



## *Origin of castiles on the Gypsum Plain of Texas and New Mexico*

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1980, pp. 173-178. <https://doi.org/10.56577/FFC-31.173>

in:

*Trans Pecos Region (West Texas)*, Dickerson, P. W.; Hoffer, J. M.; Callender, J. F.; [eds.], New Mexico Geological Society 31<sup>st</sup> Annual Fall Field Conference Guidebook, 308 p. <https://doi.org/10.56577/FFC-31>

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*This is one of many related papers that were included in the 1980 NMGS Fall Field Conference Guidebook.*

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# ORIGIN OF CASTILES ON THE GYPSUM PLAIN OF TEXAS AND NEW MEXICO

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This is a summary and modification of an article that appeared in the American Association of Petroleum Geologists Bulletin (Kirkland & Evans, 1976); we appreciate permission from the American Association of Petroleum Geologists to use figures from that article. We acknowledge the measurements of carbon-13 by R. M. Squires of Mobil Research and Development Corporation.

## INTRODUCTION

The Gypsum Plain, an expanse of outcropping gypsum of Late Permian (Ochoan) Castile and Salado Formations, occupies an area of about 2600 km<sup>2</sup> in southeastern New Mexico and West Texas (fig. 1). On the west the Gypsum Plain is bounded chiefly by the Delaware Mountains and on the east by the Rustler Hills (fig. 1). The low relief of the Gypsum Plain displays features of solution and subsidence (sinks, caves and troughs) and is interrupted by prominences of limestones (fig. 2)—the castiles of Adams (1944) or the buttes of Kirkland and Evans (1976).

## DISTRIBUTION AND SIZE

The location of 71 castiles is shown on Figure 3; at least two more occur south of the area of this figure (Motsch, 1951; West Texas Geological Society, 1960, p. 23, 24) and others may be found. The castiles are a few meters square to about a hectare in area, and they rise 3 to 30 m above the general surface of the plain (fig. 2).

## HOST ROCK

The masses of limestone are associated chiefly with the Castile Formation. In the area of its outcrop, the Castile consists principally of alternating laminae of calcium sulfate, with a mean thickness of about 1.5 mm, and calcite, with a mean thickness of about 0.4 mm. The calcium sulfate is usually gypsum within about 20 m of the surface (Anderson and Kirkland, 1966) and anhydrite at greater depths. Calcite-laminated anhydrite is characteristic of the entire formation, although the laminae are displaced by a nodular fabric in some intervals (Dean and Anderson, 1978, fig. 3).

Castile laminae are sparsely to commonly microfolded. The microfolds generally have a wavelength of less than one centimeter and on cliff faces they occur in irregularly shaped zones less than one meter across (Kirkland and Anderson, 1970).

Disruption of the Castile is common throughout the outcrop area (fig. 1), and takes the form of localized breccia masses, or extensive layers of breccia (Anderson and others, 1972, 1978; Anderson and Kirkland, 1980). The brecciation is chiefly the result of dissolution of beds of halite, which are now absent from beneath almost all of the outcrop area of the Castile (Anderson and others, 1978, fig. 1).

## SMALL-SCALE FEATURES WITHIN THE CASTILES

The limestone masses of the Gypsum Plain exhibit features of their unaltered Castile precursors. Microstratification was observed in all the castiles investigated except castiles 2 and 6 (fig. 3), and can be observed at castile 3 in the cut on the south side of state road 652. The microstratification (fig. 4D, F) results from an alternation of dark-gray calcite containing organic matter and thicker light-gray or white laminae containing little organic matter. Microfolding (figs. 4B, C, F) is present in about one-half of the castiles visited. A superb display of microfolding occurs on the

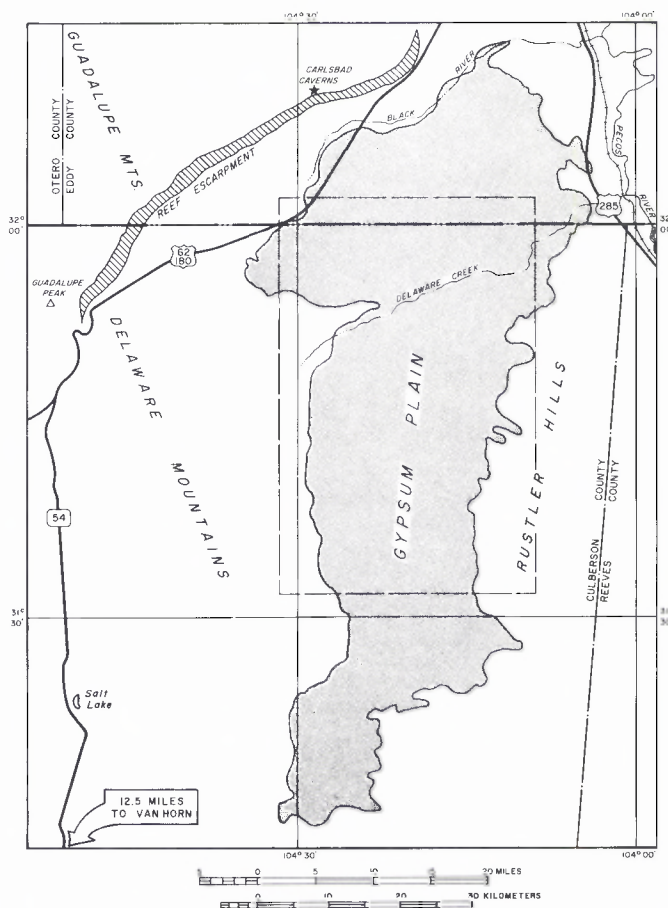


Figure 1. Location of Gypsum Plain, Texas and New Mexico. Area within dashed line shown in Figure 3.



A



B



C



D

Figure 2. Typical castiles within Block 109, Public School Lands, Culberson County, Texas: A, castile 10 (fig. 3); B, castile 9; C, castile 8; D, castile 7.

steep limestone face of castile 8 (figs. 2, 3). Brecciation (fig. 4A) also is a common feature of many castiles and appears to be a result of replacement of breccia of normal Castile.

#### ASSOCIATION OF CASTILES WITH OTHER GEOLOGIC FEATURES

##### Karst Features

A. Richard Smith has made a detailed study of solution features of the Gypsum Plain and considered that there was no correlation between karst features on the Gypsum Plain and masses of secondary limestone (person. commun., 1977; see A.R. Smith, this guidebook).

##### Sulfur Deposits

An association does appear to exist between surface sulfur accumulations and the castiles [cf. fig. 3 with pl. 9 of Porch (1917) and with fig. 4 of Zimmerman and Thomas (1969)]. Most of the surface sulfur deposits on the Gypsum Plain cover less than one-half hectare and many occur in slight depressions (Evans, 1946), which probably result from microbial alteration of part of the sulfur (see A. R. Smith, this guidebook).

Hydrogen sulfide was detected at castiles 4, 5 and 7, and sulfur mineralization is present near the bases of castiles 1, 3, 4, 5 and 7. The sulfur at these castiles has formed by oxidation of hydrogen sulfide by atmospheric oxygen.

At the easternmost castile in the group designated 4 (fig. 3), sulfur covers parts of the sides of a near-vertical cavern more than 30

m deep and 10 to 15 m in diameter. This cave was probably formed as a consequence of the alteration of the sulfur, which is geologically ephemeral and which reacts rapidly with oxygen and water to form sulfuric acid. The bacterial agent, *Thiobacillus thiooxidans* (Kuznetsov and others, 1963) is apparently involved in the process. Sulfuric acid generated at the cave reacts with the limestone to form carbon dioxide and gypsum, much of which is dissolved and removed by ground water. The natural shaft, thereby, gradually enlarged. A similar process may have been involved in the formation of caves, some of very large size, elsewhere in the vicinity of the Gypsum Plain.

##### Limestone Facies of the Castile Formation

In the Seven Heart Gap area of the Apache Mountains, several miles southwest of Loneman Mountain and south of the Gypsum Plain, the entire Castile Formation is represented by about 50 m of limestone. This limestone unit apparently has an origin distinct from that of the castiles. Delta carbon-13 values from this gypsum-free, laminated limestone are representative of bicarbonate ions in a marine environment. We have obtained  $\delta^{13}\text{C}_{\text{PDB}}$  values of +1.50‰, +1.65‰, +2.45‰ and +3.04‰ for samples from this area.

##### CARBON ISOTOPE VALUES OF CALCITE FROM THE CASTILES

Marine limestones generally have carbon-13 contents that deviate from the commonly accepted standard, a Cretaceous



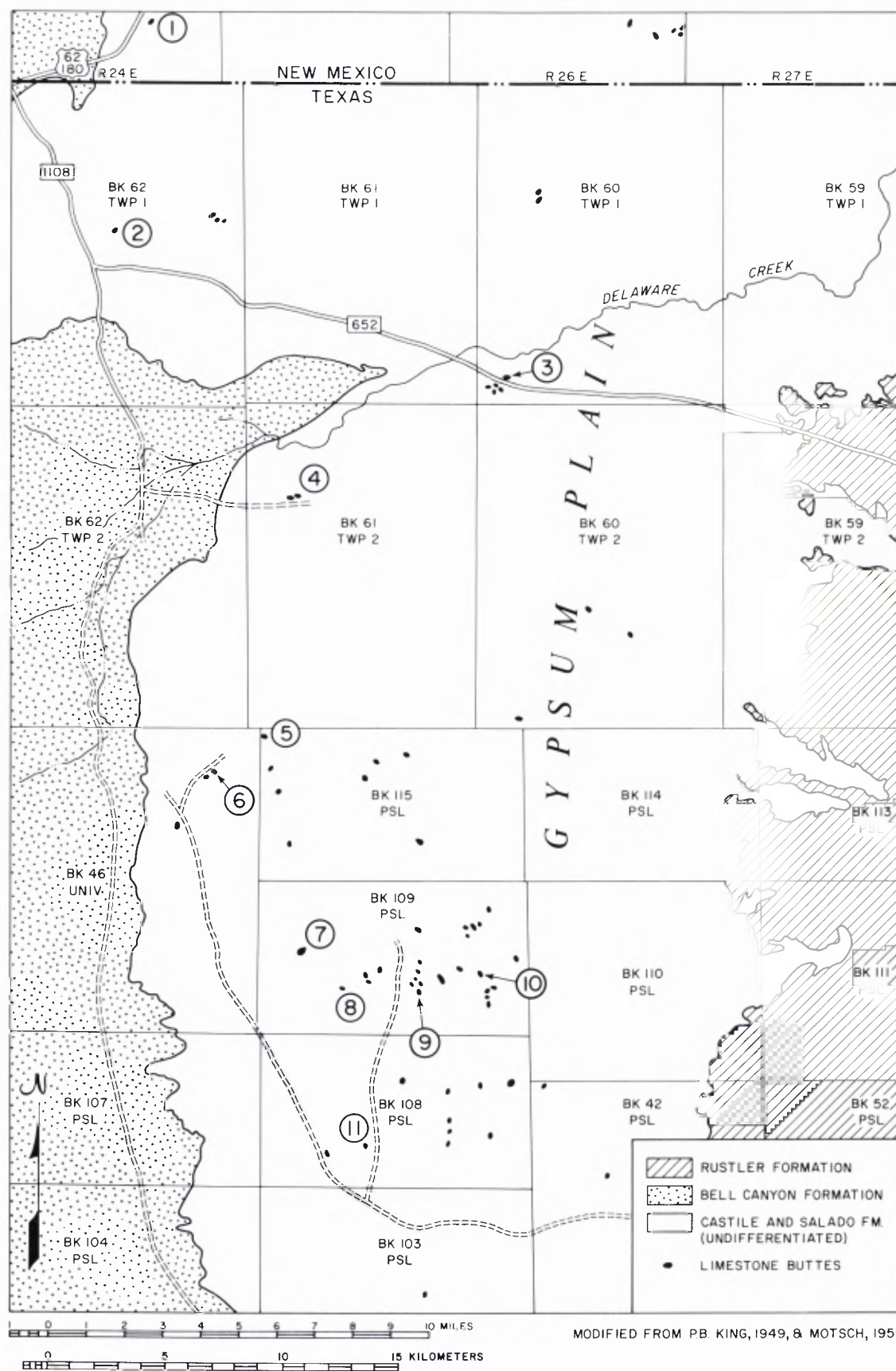


Figure 3. Locations of castiles, Texas and New Mexico.

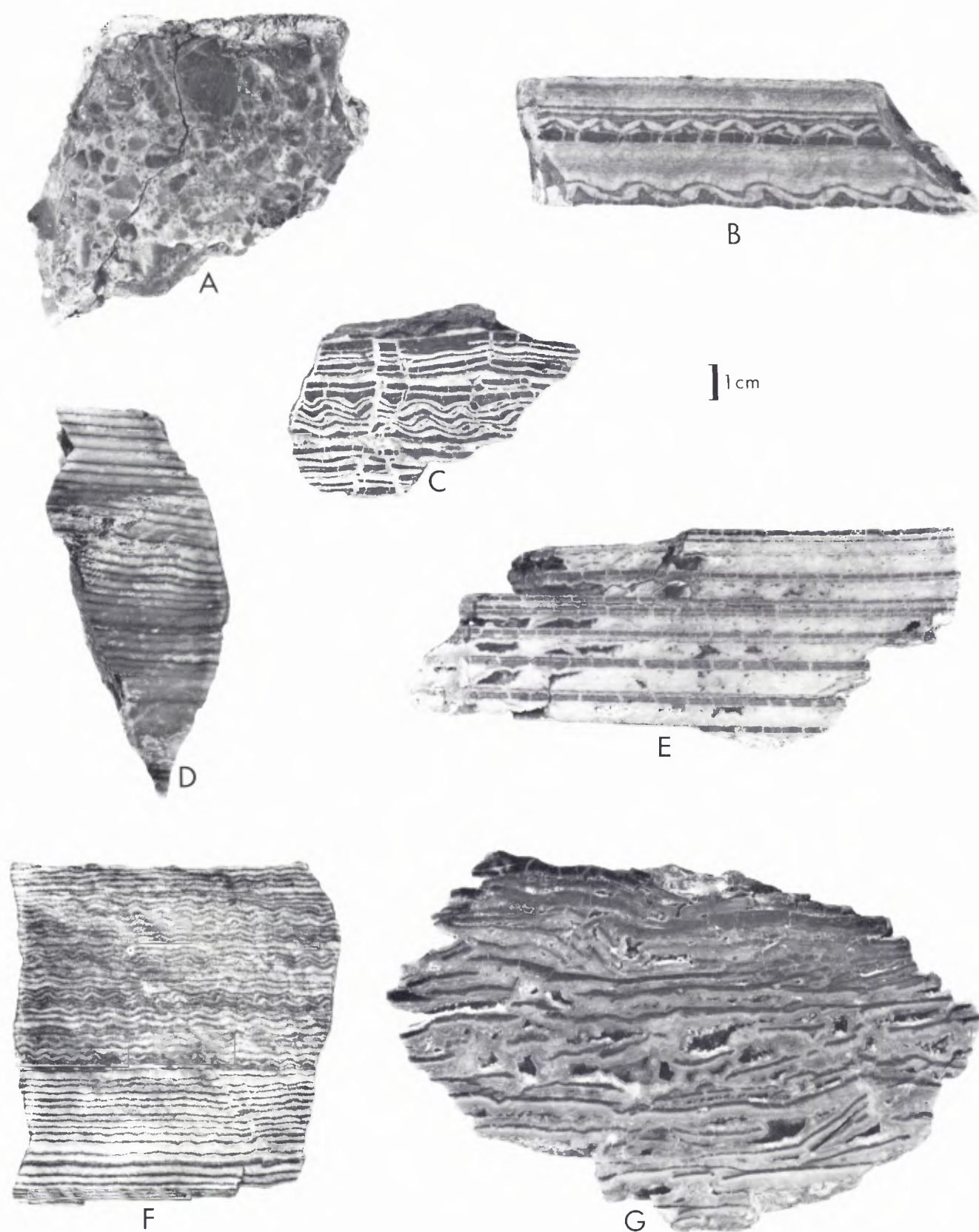


Figure 4. Polished slabs of limestone from castiles, Culberson County, Texas. Light-colored laminae: calcite, commonly porous. Dark-colored laminae: calcite containing organic matter, essentially nonporous. A, castile 3 (fig. 3); B, castile 8; C, castile 8; D, castile 11; E, castile 8; F, castile 11; G, castile 4.



belemnite, *Belemnitella americana*, from the Peedee Formation of South Carolina, by only a few parts per thousand (Keith and Weber, 1964, fig. 1). Carbonates deposited from seawater in regions of high evaporation are generally enriched in carbon-13 compared to the standard; calcite laminae in the Castile Formation, for example, are enriched by about 5.5‰ (Dean and others, 1975). Isotopic values of calcite from the castiles are greatly impoverished in the carbon-13 isotope compared to the standard:  $\delta^{13}\text{C}$  values for 20 samples from 9 castiles had a mean of  $-23.5\text{‰}$  and a considerably lower mode,  $-37.0\text{‰}$ . Only plant materials or their products, e.g., coal, kerogen, oil or natural gas, have sufficiently low  $\delta^{13}\text{C}$  values to have been a possible source of the carbon within the calcite of the castiles.

The reasonable source for the isotopically light calcite in the castiles is natural gas or oil. Upper Permian oils (Ochoan and Guadalupian) beneath, and rarely within (Davis and Kirkland, 1970) the Castile Formation have a range of  $\delta^{13}\text{C}$  values from  $-27.2$  to  $-28.2\text{‰}$  ( $n=20$ ) (McNeal and Mooney, 1968). About one-half of the calcite samples from the castiles are more negative than  $-28.2\text{‰}$ ; the isotopically light carbon of these samples can probably not be attributed to oil. On the other hand, methane, the major component of natural gases within Paleozoic strata of the Delaware Basin, has  $\delta^{13}\text{C}$  values that are more negative than  $-30\text{‰}$ . The most probable source of the great volume of isotopically light carbon within the castiles is methane, although oil may have also been a source. The isotopic values of calcite from the castiles vary because the calcite is apparently composed of a varied mixture of extremely "light" carbon from petroleum and calcite with "heavy" carbon from the unaltered Castile Formation. Limestones in the castiles have  $\delta^{13}\text{C}$  values in the same range as do limestones associated with the Pokorny sulfur deposit (Blk. 61, TWP 1, a few kilometers north of state road 652) (Davis and Kirkland, 1970).

### ORIGIN OF THE CASTILES

The extremely negative carbon isotope values of calcite from the castiles, the associated sulfur mineralization, the similarity of the distribution of the castiles to the distribution of the surface sulfur accumulations, and the similarities between the castiles and the size, distribution, mineralogy and texture of subsurface sulfur deposits in the vicinity of the Gypsum Plain (e.g. Davis and Kirkland, 1970; Smith, 1978) have led us to the conclusion that at least some of the castiles represent exhumed sulfur deposits. Some castiles may have been devoid of sulfur, hydrogen sulfide having escaped before oxidation and deposition as native sulfur (Bodenlos, 1973).

Uplift of the Delaware Basin during the late Cenozoic produced an eastward dip of about 19 m/km in the Castile Formation and in the underlying Delaware Mountain Group (King, 1948). One effect of the tilting was to stimulate updip migration of oil and gas in more permeable Permian units beneath the Castile. A second effect was to produce hydrodynamic conditions ideal for introduction of water and hydrocarbons into the Castile Formation. The mechanism by which this took place was probably brine density flow (Anderson and Kirkland, 1980).

Because sulfate ions were readily available and because hydrocarbons, chiefly in the form of natural gas, were being brought into the Castile Formation by the circulating anaerobic waters, a bloom of sulfate-reducing bacteria probably resulted. It is unlikely that conditions of salinity, temperature, pressure or pH markedly restricted growth of these microorganisms, which have a remarkably wide ecological amplitude (ZoBell, 1958, 1963). Toxic con-

centration of hydrogen sulfide did not accumulate because this gas was removed within solution in the circulating waters.

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where "n" varied from about 1.8 (average oil) to 4 (methane). At the site of the microbial action, sulfate ions were readily devoured. The calcium ions resulting from the solution of anhydrite reacted immediately with bicarbonate ions, derived indirectly from the oxidation of hydrocarbons, to form calcite. The remarkable preservation of Castile laminations and microfolds attests to almost simultaneous solution (of anhydrite) and precipitation (of calcite) along an advancing "solution front." Because the precipitating calcite occupied about 20 percent less volume than the original anhydrite, the calcium sulfate was not sealed from further solution.

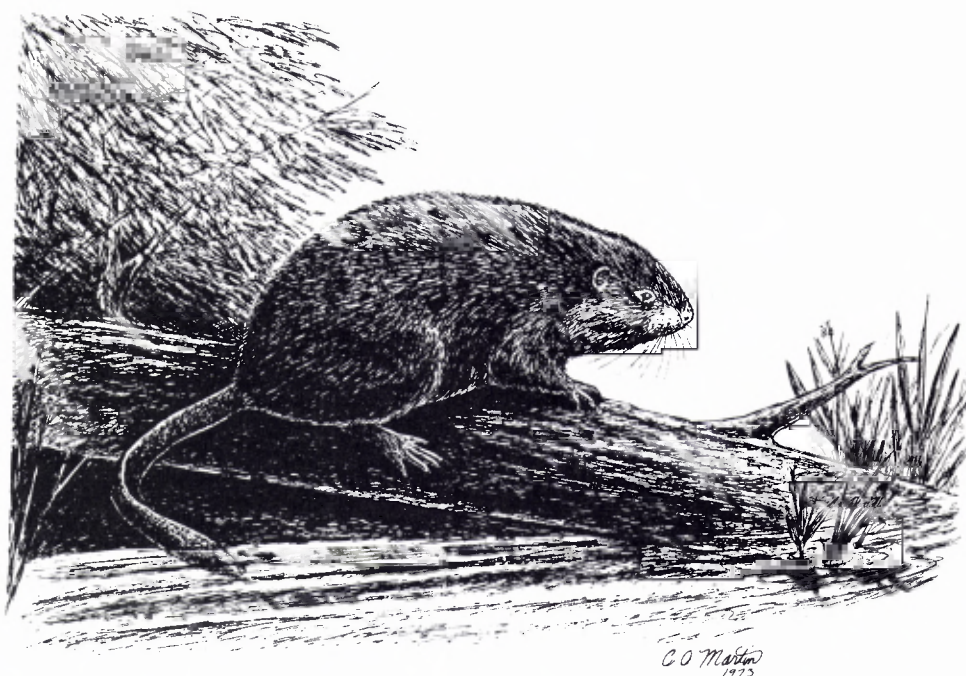
The microbial process resulted in the formation of large replacement masses of porous calcite nearly encased within impermeable anhydrite. Ground waters, however, were apparently able to move deep into the Castile Formation through fractures and solution channels. Ultimately, the hydrogen sulfide-bearing waters circulating by brine density flow within the Castile Formation may have contacted the oxygen-bearing waters moving into the formation from the surface (Davis and Kirkland, 1970). An oxidation-reduction front resulted, oxygen reacting with any hydrogen sulfide present to form elemental sulfur. As the front migrated through a limestone mass, considerable void space was commonly available for sulfur emplacement (Kirkland and Evans, 1976).

During Quaternary and Tertiary time, hundreds of meters of Castile section were removed over tens of square kilometers from the western Delaware Basin. The Castile Formation, for example, probably extended 24 km farther west than at present (King, 1949). The erosion ultimately exposed the limestone masses, most of which are in the lower one-half of the Castile, and the masses now stand in relief as castiles because gypsum is much more soluble in meteoric water than is limestone. Sulfur present near the surface of some castiles was largely destroyed by sulfur-oxidizing bacteria, leaving the limestone masses standing topographically higher.

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Muskrat, *Ondatra zibethicus*.