed analysis of the separate demand constituents. Extrapolation is possibly the only practical method, since detailed information from throughout the world is difficult at best to obtain and impossible to get in many instances.

It is now clear that sulfur users who placed orders with abandon during the recent shortage retreated to a more conservative posture as supplies improved. Such actions serve to magnify the extremes of supply and demand. Probably the shortage was not so acute and, by the same token, any over-supply may be exaggerated.

Prices.--Many factors were responsible for the 1964-1968 sulfur shortage which was accompanied by a 65 percent rise in market prices and promoted an intensive domestic exploration for sulfur. The accelerated increase in fertilizer demand was not completely anticipated. The domestic Frasch producers could not increase production rapidly enough to meet demand. No new reserves were found in the off-shore salt dome search. By early 1968 some sulfur users were being prorated to as little as 65 percent of their 1965 purchases. Mexican imports were not as large as had been anticipated. In addition, Mexico curtailed exports of sulfur to promote growth of Mexican sulfur-consuming industries. Development of other foreign deposits, such as those in Iraq, has been delayed due to political considerations.

During World War I when sulfur mining was first tried in West Texas, the market price was above $40 per long ton f.o.b. mine. Prices then dropped rapidly to an average annual price of $14 in 1922 and remained below $20 until 1950. Prior to 1950, the large sulfur companies began to explore in West Texas once again in anticipation of higher prices. The price freeze during the Korean War discouraged further exploration. The average annual posted price rose to $26.50 in 1956, but the impact of Mexican imports caused a reduction in prices of about $3 which was not overcome until 1964. At that time the U. S. Bureau of Mines estimated that 10 to 30 million long tons of recoverable sulfur were present in West Texas based on a market price of $35 per long ton (Netzeband et al., 1964). Prices rose to $42 per long ton in 1968. This strong 1964-68 price increase encouraged the exploration boom in West Texas.

Before 1958, the posted price generally meant f.o.b. mine. After the change to mostly liquid deliveries, the price was usually quoted as f.o.b. delivered or f.o.b. Gulf Coast. For sulfur produced on the United States Gulf Coast, the posted price is normally close to the realized price. However, posted price may include freight and other distribution costs, depending upon conditions of supply and demand.

All information concerning posted prices included in this paper was obtained from the Bureau of Mines or Hazleton (MS.).

Prices have slipped back to about \$38 per long ton with some small lots selling for less. It is generally believed by industry observers that prices will soften during the next one or two years but should stabilize in the \$35 to \$40 range over the long run. A projection of future prices in a governmental study postulates a price range of \$34 to \$40 through 1980.

F. Alan Ferguson, Industrial Economist of the Stanford Research Institute, in his discussion of future sulfur sources, concludes, "Therefore, we expect the price of sulfur--if it declines--to stay between \$30 and \$40 per long ton (in constant 1967 dollars), f.o.b. Gulf Coast between now and 1975" (Ferguson, 1968).

M. C. Manderson, of Arthur D. Little, Incorporated, warns that prices are likely to decline to the mid-30s and possibly as low as the mid-20s if producers do not exercise restraint. Manderson (1968) concludes, "It seems fairly clear that future sulfur pricing during a period of adequate supply, which we foresee emerging in the next several years, will depend not so much on the economics of the highest cost producer, but on the pricing and inventory buildup strategy which Frasch producers decide to employ."

GEOLOGY OF WEST TEXAS DEPOSITS

Shows of sulfur have been encountered in most counties in West Texas. The surface occurrences in Culberson and Reeves counties have been known for 114 years. Shows ranging in character from slight to very good have been encountered in hundreds of oil wells from all formations of Paleozoic age. The most significant shows, however, have been in rocks of Permian age. Wolfcamp and Clear Fork age rocks contain good shows of sulfur in Tom Green, Irion, Schleicher, and Crockett counties, and the San Andres and Grayburg Formations contain fair shows of sulfur over much of the southern portion of the Central Basin Platform and Reagan Uplift, but the commercial occurrences of sulfur discovered to date have been in the Seven Rivers, Yates, Tansill, Castile, Salado, and Rustler Formations located along the western edge of the Delaware Basin and on the south end of the Central Basin Platform (fig. 3).

The lithology of the host rocks and contained sulfur is summed up as follows:

Sulfur: Usually canary yellow; commonly crystalline, orthorhombic, some acute pyramidal.
Calcite: Clear to white crystalline to brown fibrous; dogtooth spar common, drusy occurrence common.
Gypsum: White to brown, selenite common.
Limestone: Light brown to black, fractured, porous to vuggy, sometimes dolomitic or calcitic.
Dolomite: Tan to brown, vuggy, fractured.

As the percent of sulfur and calcite decreases, the amount of gypsum increases. Calcite is nearly always associated with the sulfur, but it is common for crystalline calcite to occur alone in individual vugs. Some sulfur is included in brown massive calcite. Only minor amounts of sulfur occur in gypsum and anhydrite.

In Pecos County the commercial sulfur is associated with calcite and both occur together as secondary minerals in limestone or dolomite with slight amounts of gypsum. Dead oil and oil staining are common. In Culberson County sulfur occurs in a limestone host rock in association with calcite and oil staining, as in Pecos County. Selenite is less common. In one sector of the reservoir, barite occurs in association with the sulfur. In isolated wells, commercial sulfur is in a breccia composed chiefly of anhydrite and limestone. In one instance, a good deal of sulfur occurs in a gray shale. In Tom Green County sulfur occurs in association with calcite, in fractures and vugs, in a dolomite.

The sulfur accumulation seems to be primarily due to the porosity afforded by the carbonate rock; reservoirs (sulfur accumulations) terminate laterally due to a decrease in porosity. Folds appear to have controlled the sulfur accumulations in the younger formations in Pecos County. The folding resulted from reef development and probably does not continue below the reef horizon.

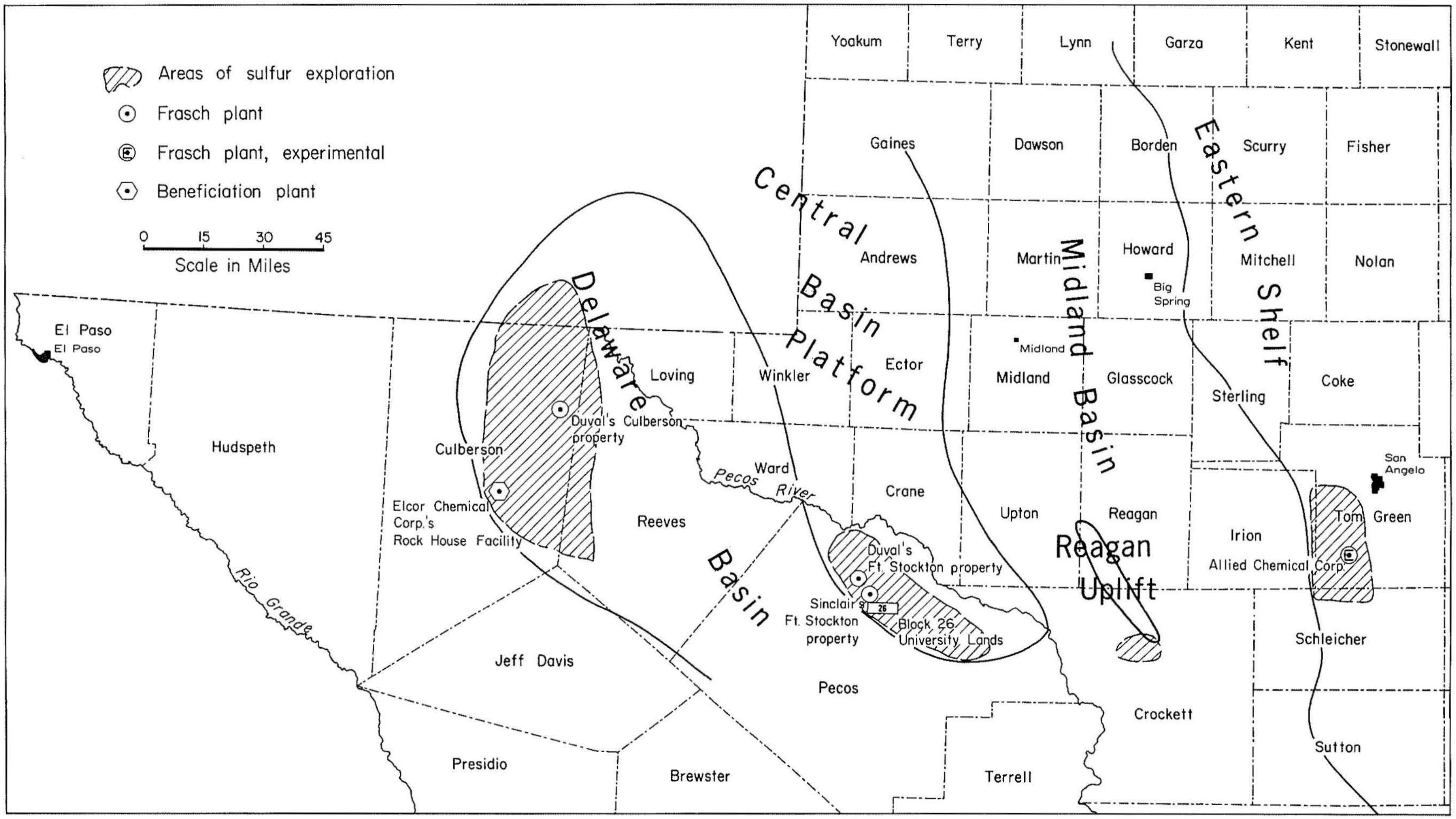

Fig. 3. Index to sulfur deposits and developments in West Texas.

The surface rocks in Pecos and Tom Green counties at the sulfur extraction plant sites are limestones of Cretaceous age. Permian Rustler limestone and alluvial material form the surface rocks in Culberson County at the Duval site. Permian Castile gypsum is the surface rock at Elcor's Rock House Facility but this operation is concerned with processing of gypsum to produce sulfur rather than mining of native sulfur.

There are numerous locations in Culberson and Reeves counties where sulfur is exposed on the surface. Some of these exposures have been described in detail by Porch (1917) and Evans (1946) (fig. 4). Most of the surface shows occur in the Castile or in alluvium called gypsite-alluvium by Evans (1946, p. 7).

There is no doubt that some type of relationship exists between many of the surface shows of sulfur, particularly those occurring in the Castile in association with limestone, and the sulfur occurrence at depth. The Dot prospect and the old Michigan mine seem to be connected to Duval's Culberson County deposit. The surface exposures in some instances may be vents or plugs from larger subsurface deposits. However, some of the surface shows in the mantling soil material may contain sulfur of a more recent age and therefore do not indicate the presence of deeper deposits.

Stratigraphy.--Stratigraphic relations are summed up as follows: In Pecos County the sulfur occurs in the Seven Rivers, Yates, Tansill, Salado, and Rustler Formations of the Upper Guadalupe and Ochoa Series of the Permian System. There is more sulfur in the Tansill and Salado than in any other formations (figs. 6 and 7).

The shape and character of the limestone and/or dolomite host rock containing the commercial sulfur and associated minerals suggest it is a limestone bank or reef. The limestone was formed on the Fort Stockton high and is thicker and higher than equivalent age sediments. The bank can be mapped for several miles (fig. 5). The limestone grades into anhydrite and gypsum in a direction perpendicular to the bank axis. Along the axis Salado limestone commonly contains vugs filled with gypsum and anhydrite. Limestone of Tansill age grades laterally into gypsum and anhydrite in all directions.

The limestone reef "reservoir" rock is overlain by gypsum and anhydrite in some areas and by shaly sandstone or shale in others. The base of the host rock is limestone or dolomite.

In Tom Green County the sulfur occurs in the Clear Fork Formation of the Leonard Series of Permian age. The "reservoir" rock is reef dolomite (figs. 8 and 9).

In Culberson County the sulfur occurs in the Castile, Salado, and Rustler Formations of the Ochoa Series of the Permian System.

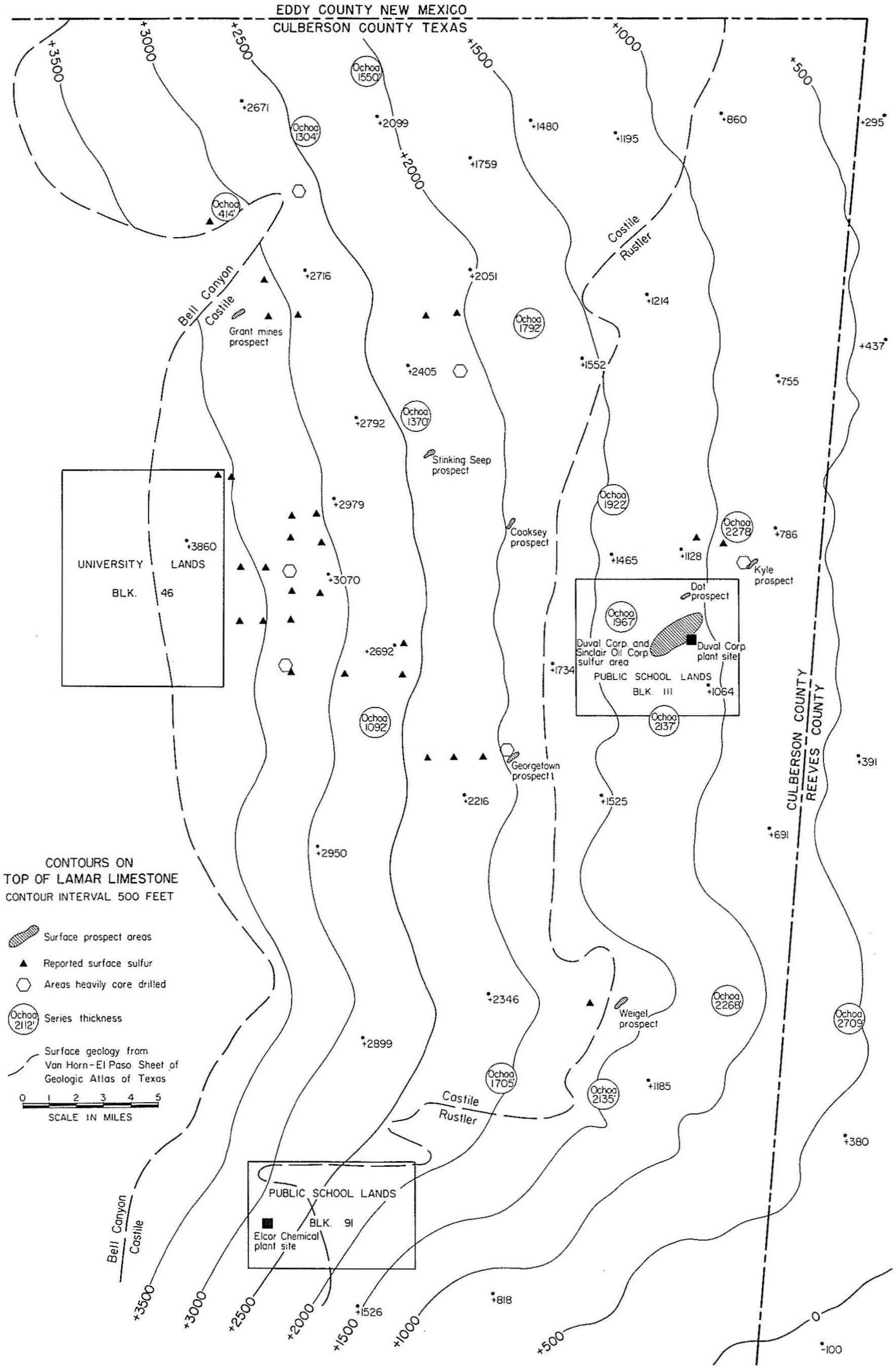

Fig. 4. Sulfur occurrences and mining operations, eastern Culberson County, Texas.

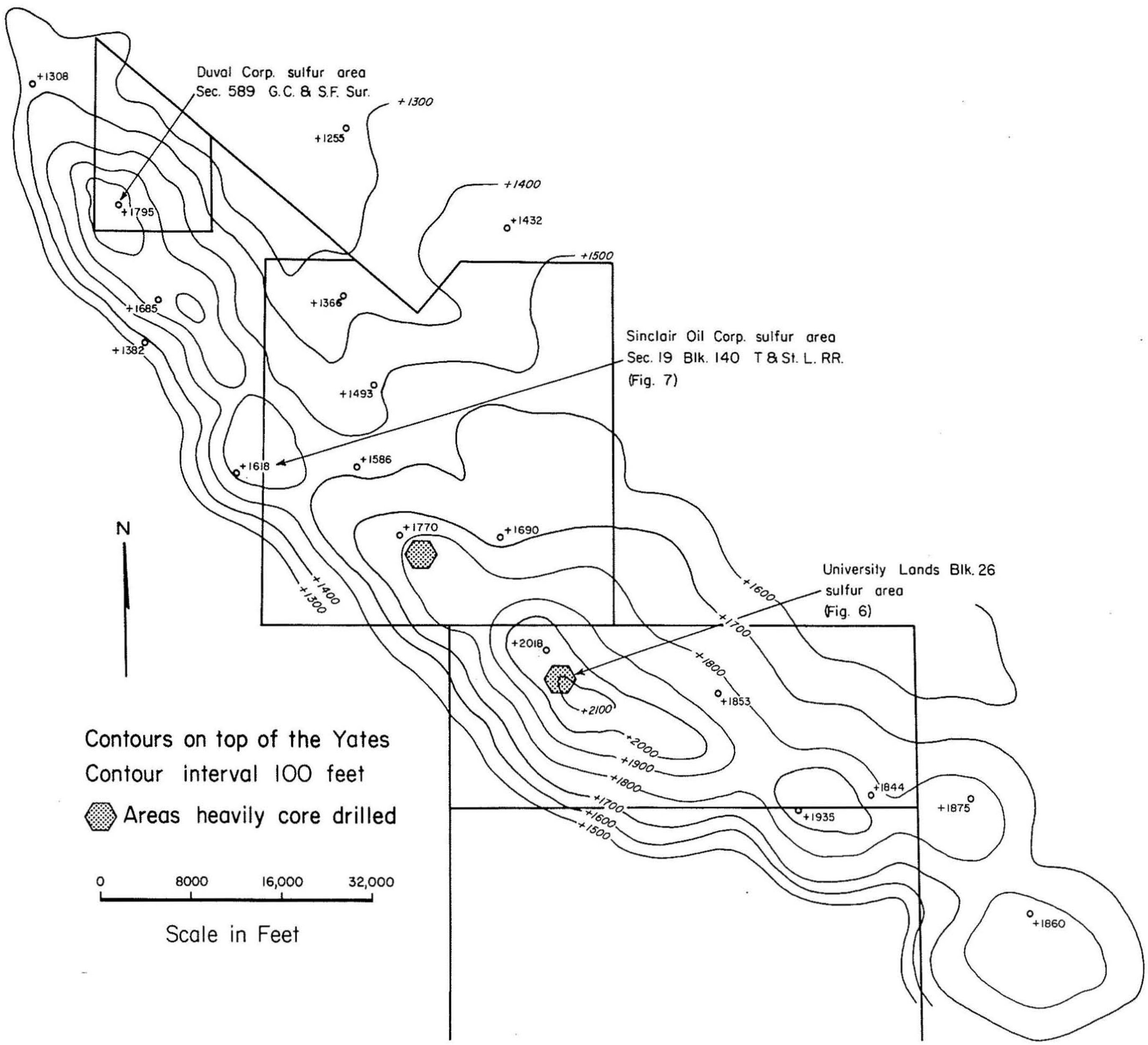

Fig. 5. Occurrence of sulfur in Fort Stockton area, Pecos County, Texas.

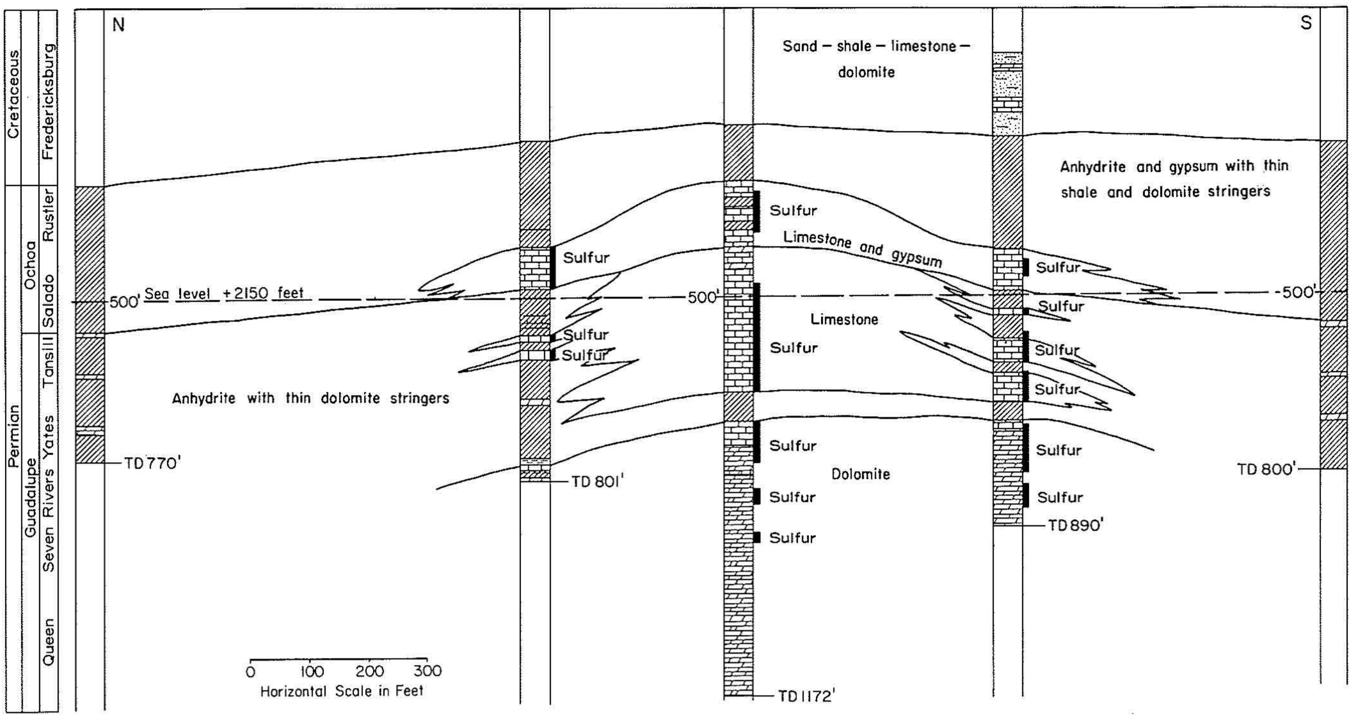

Fig. 6. Stratigraphic distribution of sulfur, University Lands Block 26, Fort Stockton area, Pecos County, Texas.

The limestone host rock grades laterally in all directions into gypsum and anhydrite. The "reservoir" rock is underlain by banded anhydrite and is overlain by anhydrite, gypsum, or shale.

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.

The sulfur and associated calcite appear to be secondary deposits in the limestone. The limestone is probably marine in origin. Adams (1944, p. 1602) described marine limestone lenses in the Salado in eastern Culberson County. He (personal communication, February 8, 1969) believes that salt was originally present in eastern Culberson County but has been removed by solution. Removal of the salt probably caused slumping which resulted in thicker broken or faulted marine limestones. The brecciation is younger than the carbonate rock but older than the sulfur.

Origin of the native sulfur.--A biogenetic epigenetic origin of the sulfur is proposed. This hypothesis is based on preliminary studies of cores and samples. The sulfur and calcite appear to be secondary deposits in the limestone and not syngenetic.

Most theories of origin of sulfur suggest reduction of calcium sulfate by anaerobic bacteria and/or the oxidation of hydrogen sulfide by ground waters to produce calcium carbonate as well as sulfur (Ambrose, 1965, p. 903; Netzeband et al., 1964, p. 6). Most industry personnel believe that the limestone is derived from gypsum and anhydrite.

Most theories of origin were derived from studies of salt dome sulfur deposits where the nature of the "trap" was well known. In West Texas, there is evidence to indicate that deposits of commercial sulfur occur in old oil traps. Dead oil and oil staining are common in all deposits. Petroleum is produced in the same areas from the same formations which contain the sulfur. The oil could have supplied both the bacteria and hydrogen sulfide for the reduction of the associated gypsum and anhydrite.

No theory explains why there are many limestone lenses which contain no sulfur in the Castile and Salado Formations in an evaporite environment. Neither is it understood why no sulfur has been found in Pecos County on shallow structures which parallel the elongated structure containing the deposits.

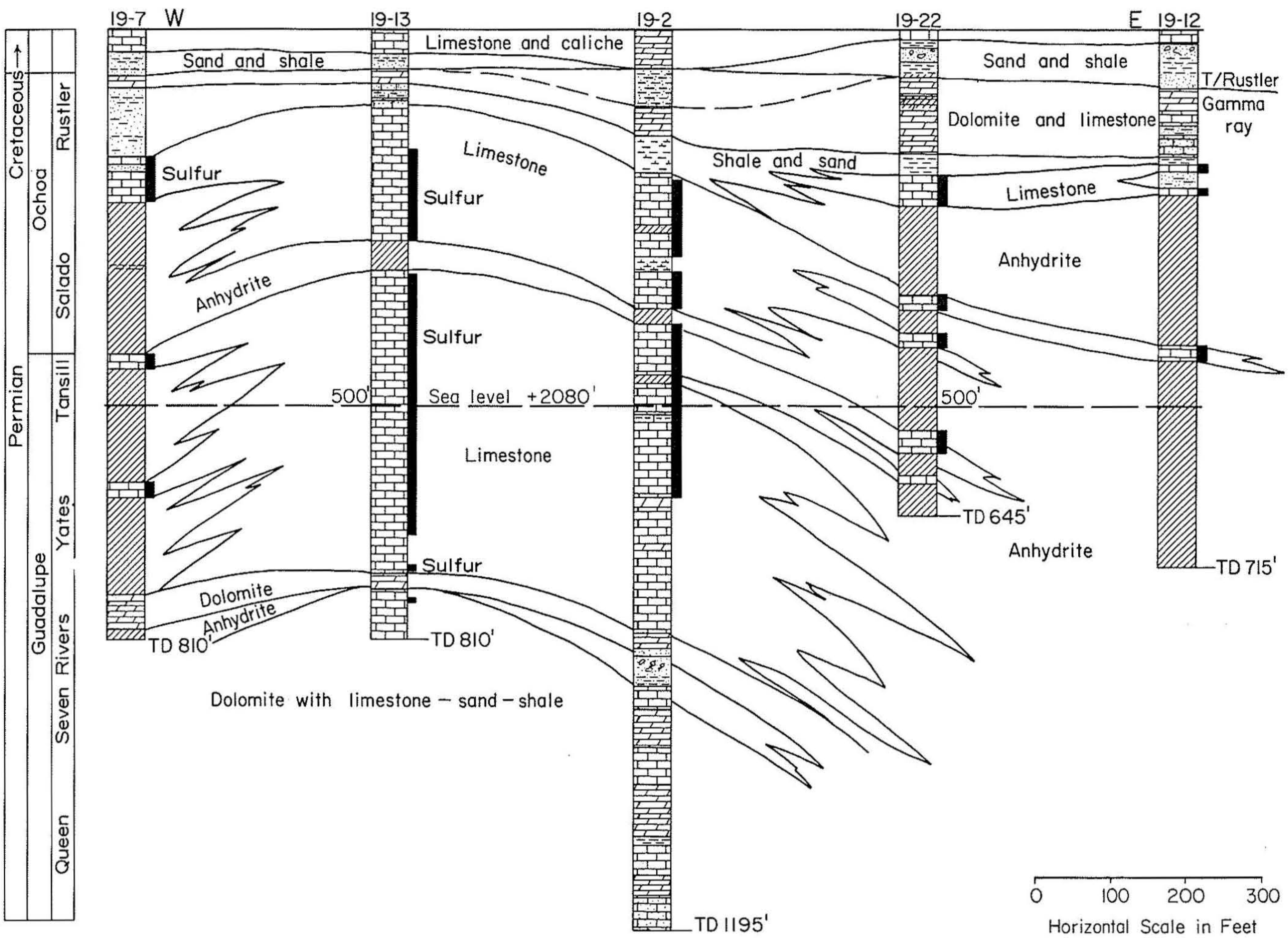

Fig. 7. Stratigraphic distribution of sulfur, Sinclair Oil Corporation's Fort Stockton area, Pecos County, Texas.

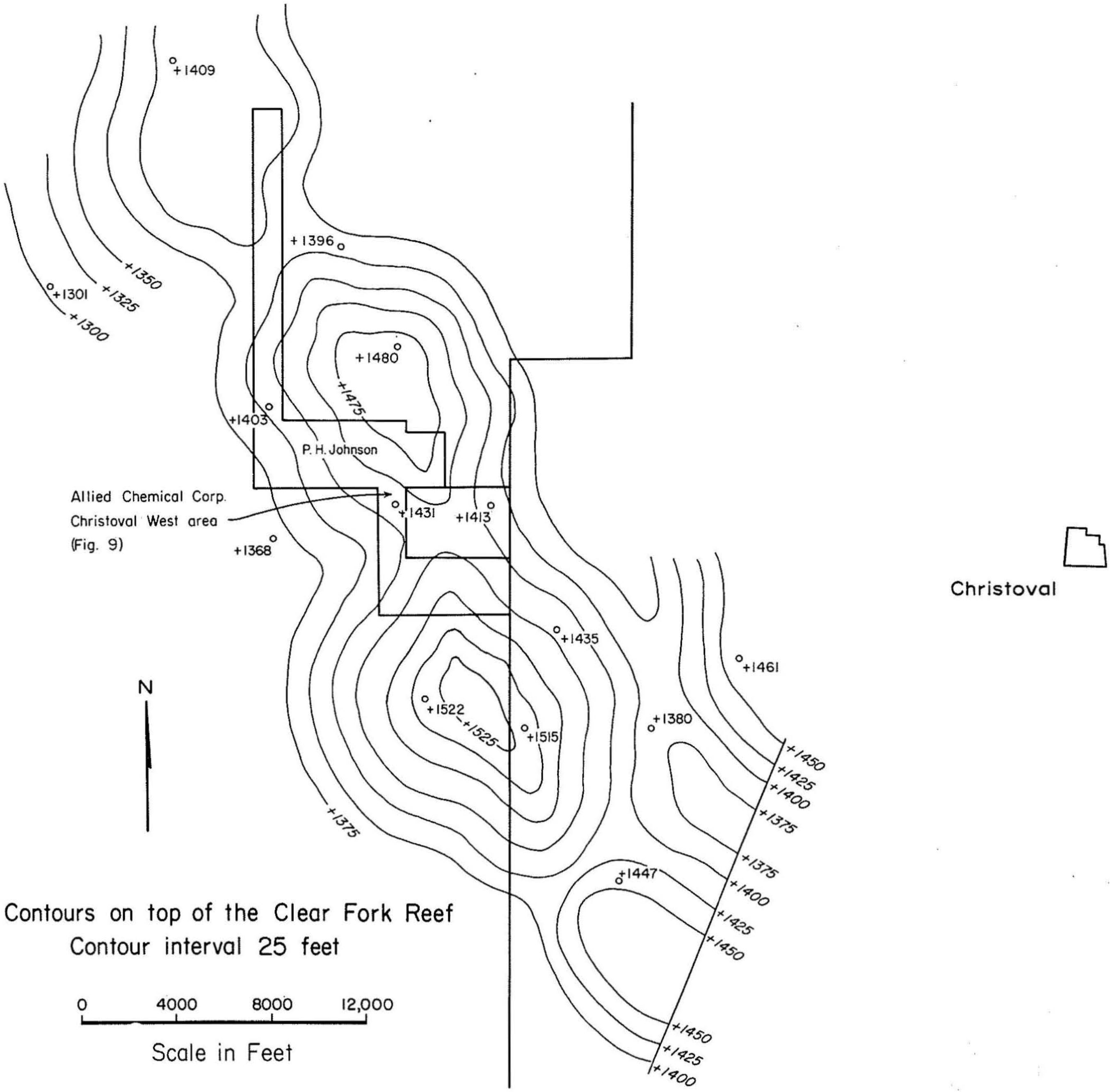

Fig. 8. Occurrence of sulfur in Christoval West area, southwestern Tom Green County, Texas.

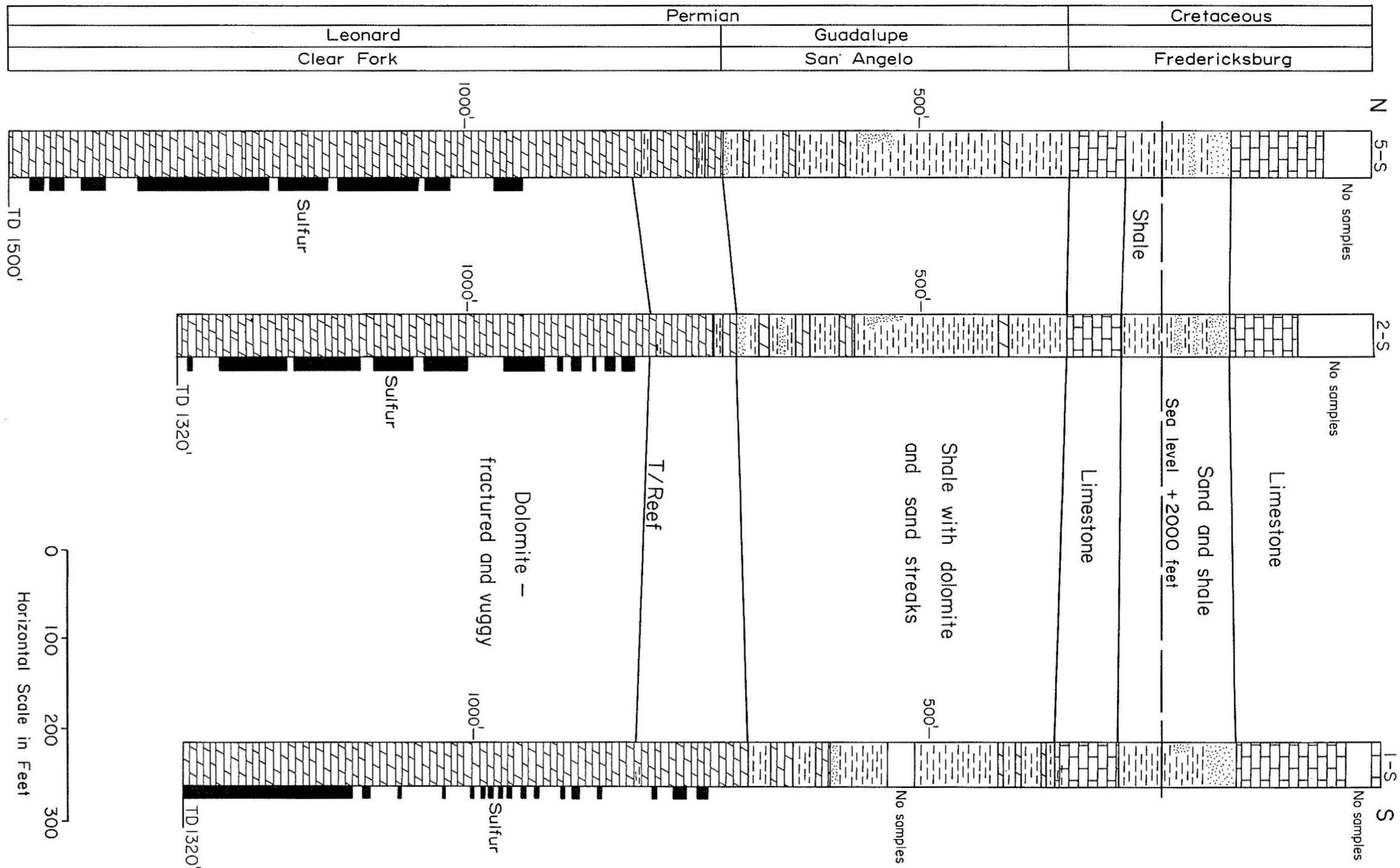

Fig. 9. Stratigraphic distribution of sulfur, Allied Chemical Corporation's Christoval West area, southwestern Tom Green County, Texas.

LAND AND LEASING

Acquisitions of sulfur rights in West Texas reached a significant volume in 1966 and continued at a heavy pace through 1968. The three-year land play has been concentrated mostly in Culberson, Pecos, and Tom Green counties, with some accompanying activity in Irion, Reeves, and Schleicher counties. Most of the exploration drilling has been in the same counties, with isolated testing in Crockett and Hudspeth counties.

Sulfur rights have been obtained through acquisitions of minerals in fee, mineral claims, leases granting rights to explore for and produce oil, gas, and other minerals, leases granting rights to sulfur only, and leases with rights to sulfur and potash only.

At the end of 1968, over 450,000 acres of sulfur rights had been acquired in Culberson, Pecos, and Tom Green counties, with the following distribution: Culberson County, over 280,000 acres; Pecos County, about 150,000 acres; and Tom Green County and others, about 25,000 acres. Sulfur rights are included in many oil and gas leases throughout West Texas, but only those leases purchased primarily for sulfur rights are included in this study.

Most of the leading sulfur companies have substantial leaseholdings. Duval, first into the area, has more than 40,000 acres in Culberson County alone. Texas Gulf Sulphur and Jefferson Lake Sulphur also have rather large amounts of acreage. Freeport Sulphur Company recently leased about 34,000 acres in Culberson County.

Some of the major oil companies have substantial holdings and many have established separate departments for handling minerals other than oil and gas. Texaco probably controls the largest number of acres in the sulfur play, particularly in Culberson County, by virtue of its minerals owned in fee. Sinclair Oil Corporation is the largest oil company owner of leases and claims, with about 53,000 acres. Other oil companies owning fair to large acreage spreads, listed in descending order, are Phillips, Cities Service, Gulf, Continental, Union Oil of California, Union Texas Petroleum, Holly, Shell, Warren American, Humble, Atlantic Richfield, and Pan American.

Early in 1968, the Railroad Commission of Texas began requiring that information concerning location, depth, and plugging be filed on all test holes drilled in search of sulfur. Prior to that time, it was difficult to follow exploratory drilling accurately, but a reasonable estimate is possible. As of January 1, 1969, about 980 test holes, including 28 holes drilled in 1948 and 1949 in Culberson and Reeves counties, had been drilled and had cut a cumulative total of about 1.5 million feet of rock. The bulk of the drilling was done in 1967 and 1968. Most of the drilling has been done by the following companies either on their own leases or under farmout arrangements: Duval, Sinclair, Cities Service, Phillips, Texaco, Jefferson Lake Sulphur, Texas Gulf Sulphur, American Metals

Climax, Bear Creek Mining, Humble, Piper, Atlantic Richfield, Continental, Gulf Resources and Chemical, Tucker Drilling, Pan American Petroleum, Union Texas Petroleum, and Texas American Sulphur.

After Duval's discovery in Culberson County, intensive drilling commenced in that county. About half of the exploratory drilling in 1968 was done there.

Lease bonuses and royalties have varied widely. Royalties range from 1/16 to 1/6. Large spreads of acreage lying in general trends have leased from $5 to $35 per acre. Individual rank wildcat leases of section size have brought $5 to $10 per acre.

The University of Texas leased 10,000 acres on trend with Duval's Fort Stockton plant in December 1967 in section-size tracts carrying a sliding scale royalty of 1/6 to 1/10 based on monthly production. The average per acre price was $75 with individual tracts ranging from $20 to $520.

In Culberson County, tracts with favorable leads have sold for $200 per acre and one semi-proven section-size tract brought $1900 per acre.

EXPLORATION METHODS, RESERVE CALCULATIONS, AND COSTS

Methods of exploration. --Studies of subsurface geological data based on reported occurrences of sulfur in old well borings led to the discovery of the deposits in Pecos and Tom Green counties. The Sinclair discovery in Pecos County resulted directly from a description by J. A. Udden, of the Bureau of Economic Geology, The University of Texas at Austin, of the driller's log (reprinted below) of the old Turney well drilled in 1900. That well is now in the center of the deposit. Subsurface geological studies based on surface shows of sulfur led to Duval's discovery in Culberson County.

Driller's log of old Turney well, drilled in 1900, located in section 19, block 140, Texas & St. Louis Railroad Survey, Pecos County, Texas. From Richardson (1904, p. 65) and Udden (1917, pp. 2-3). (See also Adkins, 1927, pp. 102-103.)

	Feet
Black loam	0 to 10
White marl	10 to 22
Honey-comb gravel	22 to 40
Quartz rock carrying oil	40 to 200
Quartz rock richly impregnated with sulphur	200 to 250
Quartz rock carrying oil and sulphur	250 to 400
Quartz rock richly impregnated with sulphur	400 to 525
Brown sandstone	525 to 540
Quartz rock carrying crystallized sulphur	540 to 600
Brown sandstone carrying oil	600 to 610
White and blue quartz rock	610 to 620
Brown sandstone carrying oil	620 to 630
Blue sandy limestone	630 to 640
Brown sandstone carrying oil	640 to 665
Impure limestone carrying oil	665 to 685
Black sandstone carrying oil and gas	685 to 920
Impure limestone	920 to 940
Black sandstone	940 to 959
Blue sand	959 to 960
Black sandstone carrying oil	960 to 975
Light blue sandstone	975 to 1005
Black sandstone carrying oil	1005 to 1025
Light blue sandstone carrying gas	1025 to 1035
Black sandstone carrying some oil	1035 to 1050
Light blue sandstone carrying gas	1050 to 1065
Black sandstone	1065 to 1070
Brown sandstone	1070 to 1080
Blue sandstone	1080 to 1120
Brown sandstone	1120 to 1130
Blue sandstone carrying oil	1130 to 1200

Surface and subsurface geology are the primary methods of exploration. Targets are measured in tens of acres and lie at depths up to 1,250 feet.

A sulfur deposit which underlies 640 acres or more is an exception. Excluding the two larger salt dome deposits, the smaller deposits average about 100 acres or so in areal extent. A good commercial deposit may underlie 40 acres or less.

Aerial color photography is being used as an aid in studying surface exposures and structural relationships. Infrared photography has been used to locate anomalous sources of heat which may be an indication of surface or near-surface sulfur occurrences.

Two geophysical methods that offer some promise have been used in West Texas. One method is an electrical prospecting method based on measurements of resistivity to an artificially induced electric current. Electrical methods wherein natural currents in the earth are measured have been tried without promising results. Gravity surveys may also prove useful to map differences in density caused by stratigraphic changes. Gravimetric data have been used to delineate the cap rock on salt domes (Barton, 1948).

One problem faced by both electrical and gravity methods, however, is weathering in the near-surface rocks. Near-surface weathering causes density contrasts and conductivity changes which mask the subsurface conditions.

Test holes on 40-acre centers would result in a costly reconnaissance program. All available geological evidence must be used to determine the more favorable areas and eliminate unnecessary drilling. Four test holes per section, located on alternate 80s, should prove sufficient for preliminary evaluation. Further testing of a section may then be warranted if rock examination reveals sulfur shows or evidence of favorable structural or stratigraphic relationships.

Drilling problems.--Drilling in a sulfur area means drilling under the most adverse downhole conditions. It is most important to obtain good samples or 100 percent core recovery. Sulfur is friable and the fractured, vuggy host rock commonly results in lost circulation. This is the most common problem encountered in drilling or coring. The cost of hauling water can equal the cost of drilling. Most types of coring have been tried (wire line, Con-Cor, Reed & Diamond), and size of cores has run from 2 to 6-1/2 inches, all with about the same degree of success.

In the writers' opinion, the drilling method that gives the best over-all results is the Con-Cor reverse circulation method. This method has two weaknesses: (1) Lost circulation and loss of samples are not completely eliminated, and (2) it is easy to stick drill pipe when hole is caving. With good sampling procedures, almost 100 percent of each foot of formation drilled can be recovered by the reverse circulation method.

Reserve calculations.--All recoverable reserve estimates are based on costs and market price. Any changes in costs or prices make a corresponding change in recoverable reserves. Two conventional volumetric methods are mostly used for calculating recoverable sulfur reserves: (1) planimetering isopach maps of the deposit, or (2) subdividing the deposit into triangular or polygonal segments or blocks. Normally, planimetered isopach maps are used first and the results checked by a segment method. The method of triangles is currently preferred over other block methods for calculating sulfur in place. Triangles are formed by connecting exploration drill holes by straight lines, the average net thickness of the three holes is used to determine the reserves in each triangle, and all triangles are added to determine total volume.

Commonly, due to circulation losses in the more porous zones, less than 100 percent rock recovery will occur. Recovery losses are most likely in the zones containing the most sulfur.

After the character of the deposit is determined, thin discontinuous zones are eliminated. A residual allowance in percent must also be made, based on thickness, percent of sulfur in the host rock, porosity, and permeability. A residual allowance of 2 to 5 percent is minimum. Some companies increase the residual percentage at the top and base of the deposit.

Percent of sulfur recovered is governed by the grade of the deposit (percent of sulfur in total rock volume) and porosity of the host rock. Ignoring thickness, as the grade (percent sulfur) increases, percent of recovery will increase. The percent of recovery increases very rapidly from zero recovery from an ore containing 2 to 3 percent sulfur to 80 to 85 percent recovery from an ore containing 20 percent sulfur. Percent of sulfur recovery rises slowly from 85 percent as the percent of sulfur in the ore increases above 20 percent. A good rule of thumb: in a good zone without many barren stringers, averaging 12 to 16 percent sulfur, about 75 percent recovery can be expected.

Costs.--The following costs are applicable in the West Texas area for exploration, mining, and production of sulfur:

(1) Exploration drilling: including some core analyses, borehole logging, surface damages, and plugging; \$8 to \$11 per foot; normally about \$9 per foot.

(2) Frasch production wells: about 3 to 4 wells required per acre; \$15 to \$25 per foot; normally about \$18 per foot, depending on amount of pipe reused.

(3) Purchased potable water: 40¢ to 50¢ per thousand gallons delivered raw, depending upon pipeline distances.

(4) Water treatment: 15¢ to 20¢ per thousand gallons for potable water.

(5) Purchased electric power: 6 to 8 mills per kilowatt hour, depending on size of load.

(6) Natural gas: 19¢ to 21.5¢ per 1,000 cubic feet, depending on volume and whether pay or take contracts in force.

(7) Refining: about $1.00 per long ton but not necessary at present.

(8) Royalties: 1/16 to 1/6 for older acquisitions; current royalties 1/8 to 1/6 on mineral leases. Rock House Facility, no royalty cost.

(9) Transportation: by rail, about $5.50 to $8.00 per long ton to Gulf Coast, depending on location and whether or not unit trains are utilized.

(10) Heaters: about $70,000 for 1/2 million gallons per day water capacity.

(11) Plant: $1200 to $1400 per 1,000 gallons of hot water capacity, depending upon total heating capacity and hardness of water used.

(12) Severance taxes: $1.03 per long ton.

(13) Produced Frasch sulfur: $15 to $20 per long ton, including royalties and depreciation but not transportation, and depending among other things upon water ratio, hardness of water, and whether or not plant is operating at capacity. Depletion allowance for sulfur is 23 percent.

Hazleton's (MS.) study of existing on-shore sulfur plant costs on the United States Gulf Coast shows that plants with 1 million gallon daily capacities cost about $1500 per 1,000 gallons of capacity for construction, whereas plants with about 8 million gallons daily capacity cost about $900 per 1,000 gallons. He does not believe that any significant savings per 1,000 gallons heating capacity are realized when the total capacity goes beyond 8 million gallons per day.

Although present Frasch sulfur is costing $15 to $20 per long ton to produce in West Texas, those costs will rise for future Frasch sulfur because of exploration costs. Most sulfur deposits have been found in the past by oil companies while searching for oil. With exceptions, the sulfur companies have explored for sulfur only during periods of shortages and high prices. It would appear that exploration costs are now going to be borne entirely by the sulfur industry. These exploration costs for geology, geophysics, land and lease acquisitions, and wildcat drilling are difficult to estimate and even more difficult to relate to future prices and profits because of a lack of established guidelines.

Future exploration for sulfur will probably follow the historical pattern of exploration in the oil industry, since occurrences are similar and techniques are about the same. The larger deposits are usually found during the early phases of exploration. The longer exploration continues in a given area, the lower the incidence of recoverable sulfur remaining in the unexplored volume of favorable rock.

Based on present economics and prices, industry can probably afford to drill one foot of exploratory hole to discover two tons of recoverable sulfur.

Exploratory drilling through 1968 had cut about 1.5 million feet and had resulted in the discovery of more than 65 million long tons of recoverable sulfur, or 43.3 long tons of recoverable sulfur has been found for each foot drilled. This ratio of sulfur discovered to footage cut is very favorable, but the exploration time period has been too short for developing a dependable ratio.

Future exploration costs in the Gulf Coast area will be higher than those in West Texas. The costs for off-shore heating plants will be six or seven times greater. Recently estimated costs for off-shore Gulf Coast plants with 6 to 8 million gallons daily heating capacities are as follows: off-shore, shallow water, about $4000 per 1,000 gallons daily capacity; off-shore, deep water, about $7000 per 1,000 gallons daily capacity.

WATER SUPPLY

Water in large volumes is essential for Frasch sulfur production. Some of the Frasch heating plants on the Gulf Coast use from 3 to 8 million gallons of water per day; storage facilities for more than 700 million gallons of water are maintained at one plant. "Soft" water containing less than 300 parts per million total solids is preferred because treating costs are lower. All scale-forming compounds and corrosive particles must be removed or neutralized. Brackish water can be used but it requires special higher-cost equipment.

In West Texas brackish water from underground formations can usually be found on site or in proximity to the plant, but costs of treating hard water may be higher than the cost of pipelining more suitable water from distances of 50 or 60 miles. Ample sources of potable water from underground reservoirs are available within reasonable distances of all plants.

The amount of water used for Frasch mining is dictated by the heating capacity of the plant or the water-sulfur ratio. Water-sulfur ratios on the Gulf Coast vary from 1,100 to 12,000 gallons of water per ton of sulfur recovered, with the average being about 5,000 gallons. Water-sulfur ratios have averaged from 3000:1 to more than 6000:1 in Pecos County. Although the ratio has not been determined in Culberson County, it is predicted that it will be as good as or better than in Pecos County. Water loss problems were encountered at one plant in the initial stages of hot water injection, but these have been overcome by mudding with caliche and by injecting cold water into the "thieving zone."

DESCRIPTIONS OF OPERATIONS

Sinclair Fort Stockton sulfur plant.--Sinclair completed construction of their pilot plant in Pecos County, about 14 miles northeast of Fort Stockton, in December 1967. Expansion of the plant was announced in May 1968.

The heating plant utilizes two heaters with a combined capacity of 1 million gallons of hot water per day.

The mine produced 60,000 long tons of sulfur in 1968. The present rate of production averages about 330 long tons per day, but output varies from 200 to 700 long tons per day.

The sulfur occurs at depths of about 160 feet to 750 feet. The reserves have not been determined and total surface acres are not fully defined.

The source of water is on-site brackish water from the Rustler Formation at a depth of about 150 feet. The water reserves are considered ample and water from bleed wells is being reused. Water treatment costs are about 50 cents per 1,000 gallons. Storage for about 200 thousand gallons of water is maintained at the plant.

About 1 foot of surface subsidence has occurred.

Sulfur shipments are in molten form by rail.

Allied Chemical Corporation Christoval West experimental project.--Allied Chemical Corporation conducted a successful experimental pilot Frasch operation about 5 miles west of Christoval in Tom Green County during the last half of 1968.

One Frasch well containing about 16 net feet of sulfur was utilized for mining during irregular intervals. The well produced about 200 long tons of sulfur.

The sulfur occurs at depths of 800 feet to about 1,500 feet. The sulfur was mined from 1,155 to 1,262 feet after the interval was acidized with 1 thousand gallons of 15 percent hydrochloric acid.

The source of the water was potable on-site shallow water from Cretaceous limestone. The project was discontinued when the water was depleted. The final water-sulfur ratio was 17,000:1.

The size of the deposit has not been determined. Only a relatively few wells have been drilled on the Eastern Shelf in search of sulfur.

Duval Fort Stockton property.--Duval Corporation, a subsidiary of Pennzoil United, Inc., in late 1966 began construction on their Fort Stockton property in Pecos County, about 16 miles northeast of Fort Stockton, of the first Frasch pilot plant ever built in West Texas. Pilot mining was initiated in March 1967. Based on the pilot success, the decision was made to construct a plant capable of producing 500 long tons of sulfur per day. Commercial operations commenced in June 1967. In December 1967, Duval announced plans for doubling the capacity of the plant to 1,000 long tons per day, or about 350,000 long tons per year. Capacity production is scheduled for 1969.

The total investment to date is about 7.5 million dollars, including among other things, costs of land and leases, exploration, hot water plant, production wells, hookups, drilling rigs, and storage.

The mine produced 11,680 long tons of sulfur during 1967 and 178,722 long tons in 1968. The present rate of production is about 800 long tons per day.

The sulfur occurs at depths of 250 to 800 feet under 400 surface acres. The announced recoverable reserves are 3 million long tons based on present market prices.

The heating plant utilizes 12 heaters or boilers with a total capacity of over 5 million gallons of hot water per day.

The source of water is on-site brackish water containing about 5,000 parts per million total solids from the San Andres Formation at a depth of about 2,000 feet. The water reserves are considered ample and, due to the type of equipment installed, water is reused. Storage for about 12 million gallons of water is maintained at the plant.

The sulfur is shipped in molten form by rail.

Duval Culberson property.--Duval Corporation also operated a Frasch pilot plant from mid-June to early July 1968 on their Culberson County property located about 18 miles southwest of Orla.

Based on the quick success of that pilot operation, Duval is presently constructing plant facilities with a design capacity of 1.5 million long tons of sulfur per year and capable of being expanded to a capacity of 2.5 million long tons per year. When operating at the full expanded capacity, it will be the largest sulfur mine in the United States and probably the largest in the world. The initial planned cost is 50 million dollars, including among other things, costs of leases, land, exploration, water pipelines, hot water plant, power generation equipment, production wells, hookups, drilling rigs, and storage. Production should begin by late 1969 and capacity production is anticipated in about two years.

The sulfur occurs between the depths of 240 feet to about 1,250 feet and underlies about 1,200 surface acres. The announced reserves are 57 million long tons based on present market prices.

The number of boilers needed or the total heating capacity will not be known until the water-sulfur ratio has been determined. It is thought that the water-sulfur ratios will be lower than those in Pecos County, but the heating plant will be large, possibly capable of handling 16 to 25 million gallons of hot water per day.

The source of water will be potable water in alluvial gravels from an area near the Davis Mountains west of Toyah in Reeves County, about 38 miles southeast of the plant. Another back-up source of potable water, also from alluvial gravels, is located in Jeff Davis County about 55 miles southeast of the plant. A contemplated third source of potable water which can be utilized by either the Culberson or Fort Stockton properties is located near Pyote, in the alluvial fill in Monument Draw. The water reserves are considered ample for all anticipated mining.

The sulfur will be shipped in molten form by rail.

Rock House Facility.--Elcor Chemical Corporation has constructed a plant to extract sulfur from gypsum in Culberson County, about 40 miles northeast of Van Horn, called the Rock House Facility.

The plant commenced initial operations of all systems in February 1969; a small amount of sulfur was recovered. Minor modifications are currently under way and full-scale operation is scheduled for April 1969. The design capacity is approximately 1,000 long tons of sulfur output per day, or about 350,000 long tons per year.

The announced cost for the Rock House Facility was about 24 million dollars, including among other things, costs of mine and plant equipment installed, piloting, pre-operating costs and interest, start-up and interest, sulfur storage, design and engineering, water wells, and water supply lines. Land acquisitions have cost an additional $2,111,290, including some surface lands in the immediate area prospective for gypsum to be retained for future evaluation.

Elcor has not released any information concerning their "process" for obtaining molten sulfur from gypsum, or any detailed costs, but stated that sulfur recovery costs should be comparable to most of the other primary sources of sulfur now being placed in production.

Based on the results of a pilot plant built in 1966, Elcor believes that it will require the processing of between 9.5 and 11.7 short tons of gypsum ore to recover 1 long ton of sulfur. Elcor says that substantial quantities of natural gas and water will also be required.

The gypsum is being mined by open-pit methods. Announced proven reserves of gypsum are 304 million short tons, which should be sufficient to produce about 29 million long tons of sulfur, based on a ratio of 10.6 short tons of gypsum ore per long ton of sulfur. Apparently, more than 10,000 short tons of gypsum per day will be mined and processed when plant capacity output is achieved. The total crude gypsum mined in Texas is now about 3,000 short tons per day.

Elcor has about 28,000 acres of surface and water rights located in the Apache ranch area about 15 miles southwest of the plant. The reserves are in the Capitan Reef and are thought to be adequate and substantial. The company also has an option on an additional 28,000 acres of water rights in that same area.

Elcor has announced the acquisition of long-term contracts with some of the leading sulfur users calling for purchase of 1,300,000 long tons of sulfur through June 30, 1974, at a minimum price of $35.50 per long ton f.o.b. plant. Shipments will be in molten form by rail. Elcor is the only non-Frasch member of Sulphur Export Corporation (Sulexco).

CONCLUSIONS

The West Texas region contains proven reserves of native sulfur of about 100 million long tons in place. At present market prices it is estimated that at least 61 million long tons can be recovered by the Frasch process. The Duval Culberson County mine could develop into the largest mine in the world.

A rise in market price of 65 percent during the 1964 to 1968 world-wide sulfur shortage brought about the sulfur exploration boom in West Texas. The successful operation of two Frasch sulfur plants in Pecos County plus two successful experimental Frasch pilot projects has proven that the Frasch process can recover native sulfur from sedimentary deposits not associated with salt domes.

Ample reserves of sulfur are present throughout the Free World to meet any anticipated demand. Frasch reserves, however, are limited and should be handled with restraint. The West Texas reserves should enable the Frasch producers to hold their share of the world market for the next few years.

It costs between $15 and $20 to produce one long ton of Frasch sulfur in West Texas, but future production will bear a higher cost due to increasing exploration costs. Exploration for sulfur in West Texas will probably continue as long as prices are in the $35 to $40 range. Exploration will probably cease if prices drop to $30 per long ton or lower.

Prices should stabilize over the long run in the $35 to $40 range.

The demand for sulfur should at least double in the Free World by 1980. United States total output should at least double by 1981. This rise in demand will absorb the West Texas sulfur output over the long range.

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