Origin and Diagenesis of Cap Rock, Gyp Hill and Oakwood Salt Domes, Texas

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ABSTRACT

Petrographic and geochemical studies of cap-rock core from two salt domes, Gyp Hill in South Texas and Oakwood in East Texas, reveal the significantly different diagenetic histories of each dome. Cap rock on Gyp Hill is now forming within a shallow meteoric aquifer. In contrast, cap rock on Oakwood Dome formed principally during the geologic past within deep, saline aquifers in the East Texas Basin.

Gyp Hill cap rock, which is 890 ft (271 m) thick, is composed of 490 ft (149 m) of anhydrite overlain by 400 ft (122 m) of gypsum. Uncemented anhydrite sandstone marks the salt/cap-rock interface. From 13 ft (4 m) above the interface to the top of the anhydrite, porosity is occluded by poikilotopic gypsum cement. Occurrence of gypsum cement indicates low-temperature, low-salinity conditions during cap-rock formation; that is, dome dissolution is occurring in a shallow meteoric aquifer. The overlying gypsum results from hydration of anhydrite by meteoric ground water.

Oakwood cap rock, which is 450 ft (137 m) thick, is composed of 256 ft (78 m) of anhydrite overlain by 194 ft (59 m) of calcite. In contrast to Gyp Hill anhydrite, Oakwood anhydrite is entirely devoid of gypsum cement except at the interface between anhydrite and calcite. The anhydrite has been recrystallized into a moderately well developed granoblastic texture that is indicative of high-temperature and high-pressure conditions. Fluid inclusions in the salt at the salt/cap-rock interface represent waters from the last dissolution event. The $\delta^{18}O$ of water from a fluid inclusion is +5.4 ‰, indicating a deep-basin origin of the water. The anhydrite section is considered to have accumulated during salt dissolution under deep, high-temperature, saline conditions. Timing of the development of major rim synclines surrounding Oakwood Dome indicates that the anhydrite cap rock formed in Early Cretaceous time.

The calcite section of the cap rock is composed of alternating layers of dark and light calcite. Petrographic, geochemical, and isotopic data on dark calcite indicate that the dark calcite is the product of calcium sulfate reduction by hydrocarbons in a saline, deep-basin fluid. Another deep-basin fluid, more enriched in Sr, Ba, Mg, and Mn, dissolved some of the dark calcite, which then reprecipitated as coarsely crystalline light calcite. The only effect of meteoric water on either the anhydrite or the calcite section of the Oakwood cap rock is the presence of gypsum in the calcite/anhydrite transition zone. Anhydrite cap rock beneath the salt overhang of Oakwood Dome (≈6,000 ft deep) had an origin similar to that of the cap rock on top of the dome.

Petrographic analyses of cap rock from Rayburn's and Vacherie Domes (Louisiana) and Cypress Creek and Richton Domes (Mississippi) further substantiate the two different types of cap rock. The cap rock from Rayburn's Dome is similar to that at Gyp Hill Dome, whereas the cap rock from Vacherie is similar to Oakwood Dome cap rock. The mineralogy and textures observed in cap rocks from Richton and Cypress Creek Domes indicate that they are intermediate between Gyp Hill and Oakwood cap rocks.

Petrographic and geochemical studies of cap rock are important in evaluating the hydrologic stabilities of salt domes being considered as repositories for high-level nuclear wastes. Anhydrite cap rocks such as those at Oakwood Dome contain recrystallized anhydrite, are devoid of gypsum, have a tight cap-rock/salt contact, and formed early in the geologic history of the basin. There is no evidence within the cap rock of recent salt dissolution by meteoric ground water. In contrast, cap rocks such as those at Gyp Hill contain unrecrystallized anhydrite, are cemented with gypsum, and have both unce-mented anhydrite sands and a cavity at the salt/cap-rock contact. They also exhibit ample evidence of recent salt dissolution by meteoric water, a condition unacceptable in a salt dome being considered as a high-level nuclear waste repository.

Keywords: cap rock, salt dome, Texas

INTRODUCTION

Salt domes commonly penetrate the fresh, meteoric, ground-water aquifers surrounding the northern Gulf of Mexico but few saline plumes or halos have been found around these domes (Kreitler and others, 1980). This situation is anomalous, considering the extremely soluble nature of halite. The occurrence of a dome in a fresh-water aquifer is a compelling argument that the dome is not dissolving at present. Dissolution rates for many domes are either zero or too low for detection. If dissolution is not occurring, an impermeable seal must be isolating the salt from circulating ground water.

Cap rock, the focus of this report, may be the impermeable seal that prevents obvious salt-dome dissolution. This sealing mechanism is critical because salt domes are being considered as potential repositories for long-term storage of nuclear wastes. A salt dome should be hydrologically secure, that is, the repository cannot be breached, nor can radioactive waste leak out of the dome as a result of salt dissolution. It should also be tectonically stable, that is, dome growth should have stopped or should be extremely slow; these conditions are necessary for a dome to be acceptable for nuclear waste storage (Kreitler, 1979). If dome dissolution is prevented by the presence of cap rock, it is important to understand the general lithology, genesis, and hydrologic characteristics of cap rock and the variability of different cap rocks. Some cap rocks may function as impermeable seals, whereas others may be ineffective permeability barriers.

Cap rock is the anhydrite, gypsum, or calcite rock that typically overlies salt diapirs and is genetically related to them. The cap rock and the salt stock are collectively called a "salt dome." A generalized cap-rock sequence from the top down is (1) an upper calcite zone, (2) a middle gypsum zone, and (3) a lower anhydrite zone. The anhydrite zone results from dissolution of the salt diapir and accumulation of anhydrite as an insoluble residue. The gypsum zone results from hydration of anhydrite if the cap rock is invaded by low-temperature, low-salinity waters. The calcite zone forms if organics (probably hydrocarbons) flow through the cap rock. The organics are oxidized to CO_2, and $CaSO_4$ (either anhydrite or gypsum) is reduced. This reaction precipitates calcite and forms H_2S, pyrite, and possibly native sulfur.

Murray (1966, p. 462) proposed a generalized sequence of events to describe the formation of cap rock (fig. 1).

(1) Intrusion of salt plug into a zone of active water circulation.
(2) Gradual truncation of the top of salt by solution.
(3) Compaction of cap rock, accumulation of residual anhydrite, and intergrowth of anhydrite grains.
(4) Repetition of steps (2) and (3) to develop the banding commonly observed in anhydrite cap rock.
(5) Influx of altering solutions that hydrate anhydrite to gypsum and alter anhydrite/gypsum to calcite.
(6) Influx of oxidizing solutions that oxidize H_2S or FeS_2 to native sulfur and that form secondary calcite.

These processes have been generally agreed upon by researchers studying the genesis of cap rock (Goldman, 1933; Taylor, 1938; Martinez, 1975). What have not been thoroughly investigated are the hydrologic and geochemical environment and the timing of cap-rock formation. Murray's (1966, p. 462) sequence of events exemplifies this problem. Murray stated that the salt diapir dissolves when the plug is intruded into "an active zone of water circulation" and that gypsum and calcite result from the "entrance of altering solution." Salt diapirs in the East Texas Basin started forming during Late Jurassic time. The diapirs have passed through 10,000 to 15,000 ft (3,000 to 5,000 m) of sedimentary rock and their associated formation waters. Salt dissolution and the flow of diagenetic solutions over domes in the East Texas Basin could have occurred at any time when the domes penetrated any of the formations.

Defining the time and locations of cap-rock genesis and diagenesis is a critical problem in evaluating the hydrologic suitability of a salt dome as a nuclear waste repository. If cap rocks are currently forming in shallow, meteoric-water aquifers, as suggested by Bodenlos (1970), then the cap rock is not acting as an effective hydrologic seal. However, if cap rock formed during Cretaceous time at a depth of 5,000 ft (1,500 m), then the cap rock may be an effective hydrologic barrier preventing present and future dissolution of the diapir.

The purpose of this report is to delineate the different hydrologic and geochemical environments in which cap rock forms and to establish a time of formation. Cap rocks of two salt domes, Oakwood Dome in East Texas and Gyp Hill
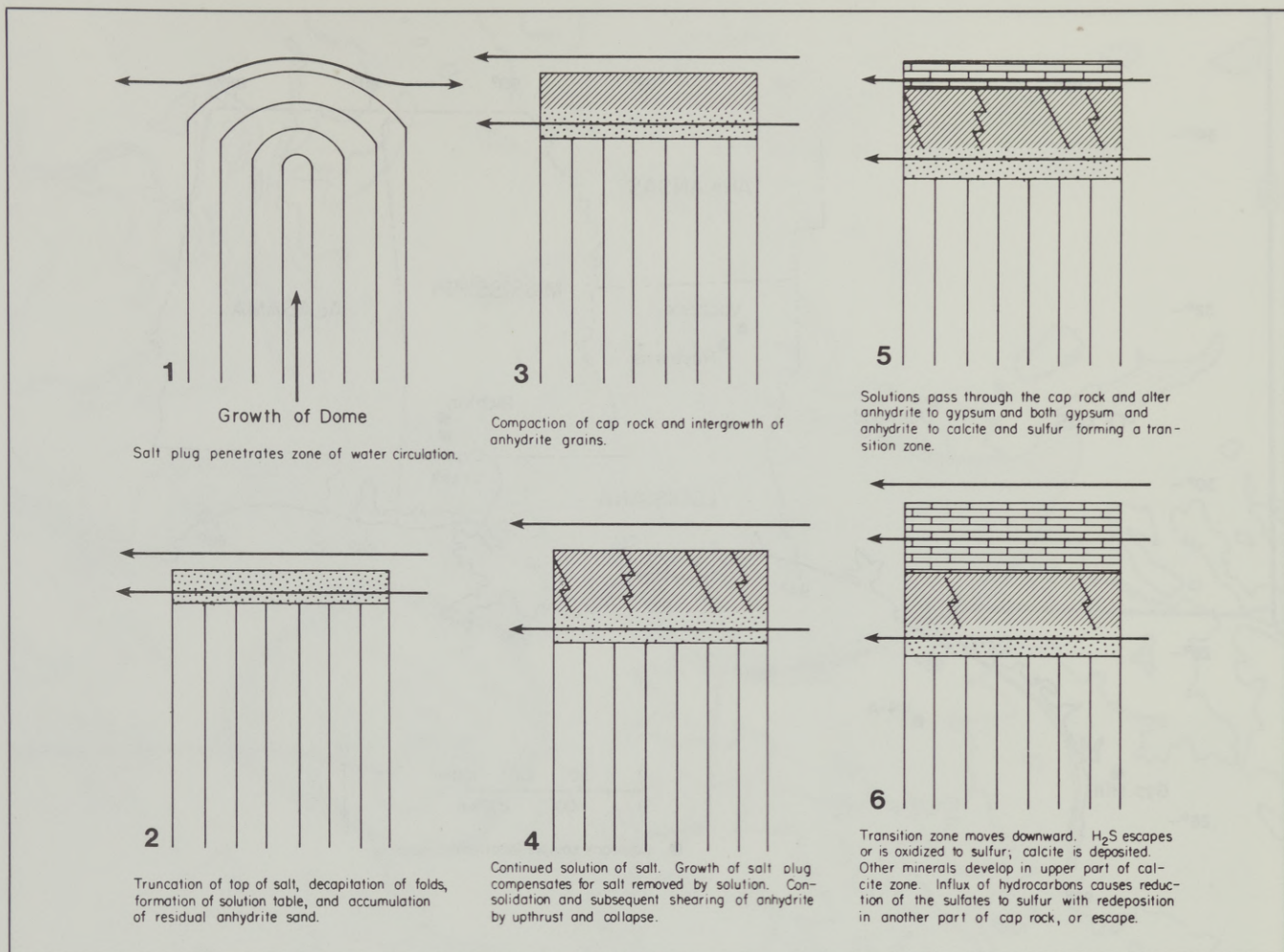
FIGURE 1. Schematic diagram of cap-rock formation (modified from Murray, 1966). Horizontal arrows show water flow.

Dome in South Texas, were studied in detail because complete cores from these domes were available. Cypress Creek salt dome and Richton salt dome in Mississippi and Vacherie salt dome and Rayburn's salt dome in Louisiana were also studied because thin sections were available from these domes.

GYP HILL DOME

Gyp Hill salt dome is located in South Texas 50 mi (80 km) southwest of Corpus Christi (fig. 2). Gyp Hill has approximately 55 ft (17 m) of topographic relief; an abandoned gypsum quarry is located near the top of the hill (fig. 3). Continuous core through the cap-rock interval was available from the quarry floor to a depth of 890 ft (271 m). The cap rock on top of the dome is in lateral contact with strata of the Pliocene Goliad Formation, Pleistocene Lissie Formation, and Holocene windblown sand (figs. 3 and 4).

Salt-Stock Lithology

Halite from the Gyp Hill salt stock was cored from 895 to 915 ft (272.8 to 278.9 m) below the quarry floor. The halite crystals are generally equidimensional and average 0.3 to 0.5 cm in diameter. Anhydrite occurs both within and between halite crystals; rare dolomite rhombs

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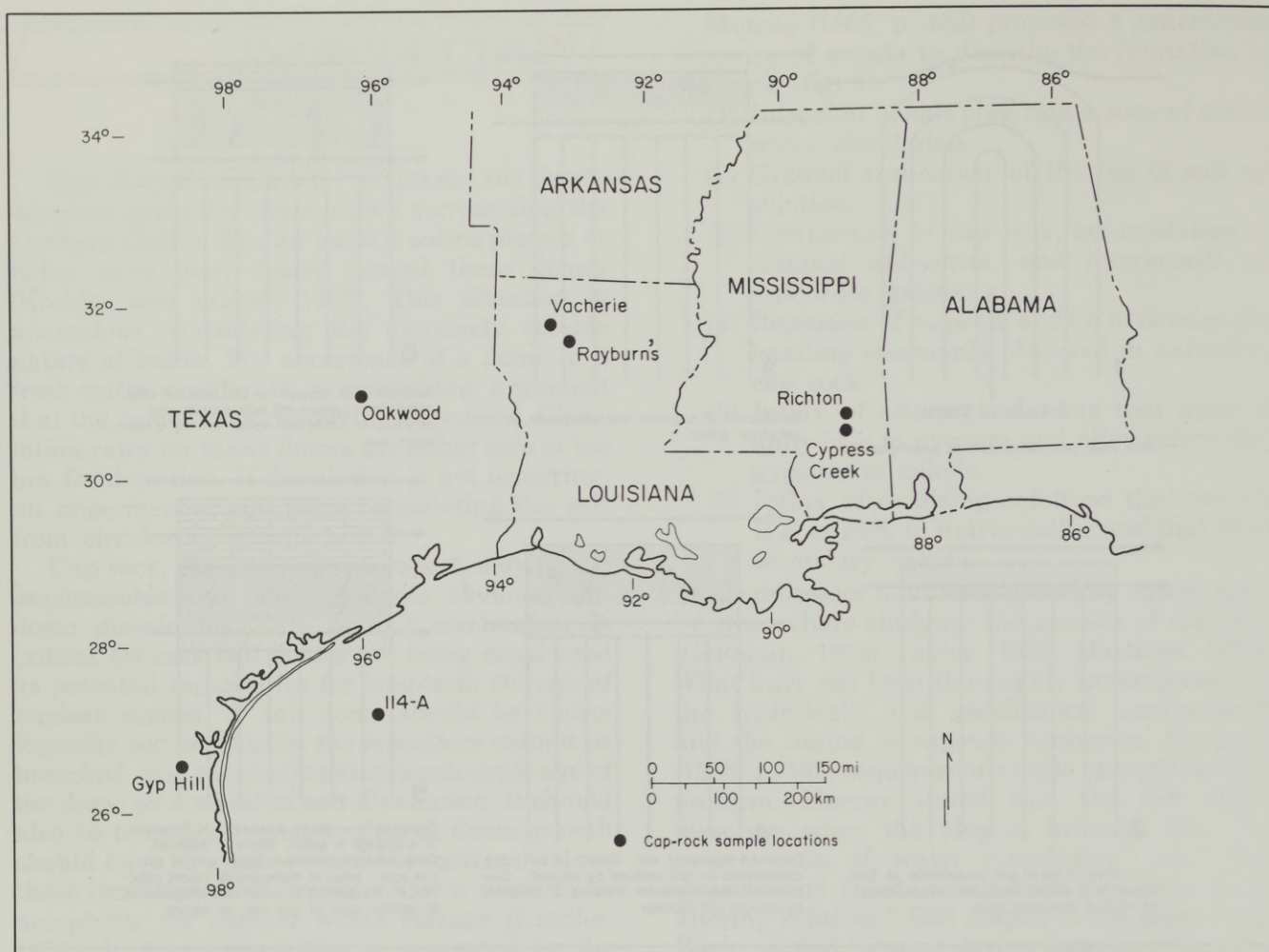
FIGURE 2. Location of salt domes with cap rock studied in this report.

are the only other mineral observed in the salt. Anhydrite is relatively abundant in the Gyp Hill salt, ranging from 13 to 42 percent by volume; other salt domes are composed of 12 to 20 percent anhydrite (Walker, 1974). Because salt samples were available only from the top 10 ft (3 m) of the salt stock, only limited information on mineral distribution is available. Dissolution near the top of the salt may have concentrated the less soluble anhydrite, and anhydrite may be more dispersed lower in the stock. However, anhydrite is most abundant (42 percent) at the base of the core, and the abundance decreases upward toward the salt/cap-rock boundary. This is contrary to what would be expected if dissolution were concentrating anhydrite near the top of the salt stock.

Anhydrite occurs in the halite both as scattered, randomly oriented, prismatic crystals (fig. 5) that are commonly 0.3 to 1.6 mm long and

as oriented groups of crystals that may be inclusions of anhydrite rock caught up in the salt stock (fig. 6). The anhydrite normally occurs as straight-sided crystals, few of which show signs of dissolution. Within the inclusions, anhydrite grains do not exhibit interlocking or recrystallized grain boundaries (fig. 6).

Cap-Rock Lithology

Gyp Hill cap rock is divided into three major lithic zones (figs. 7 and 8). The lower zone of the cap rock, from 890 to 400 ft (271 to 120 m), is primarily anhydrite with varying amounts of gypsum cement. A transition zone between anhydrite and gypsum cap rock occurs from 400 to 300 ft (120 to 90 m). Above 300 ft (90 m), the upper cap-rock zone is mainly gypsum with minor remnant anhydrite. Core recovery was poor from 891 to 911 ft (271.6 to 277.7 m), and part of

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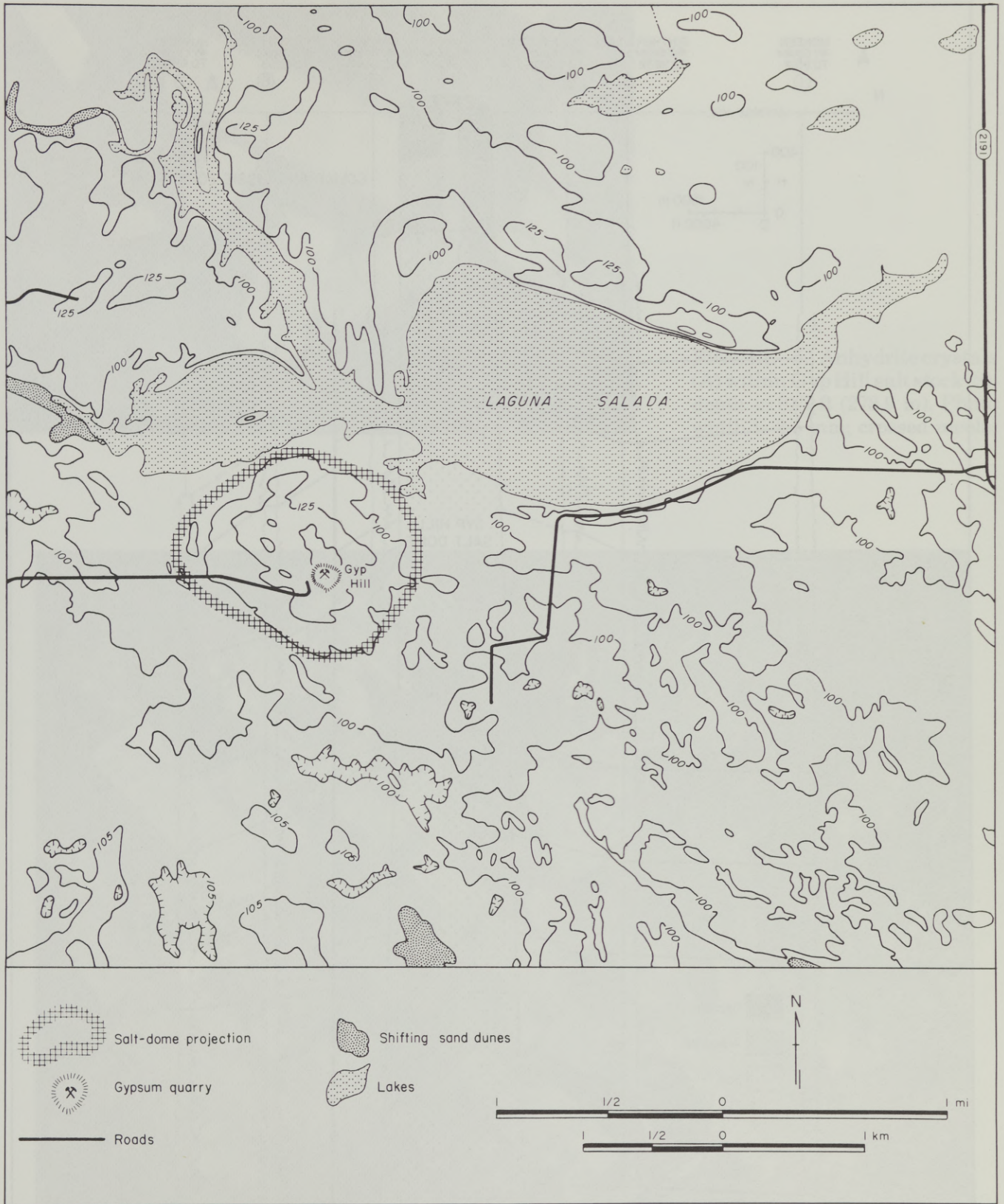
FIGURE 3. Topographic relief of Gyp Hill salt dome.
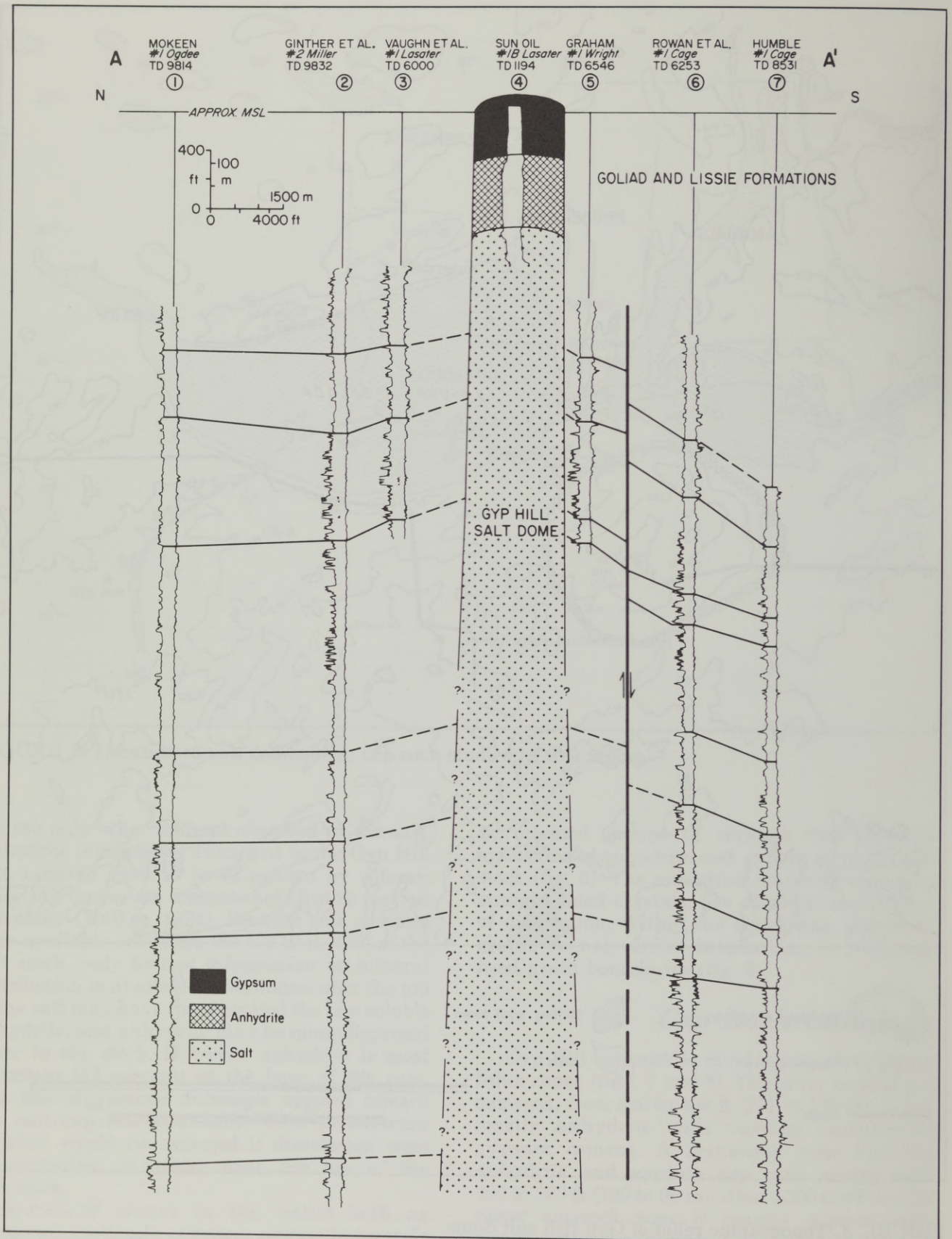
FIGURE 4. Cross section of Gyp Hill salt dome (from Finley and others, 1981).
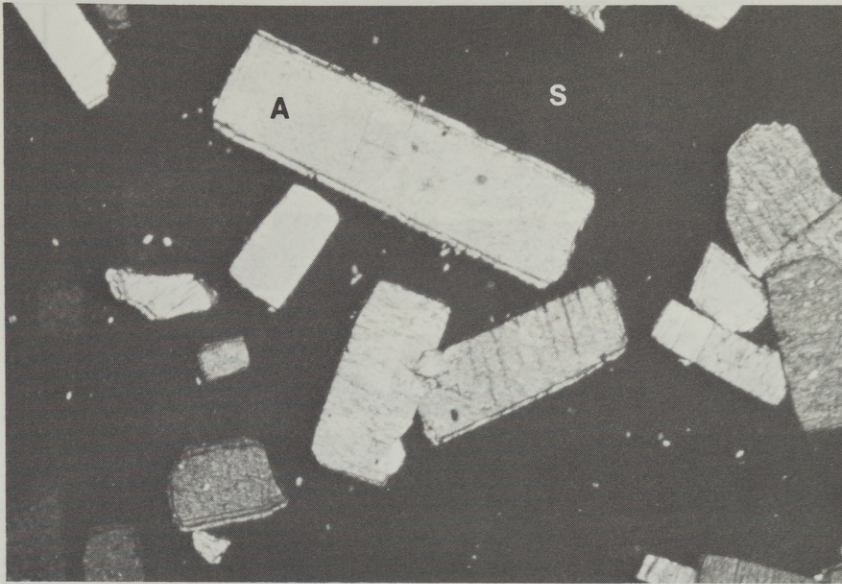
FIGURE 5. Anhydrite crystals (A) within Gyp Hill salt stock (S); depth is 915 ft (278.9 m). Photo width is 2.6 mm; crossed nicols.
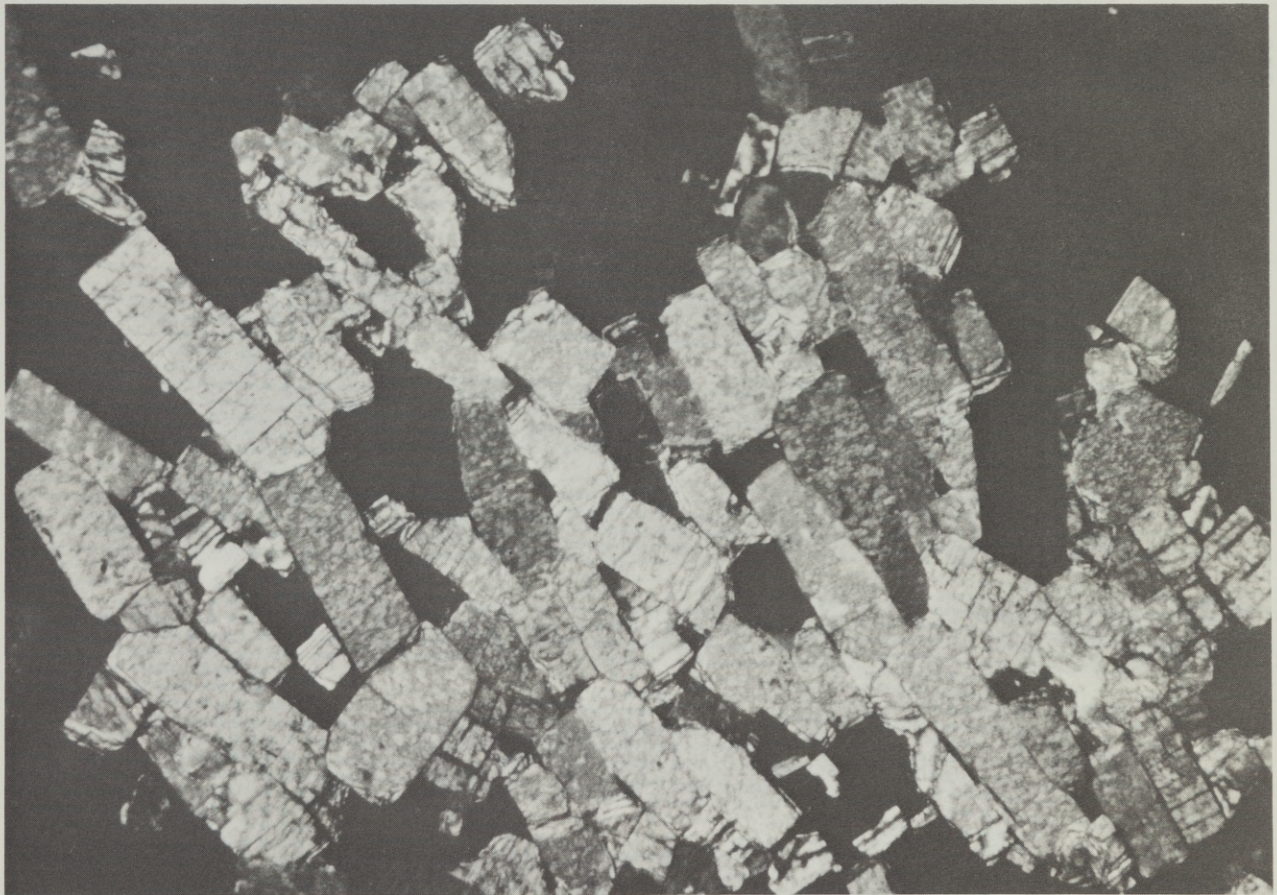
FIGURE 6. Cluster of anhydrite crystals, Gyp Hill, which may be a clast of anhydrite rock in the salt stock; depth is 915 ft (278.9 m). Photo width is 2.6 mm; crossed nicols.
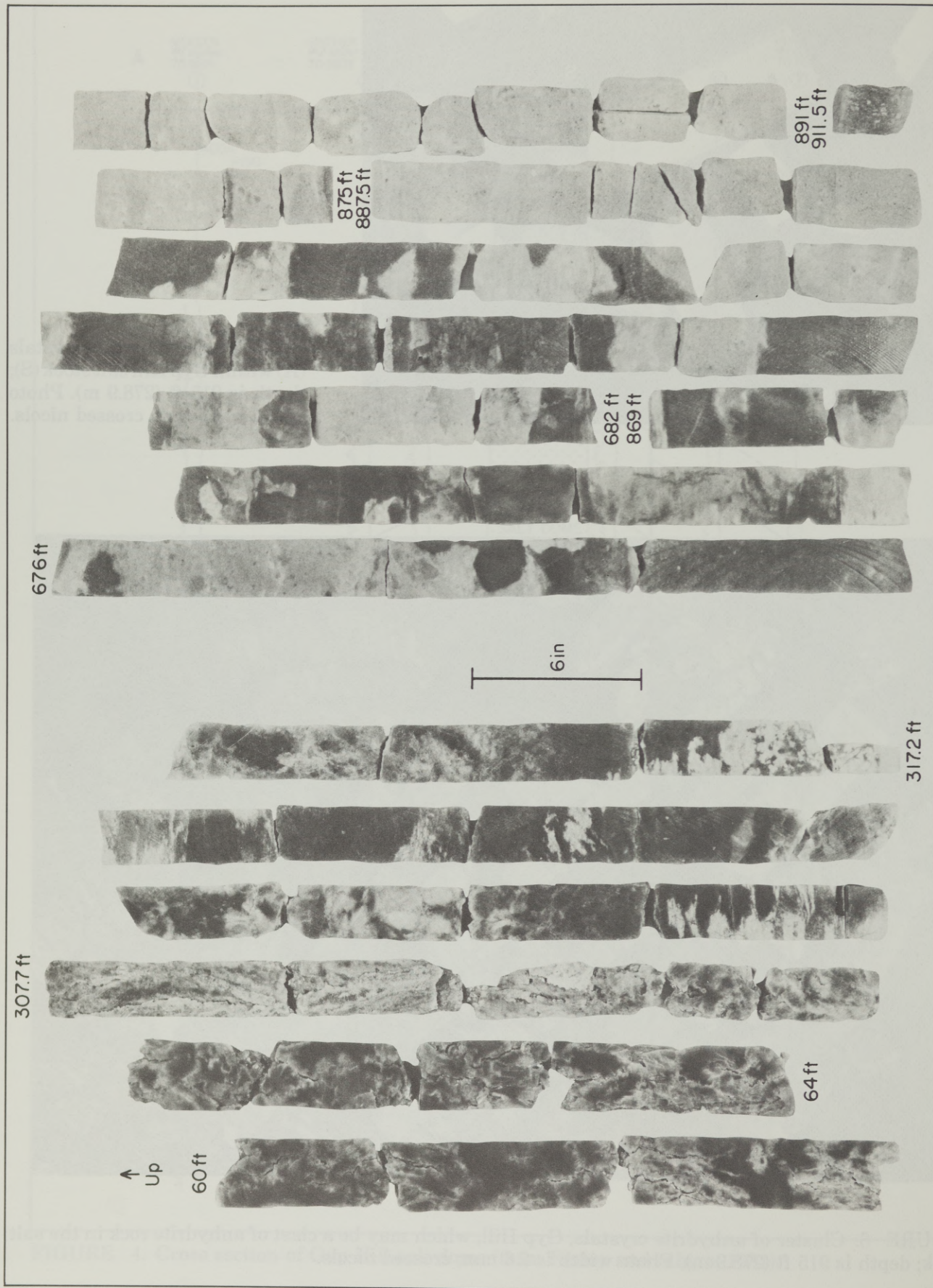
FIGURE 7. Core photographs of Gyp Hill cap rock. Depths are in feet below land surface. See figure 8 for description.

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EXPLANATION – GYP HILL CORE LOG

Lithology
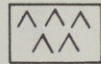
Gypsum

Anhydrite

Halite

Sandstone

P   Pyrite

S   Sulfur
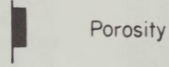
Porosity

Structures
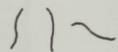
Fractures

Open fracture

Zone of anhydrite within gypsum
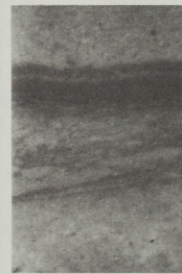
Zone of gypsum (dark) within anhydrite

Textures
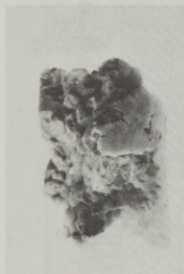
Coarsely crystalline equant gypsum

Bladed gypsum

Fine-grained equant gypsum
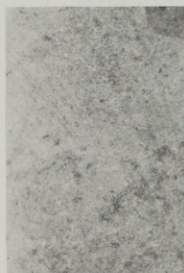
Gypsum-cemented anhydrite

Porous anhydrite

FIGURE 8. Graphic core description of Gyp Hill cap rock.
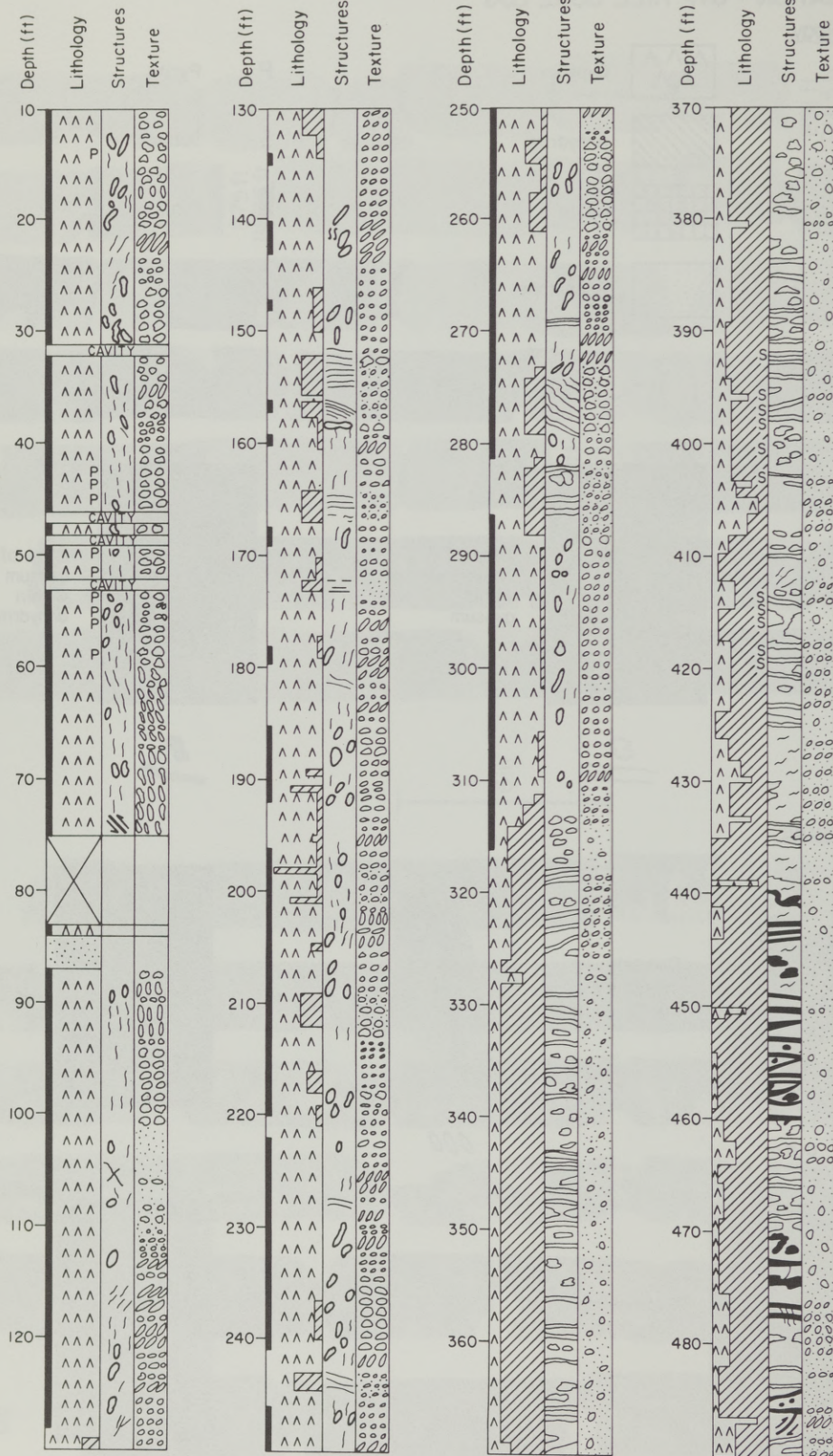
FIGURE 8 (continued)
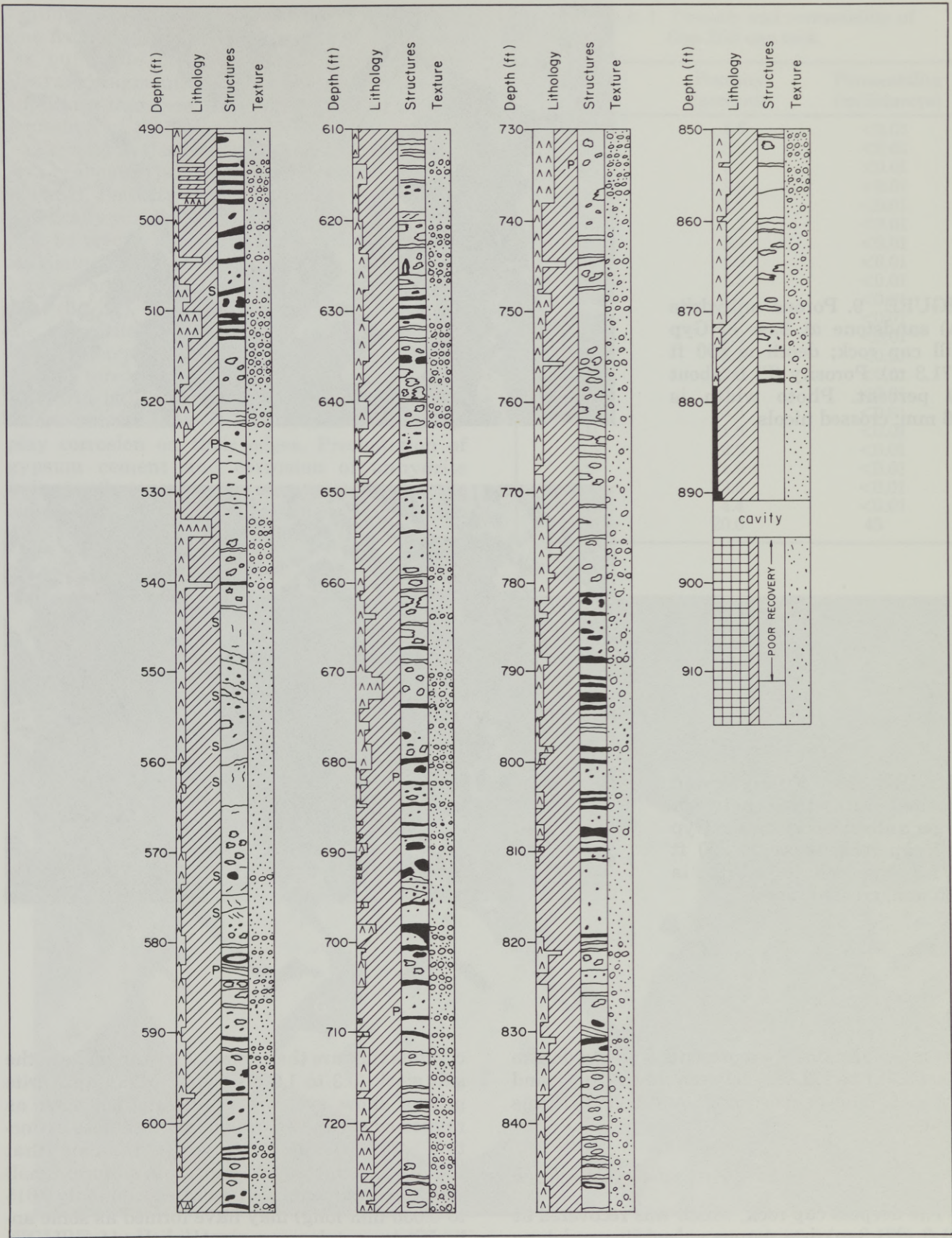
FIGURE 8 (continued)

FIGURE 9. Porous anhydrite (A) sandstone at base of Gyp Hill cap rock; depth is 890 ft (271.3 m). Porosity (P) is about 20 percent. Photo width is 2.6 mm; crossed nicols.
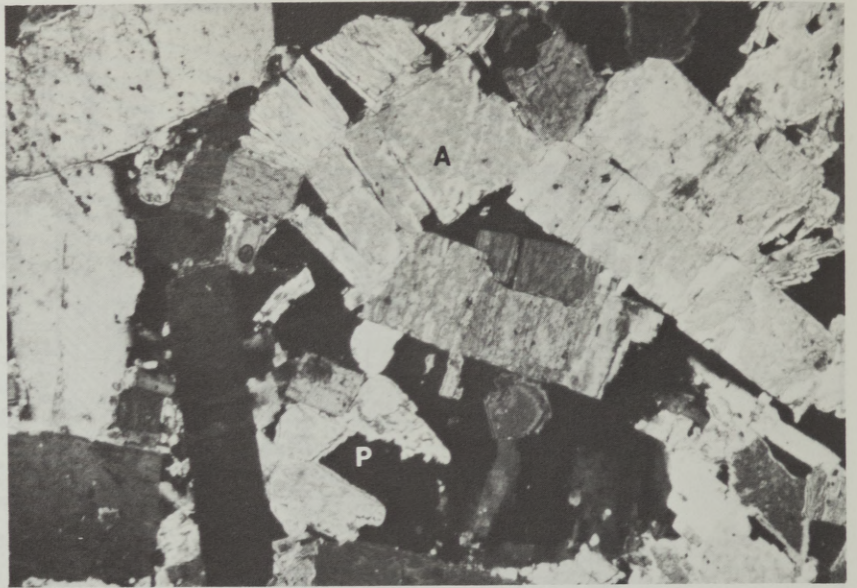
FIGURE 10. Fine-grained crushed anhydrite between larger anhydrite crystals in Gyp Hill cap rock; depth is 890 ft (271.3 m). Photo width is 0.65 mm; crossed nicols.
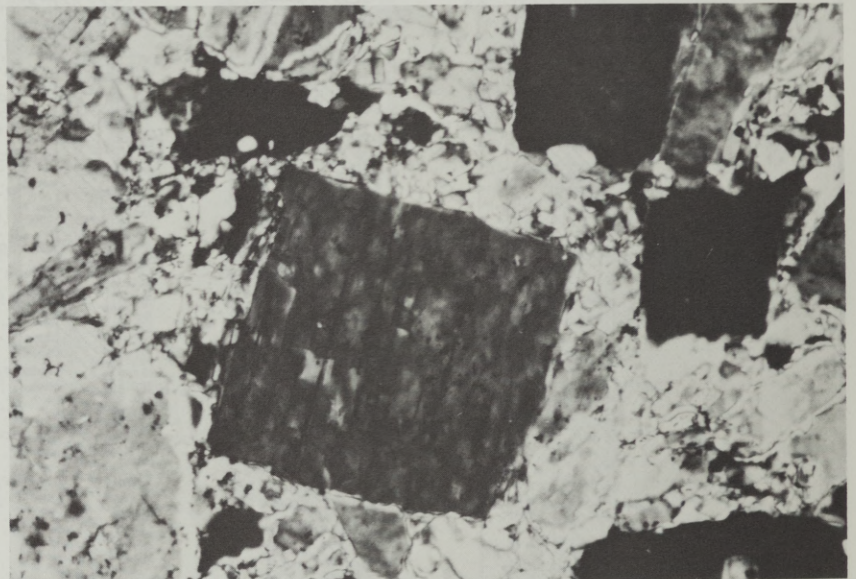
this interval probably represents a cavity (891 to 895 ft; 271.6 to 272.8 m) between the salt stock and cap rock. The caliper log shows a void in this section.

Anhydrite Cap Rock

The deepest cap rock, which was recovered at 890 ft (271.3 m), is a porous anhydrite sandstone (fig. 9). It is composed of prismatic anhydrite crystals that are the same size as anhydrite in the salt stock (0.3 to 1.6 mm long). Many anhydrite prisms show evidence of dissolution, such as ragged edges and embayments. Undulose extinction and fractured anhydrite indicate that there was some strain and grain failure. Small cleavage fragments of anhydrite (commonly 0.015 to 0.030 mm long) may have formed as some anhydrite crystals were crushed between larger grains (fig. 10) because of overburden pressure or

continued movement of the underlying salt stock. The fragments also may be points of nucleation for anhydrite crystallization. The anhydrite cleavage fragments were not observed in the salt and must, therefore, have formed during or after formation of the cap rock.

Porosity in the deepest sample of Gyp Hill cap rock is about 20 percent and permeability is 45 md (table 1). Porosity and permeability are reduced drastically within 20 ft (6 m) above the base of cap rock by precipitation of gypsum cement (table 1). Poikilotopic gypsum cement fills pore space between anhydrite grains and also replaces anhydrite (fig. 11). The amount of gypsum cement in the anhydrite zone of the cap rock ranges from 0 to 75 percent (fig. 12). The gypsum cement is not fractured, indicating that fracturing of the anhydrite laths occurred after salt dissolution but before cementation. The anhydrite crystals display corrosion on their edges. Precipitation of gypsum cement and corrosion of anhydrite indicate that anhydrite was unstable at the temperature and salinity existing within the cap rock during cap-rock formation.

TABLE 1. Porosity and permeability of Gyp Hill cap rock.

Depth (ft)	Porosity (percent)	Permeability (millidarcys)
50	1.6	<0.01
123	3.0	<0.01
152	1.4	<0.01
171	2.0	<0.01
230	2.5	<0.01
272	1.2	<0.01
284	3.4	<0.01
310	1.3	<0.01
340	1.5	<0.01
370	1.3	<0.01
400	2.6	<0.01
428	1.6	<0.01
500	5.1	<0.01
600	2.6	<0.01
690	3.1	<0.01
740	3.3	<0.01
794	1.6	<0.01
815	2.2	<0.01
835	1.6	<0.01
855	3.6	<0.01
875	4.4	<0.01
890	20.0	45
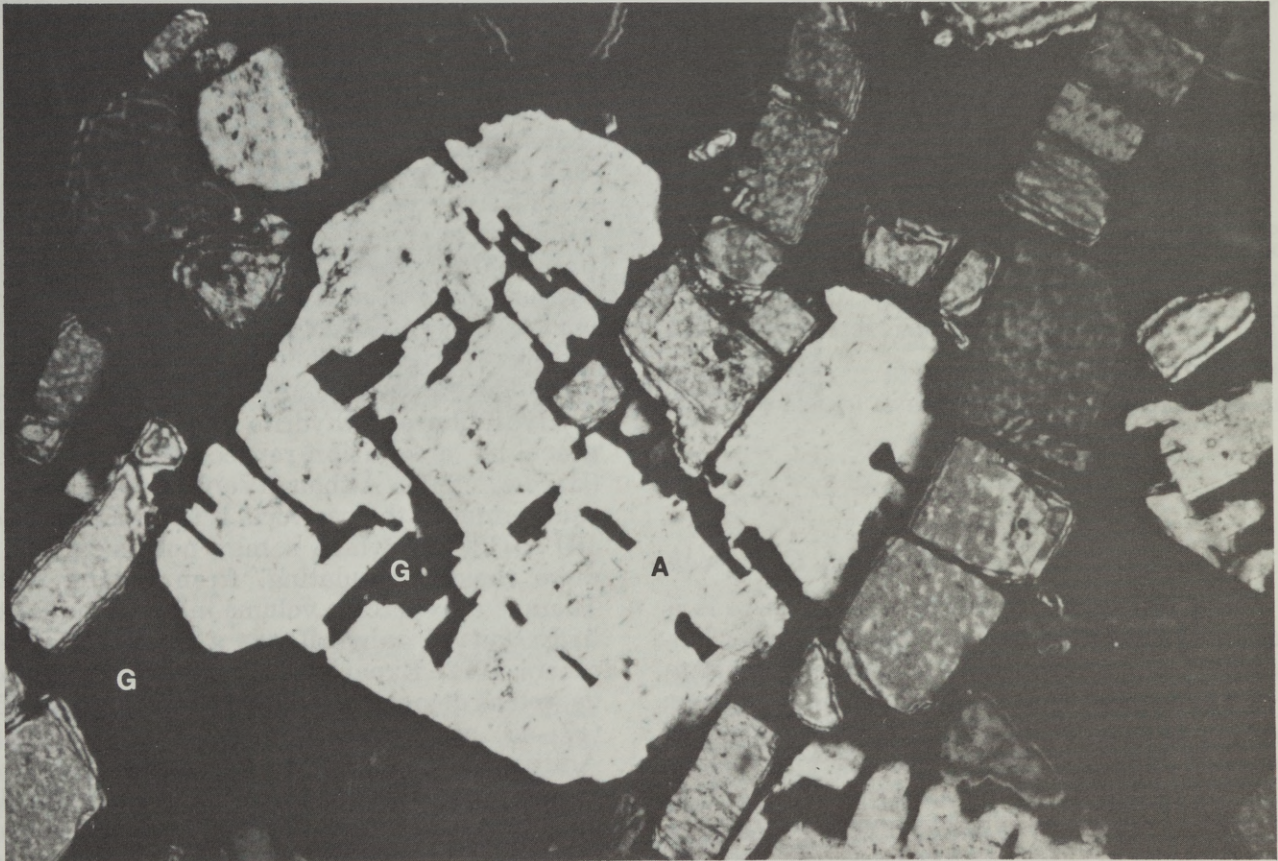
FIGURE 11. Poikilotopic gypsum cement (G) filling pore space and replacing anhydrite crystals (A) in Gyp Hill cap rock; depth is 837 ft (255.1 m). Photo width is 0.65 mm; crossed nicols.
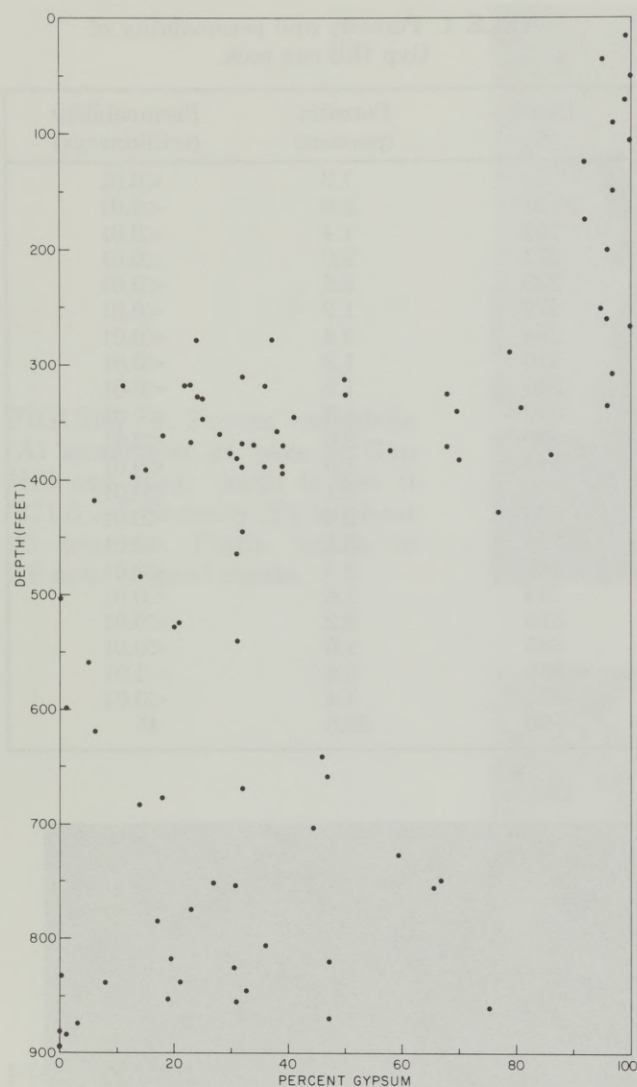
FIGURE 12. Percent gypsum versus depth in Gyp Hill cap rock.

Gypsum Cap Rock

From 300 to 400 ft (90 to 120 m), there is a transition zone in which the anhydrite has hydrated to gypsum. Within this interval, the cap-rock composition varies between 6 and 97 percent gypsum. Above the transition zone the cap rock is composed almost entirely of gypsum, having only a few percent of remnant anhydrite (fig. 12). Rare dolomite rhombs and euhedral quartz crystals are also present.

Gypsum exhibits three textures—fine-grained equigranular, coarse-grained equigranular, and bladed. The fine-grained gypsum occurs as an interlocking mosaic of equant to elongate crystals that are 0.15 to 0.30 mm in diameter (fig. 13). These crystals generally exhibit little evidence of strain. Porosity and permeability are low.

Coarse-grained equigranular gypsum is the most common form of gypsum in the upper zone of Gyp Hill cap rock. Crystals are 1.5 to 6 cm in diameter, with abundant intercrystalline porosity. The coarse crystals have undulose extinction, indicating that they have been strained (fig. 14). Unstrained, fine-grained gypsum crystals commonly exist within coarse crystals. The stable, fine-grained crystals are probably subgrains formed by recrystallization of the coarsely crystalline, highly strained gypsum.

The third gypsum crystal morphology in the cap rock is a bladed form (fig. 15). Crystals vary from 1.5 x 6.0 cm to about 6 x 30 cm. No sharp size boundary separates bladed and equigranular crystals, and small bladed crystals grade into elongate equigranular forms. Bladed crystals are also highly strained and display undulose extinction. Intercrystalline porosity is abundant in most bladed units.

Porosity and permeability values, measured in core plugs from the top 300 ft (90 m) of the cap rock, are low (table 1). However, many intervals within the gypsum cap rock have abundant inter-crystalline, fracture, and vuggy pores. Porosity in these zones could not be measured in 1-inch (3.54-cm) plugs because the plugs broke apart along fractures. This porosity is probably sufficient to conduct circulating ground water through the upper cap rock. Some pores in the gypsum cap rock are lined with gypsum crystals, but other pores have either no crystals or partly dissolved crystals. Solution-enlarged fractures and vugs are also evidence of gypsum dissolution.

Hydration of anhydrite to gypsum may take place by a solution-reprecipitation process (Hardie, 1967). Although anhydrite is not in equilibrium in the cap rock, it is preserved below 400 ft (120 m), where it may not be exposed to more rapidly circulating, fresh ground water. There is a 38-percent volume increase during the hydration of anhydrite to gypsum (Blatt and others, 1972). Expansion of anhydrite to gypsum, as well as domal uplift, may have caused the 55 ft (17 m) of topographic relief at Gyp Hill. Additional features documenting hydration expansion are strained gypsum crystals (fig. 14), shear fractures (fig. 16), and vertical selenite crystals, 1 to 3 ft (0.3 to 1 m) long in the quarry walls (fig. 17), which appear to have grown along the axis of least stress.
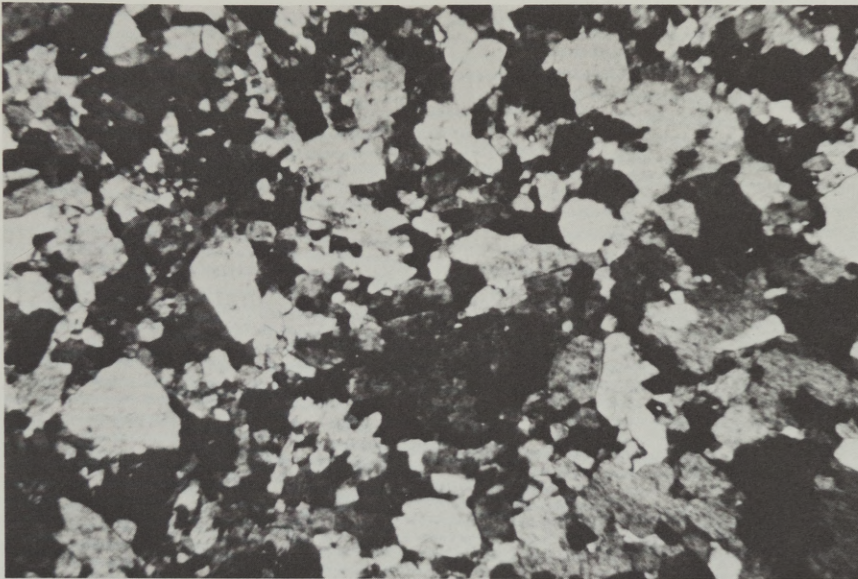
FIGURE 13. Fine-grained, relatively unstrained gypsum from Gyp Hill cap rock; depth is 106 ft (32 m). Photo width is 2.6 mm; crossed nicols.
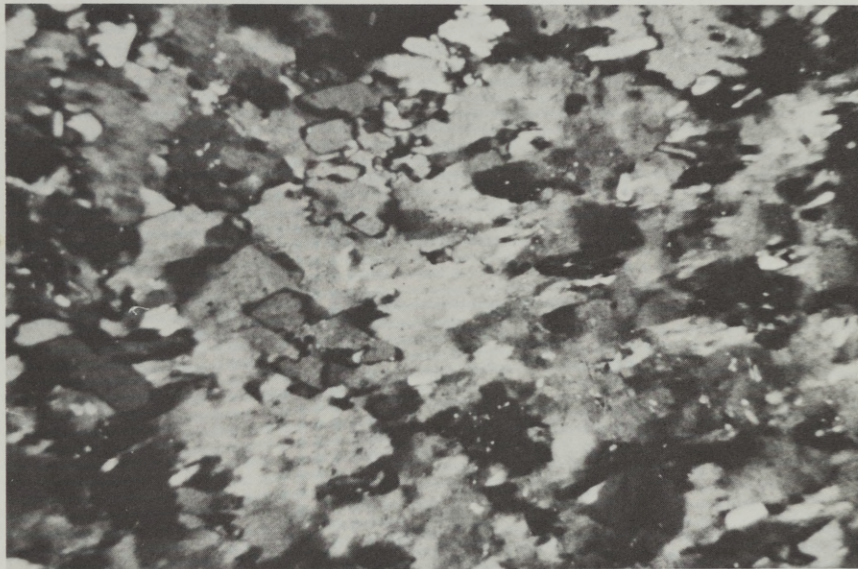
FIGURE 14. Highly strained, equigranular gypsum from Gyp Hill cap rock; depth is 15 ft (4.6 m). Black areas are all gypsum at extinction. Photo width is 2.6 mm; crossed nicols.

Diagenetic History

Anhydrite crystals in Gyp Hill cap rock that are similar in size and shape to anhydrite crystals in the salt stock indicate a residual accumulation origin of anhydrite in the cap rock. Rare dolomite rhombs (<1 percent) occur in both cap rock and salt stock; this co-occurrence also supports the residual accumulation interpretation. Euhedral quartz crystals are present in the cap rock, but none were observed in the salt. However, quartz crystals have been reported in other salt stocks (Goldman, 1952; Walker, 1974); these crystals may be present in the Gyp Hill salt but were not detected. Therefore, it is not necessary to postulate in situ direct precipitation, as suggested by Walker (1974), to explain the presence of anhydrite, dolomite, or quartz in the cap rock.

Further support of the residual accumulation hypothesis is the fact that many anhydrite

FIGURE 15. Bladed gypsum crystals from Gyp Hill cap rock; depth is 74 ft (22.6 m).

indicates that the anhydrite cap rock could not have had a precipitation origin. We conclude, therefore, that Gyp Hill cap rock formed by residual accumulation of anhydrite from the Gyp Hill salt stock.

Gypsum within the cap rock formed by two different processes. Gypsum in the upper 300 ft (90 m) resulted from hydration of anhydrite to gypsum with resultant strained crystals and shear fractures. This deformation probably is unrelated to domal uplift because the gypsum cement in the underlying anhydrite section is undeformed. Movement of shallow meteoric water through the upper zone of the cap rock is the presumed method of hydration.

Gypsum within the lower anhydrite zone (490 ft; 150 m) of the cap rock is a pore-filling cement. Precipitation of the gypsum cement does not involve volume expansion, so there is no fractured or strained gypsum in this zone. Physiochemical conditions here are different from those in the shallower zone. Temperature and salinity conditions required for precipitation of the gypsum cement may have approached the equilibrium boundary between gypsum and anhydrite (fig. 18). Although the edges of the anhydrite crystals have been corroded, massive alteration to gypsum has not occurred.

The following sequence of diagenesis is postulated. (1) The salt dome was dissolved by low-temperature, low-salinity waters (probably meteoric), leaving a residuum of ragged anhydrite crystals. Although the water became highly saline, it was undersaturated with respect to calcium sulfate, resulting in some dissolution of anhydrite. (2) Pore fluids then became saturated with respect to calcium sulfate either by dissolving the fine-grained anhydrite or by mixing of waters of different salinities (Shternina, 1960) or different temperatures (Hardie, 1967; fig. 4), which caused the gypsum cement to precipitate. Anhydrite laths are well rounded in comparison to the noncemented and deeper anhydrite because gypsum cement corroded the edges of anhydrite crystals. (3) Later, low-salinity meteoric water moved through the upper part of the cap rock and anhydrite was completely hydrated to gypsum.

The Gyp Hill cap rock is presently forming in shallow meteoric aquifers. The anhydrite crystals are relatively undeformed (in contrast to Oakwood Dome), and gypsum is the stable $CaSO_4$ phase. The void at the salt/cap-rock interface and the uncemented but cohesive anhydrite sands immediately above the void suggest that dissolution is presently occurring.

crystals at the base of the cap rock show signs of dissolution (fig. 9). If the cap rock formed in place by precipitation, anhydrite crystals should have straight crystal boundaries (for example, Goldman's [1952] regenerated anhydrite) instead of ragged, corroded edges. Precipitation of gypsum cement within 20 ft (6 m) of the base of the cap rock indicates that gypsum, not anhydrite (fig. 18), is the stable calcium sulfate phase throughout most of this environment; it also

FIGURE 16. Shear fractures in gypsum from Gyp Hill cap rock; depth is 308 ft (93.9 m). Photo width is 2.6 mm; crossed nicols.

FIGURE 17. Strained gypsum, quarry wall, Gyp Hill salt dome.
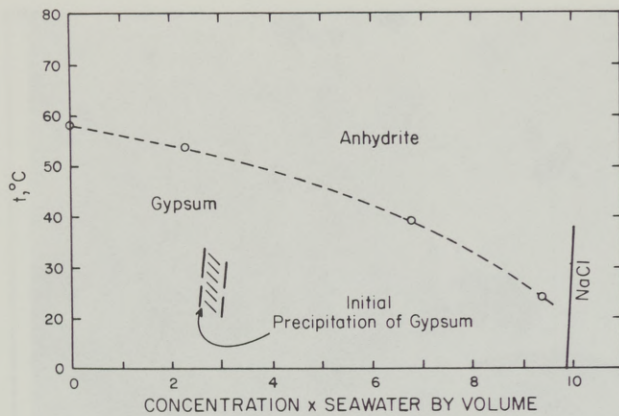
FIGURE 18. Gypsum-anhydrite equilibrium diagram (from Blatt and others, 1972). Published with permission of Prentice-Hall.

OAKWOOD DOME

Four hundred and fifty feet (137 m) of cap-rock core was recovered from Oakwood Dome in Freestone County (fig. 2). The top of the cap rock is 713 ft (217.3 m) below land surface and the top of the salt is at a depth of 1,163 ft (354.5 m). The cap rock is in sharp contact with the overlying Wilcox Group and the underlying salt. Oakwood Dome cap rock is divided into a lower anhydrite zone and an upper calcite zone; a narrow transition zone from 904 to 907 ft (275.5 to 276.5 m) separates the two types of cap rock (figs. 19 and 20). Cap rock probably also extends around the sides of the salt dome, where it is in contact with Midway Shale, Upper Navarro Marl, Pecan Gap Chalk, Austin Chalk, and Eagle Ford and Woodbine terrigenous clastics (fig. 21). An anhydrite sample was obtained from beneath the southeast overhang of the dome at a depth of approximately 5,000 ft (1,500 m) (McBee No. 1 Sherman well).

Salt-Stock Lithology

Oakwood Dome salt was cored from 1,163 ft (354.5 m) to 1,351 ft (411.8 m). The lower 181 ft (55.3 m) is foliated salt that contains numerous layers of moderately to steeply dipping disseminated anhydrite (Dix and Jackson, 1982),

separated by zones of nearly pure halite. Within the anhydrite-rich layers, the anhydrite content of the salt is generally 2 percent to about 15 percent, but it is as high as 50 percent in one 1-m interval. In the anhydrite-poor zones, the anhydrite content is less than 1.0 percent. The average anhydrite content in the entire salt core is less than 2 percent (1.3 ± 0.7 percent) (Dix and Jackson, 1982).

Halite grain size in nearly pure sections is about 23 x 7 mm, but mean grain size decreases as anhydrite content increases. The mean grain size is reduced by about half in sections with at least 5 percent anhydrite. Anhydrite crystals are commonly 0.2 to 0.6 mm long and average less than 0.5 mm long. The anhydrite occurs both as inclusions within halite crystals and along halite grain boundaries (fig. 22).

The upper 80 inches (200 cm) of salt is unfoliated. Dix and Jackson (1982) suggested that the fabric within this section was destroyed by solid-state recrystallization in the presence of small amounts of water. The unfoliated salt section ends at 1,163 ft (354.5 m), where it is in sharp contact with the cap rock.

Salt/Anhydrite Interface

Within the core, the contact between the cap rock and salt is sharp and nearly horizontal. No cavity is present at the contact; porosity in the anhydrite at 1,162 ft (354.2 m) is 1.1 percent (table 2). A 1- to 6-mm-wide layer of salt-cemented anhydrite separates the salt stock from the tightly compacted anhydrite cap rock (fig. 23). The amount of halite decreases from about 30 percent to zero across this layer. Anhydrite within this zone varies from idioblastic, prismatic crystals in halite to the interlocking, xenoblastic crystals of the cap rock (Dix and Jackson, 1982).

Veins of salt extend 0.8 to 4 inches (2 to 10 cm) up into the anhydrite cap rock in places. The halite fills extension fractures within the cap rock. Some of the salt-filled fractures have an anhydrite-rich layer across the openings, which is evidence that the cap rock formed by basal accretion of anhydrite (Dix and Jackson, 1982).
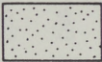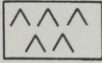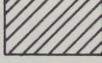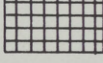
Cap-Rock Lithology

Anhydrite Section

From the contact with the salt stock at 1,163 ft (354.5 m) to a depth of 908 ft (276.8 m), the cap rock is composed predominantly of anhydrite.

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FIGURE 19. Graphic core description of Oakwood cap rock.
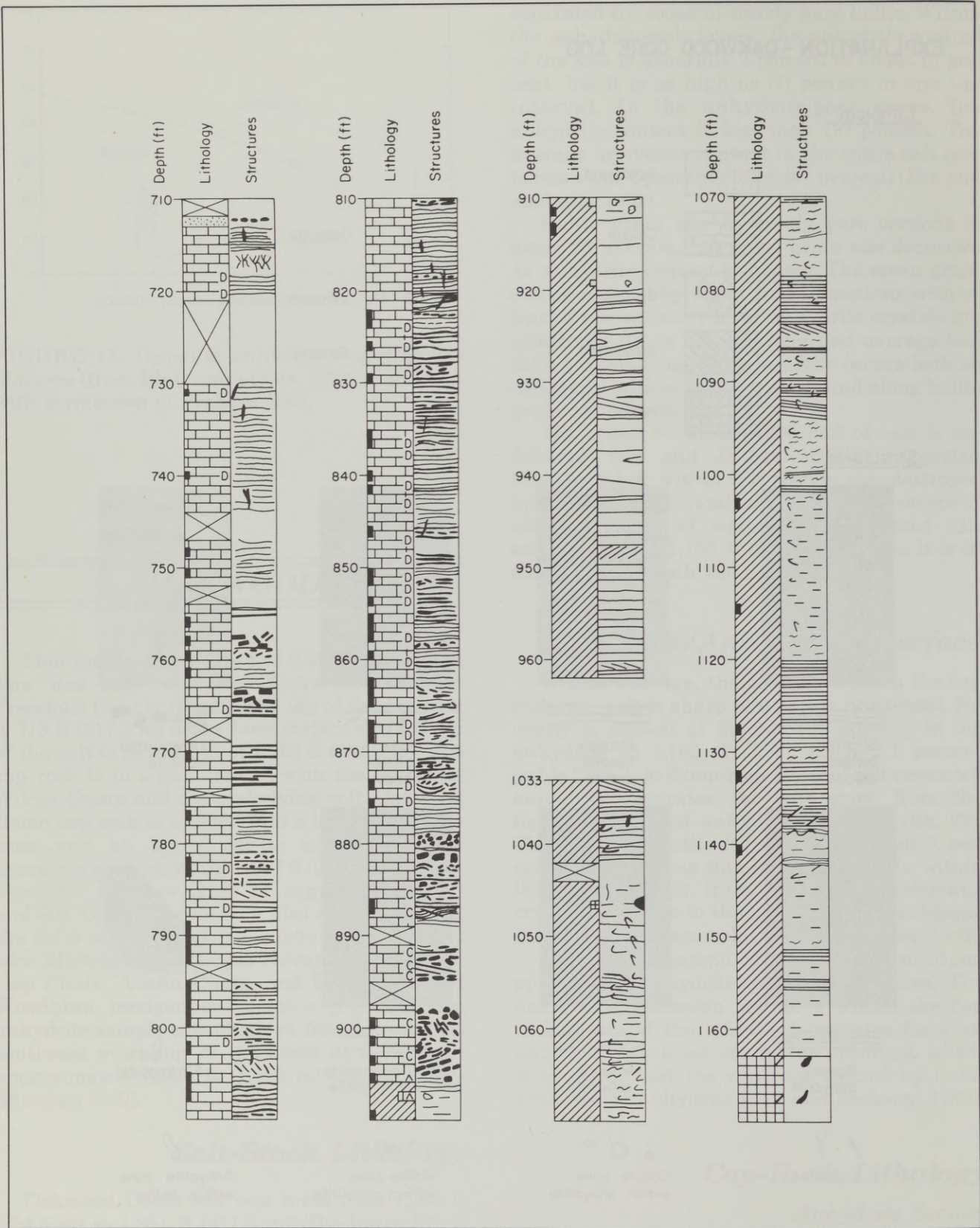
FIGURE 19 (continued)
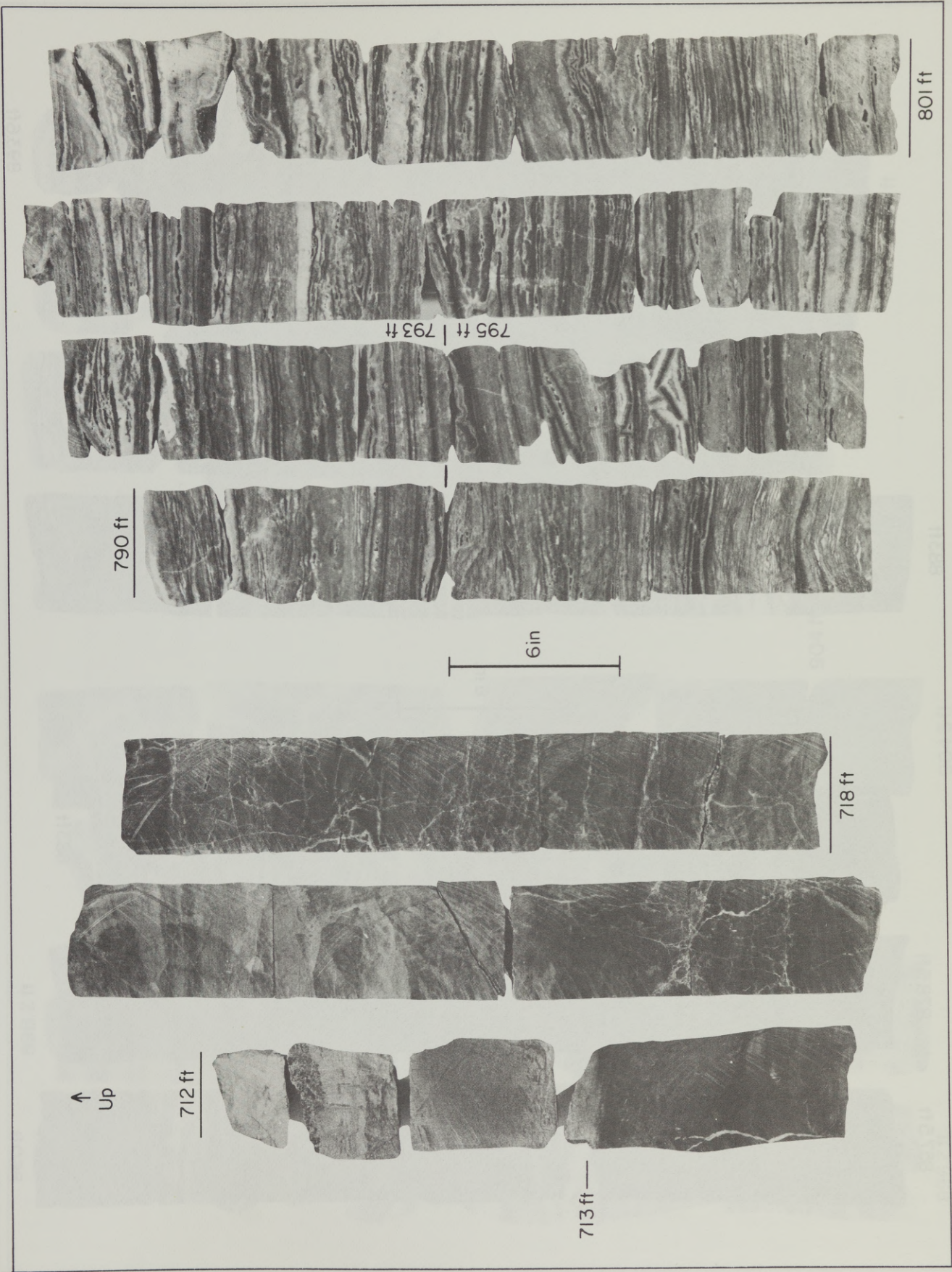
FIGURE 20. Core photographs of Oakwood cap rock. Depths are in feet.
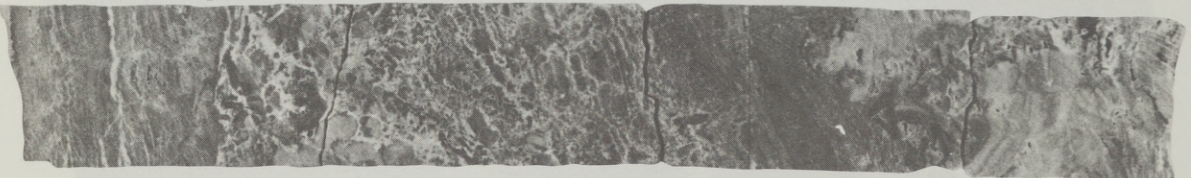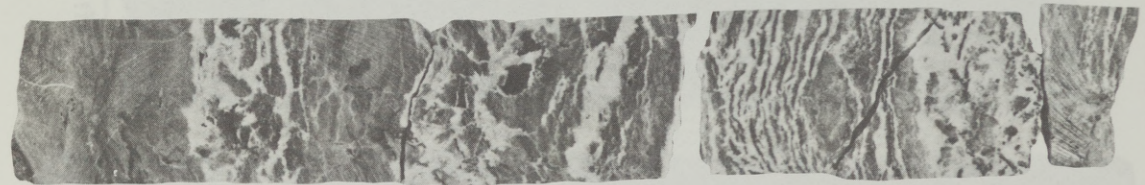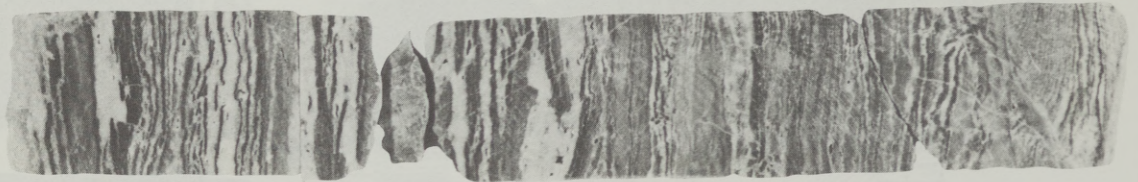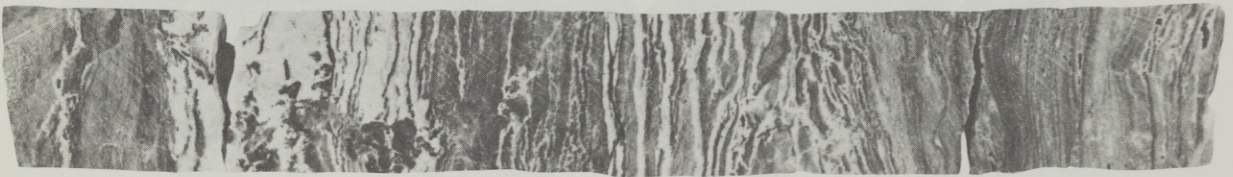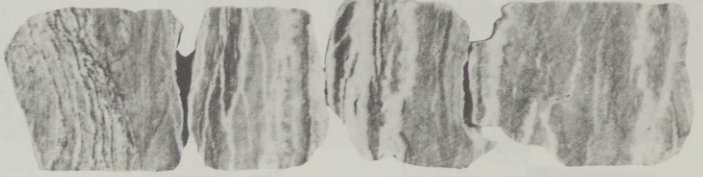
FIGURE 20 (continued)

22

FIGURE 20 (continued)

23
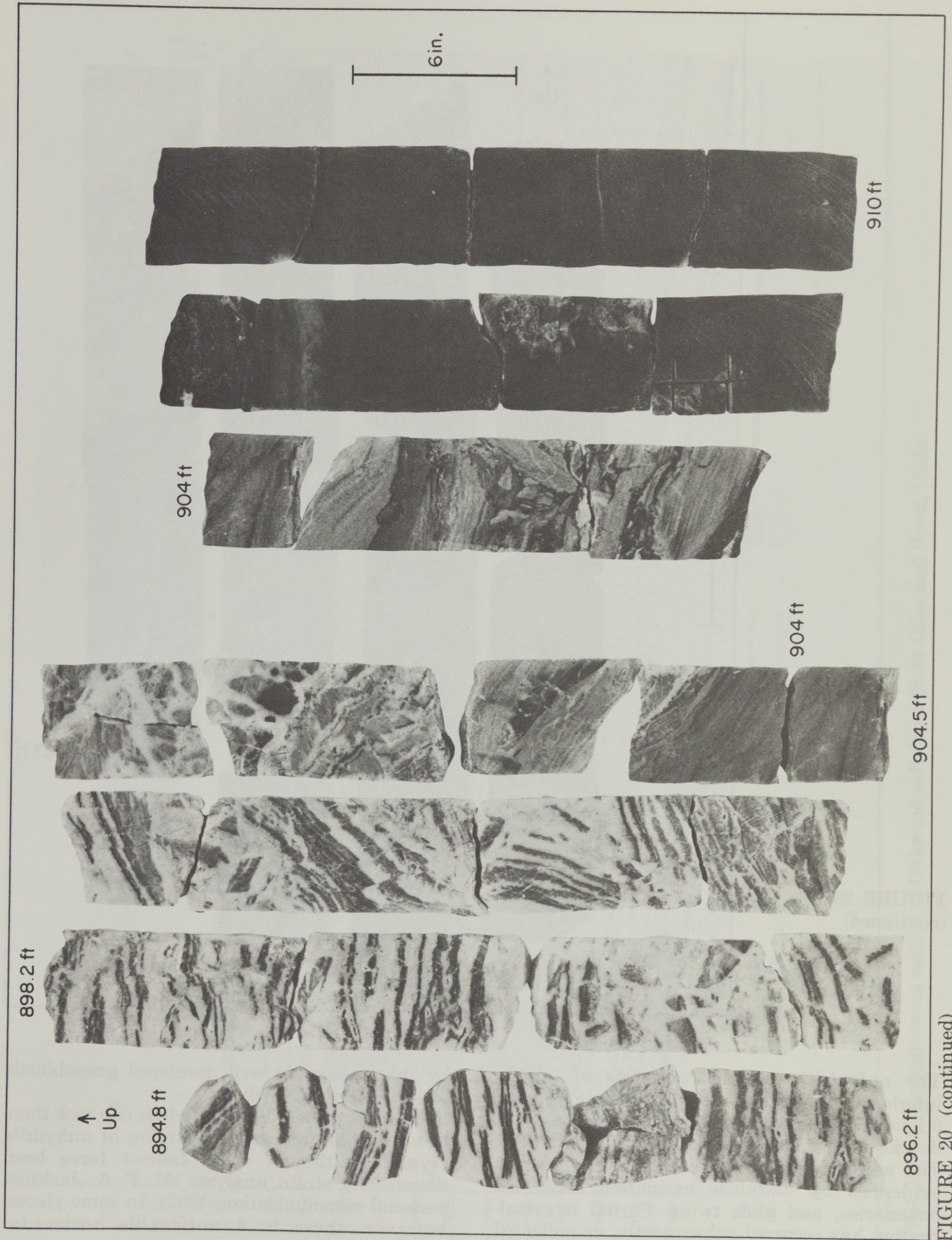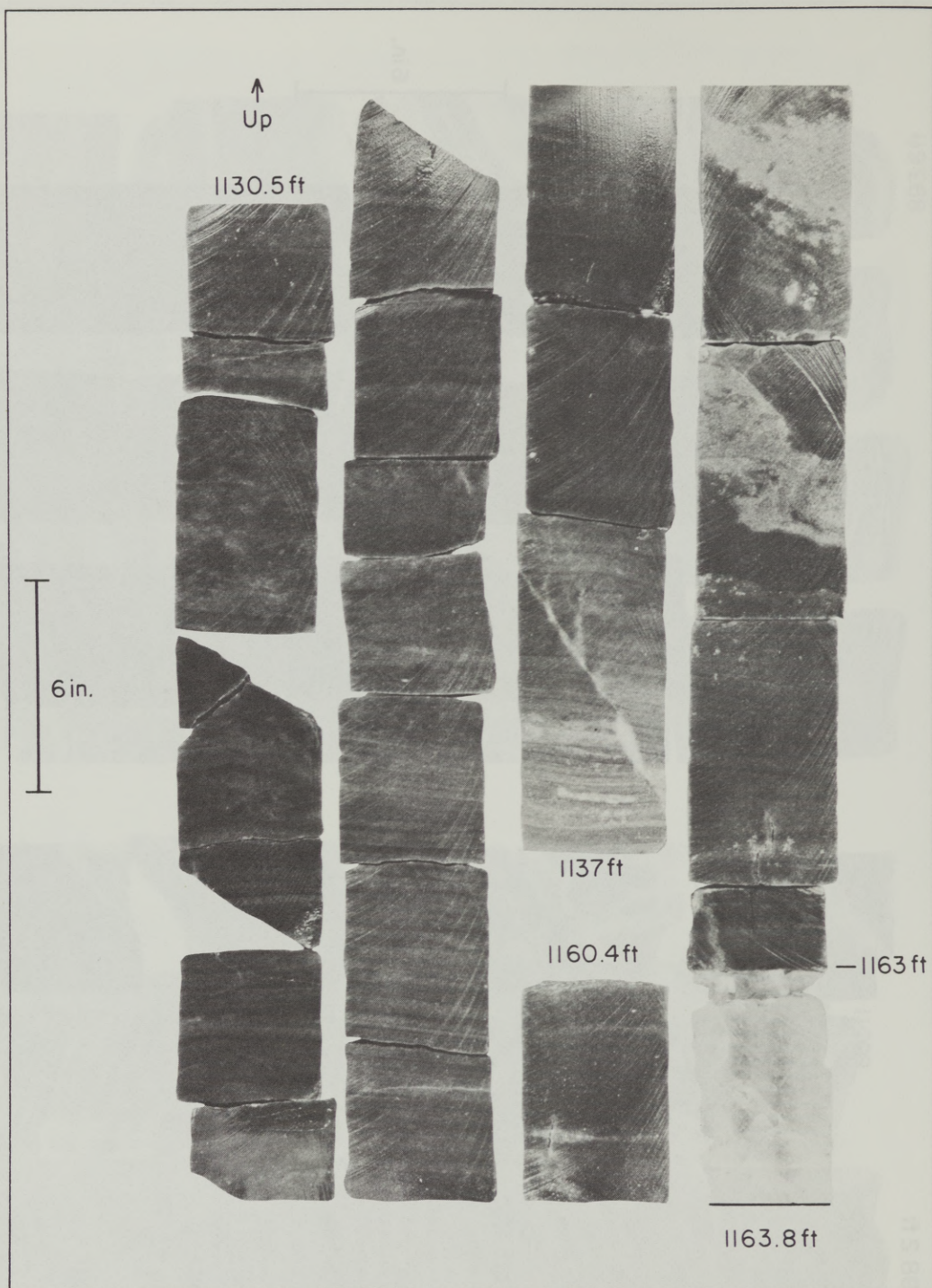
FIGURE 20
(continued)

The anhydrite cap rock consists of tightly interlocking, predominantly xenoblastic crystals, 0.1 to 1.0 mm long, that have a moderately well developed granoblastic texture (figs. 23 and 24). The anhydrite crystals have been strained, as evidenced by undulose extinction, subgrain boundaries, and glide twins. Partial recrystallization has occurred subsequently, as indicated by the moderately well developed granoblastic texture (Vernon, 1976).

In most parts of the anhydrite cap rock there is no visible preferred orientation of anhydrite crystals, although weak fabrics have been detected by strain analysis (M. P. A. Jackson, personal communication, 1982). In some places, however, there is a noticeable horizontal
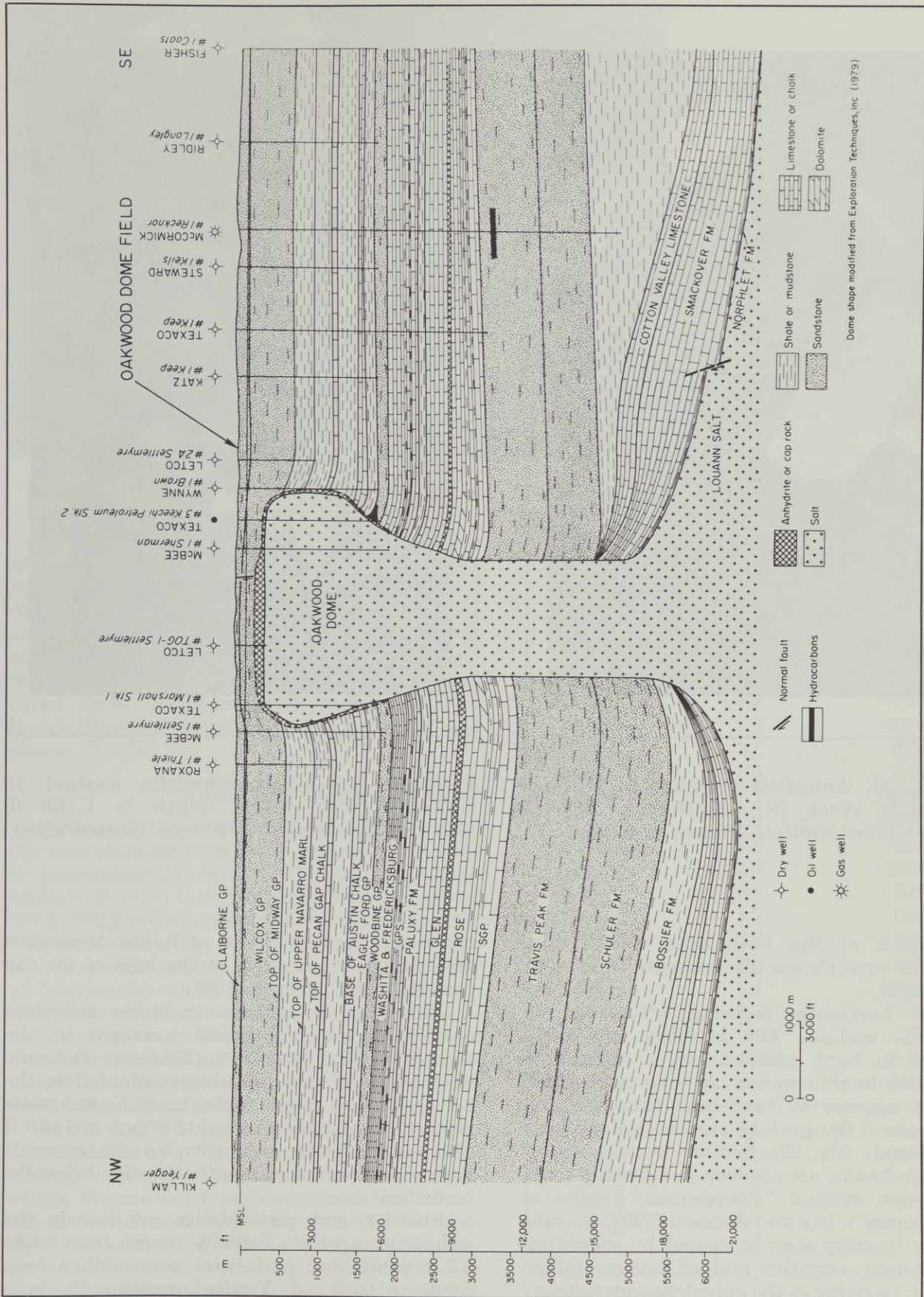
FIGURE 21. Geologic cross section of Oakwood salt dome (from Giles and Wood, 1983).

25
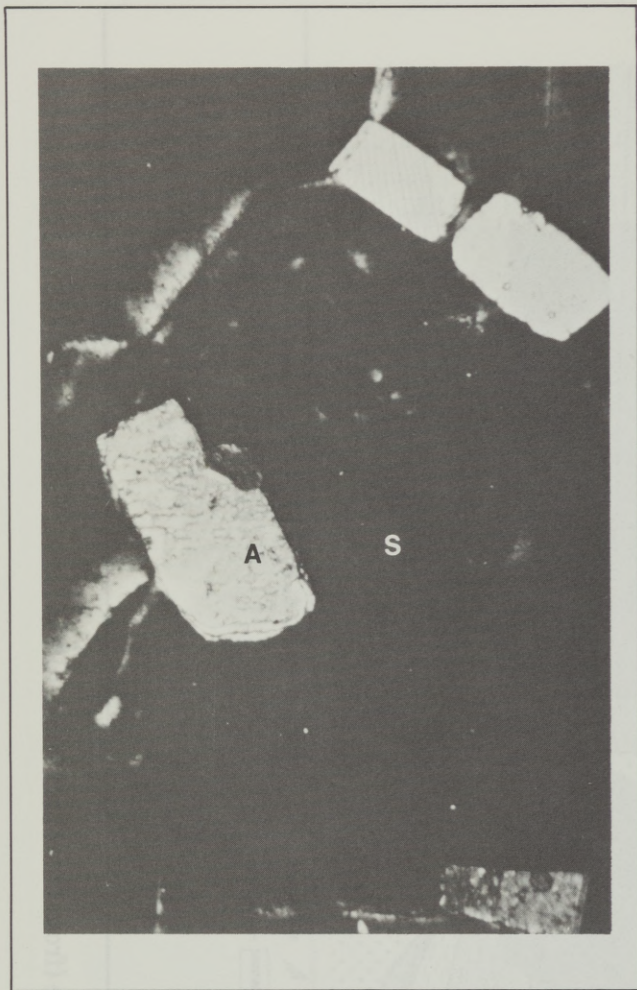
FIGURE 22. Anhydrite crystals (A) in Oakwood salt stock (S); depth is 1,163 ft (354.5 m). Photo width is 2.6 mm; crossed nicols.
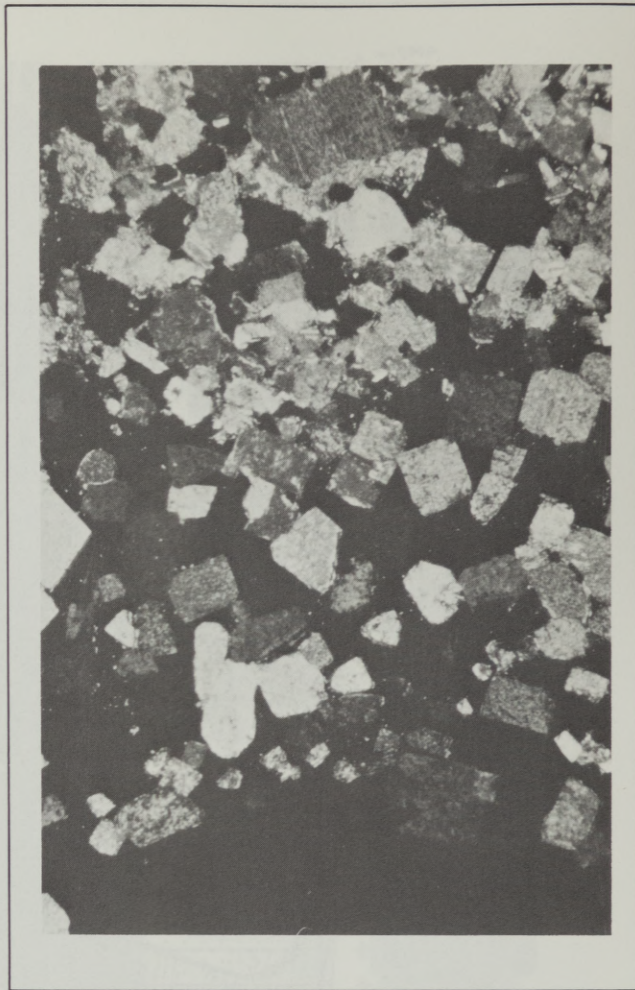
FIGURE 23. Salt/anhydrite contact at Oakwood salt dome; depth is 1,163 ft (354.5 m). Photo width is 6.2 mm; crossed nicols.

orientation of the long axes of crystals. Anhydrite crystals are also strongly oriented in shear zones.

Some horizontal layering occurs in the anhydrite section. The layering is readily observed in hand samples but is difficult to distinguish in thin section. At least some of the layering appears to have been caused by an abundance of fine-grained anhydrite along horizontal bands (fig. 25). Similar features, called katatectic bands, are common in other cap rocks (see section entitled "Petrographic Studies of Other Domes"). Dix and Jackson (1982) thought that the layering may be caused by concentrations of dark, very fine grained intercrystalline material. Layering in the anhydrite cap rock may

represent repeated cycles of halite dissolution and anhydrite accretion at the base of the cap rock (Dix and Jackson, 1982).

Few other minerals occur in the anhydrite section. Gypsum is absent except in the transition zone at 907 ft (276.5 m). Dolomite rhombs, which are probably residual from the salt stock, are found throughout the anhydrite section. An inclusion of halite occurs at 1,046 ft (318.8 m) within the anhydrite. No other minerals were observed in the anhydrite section below the transition zone.

Porosity and permeability are low in the anhydrite cap rock. Porosity ranges from 0.8 to 3.3 percent, and horizontal permeability from <0.01 to 0.02 md. Vertical permeability in a
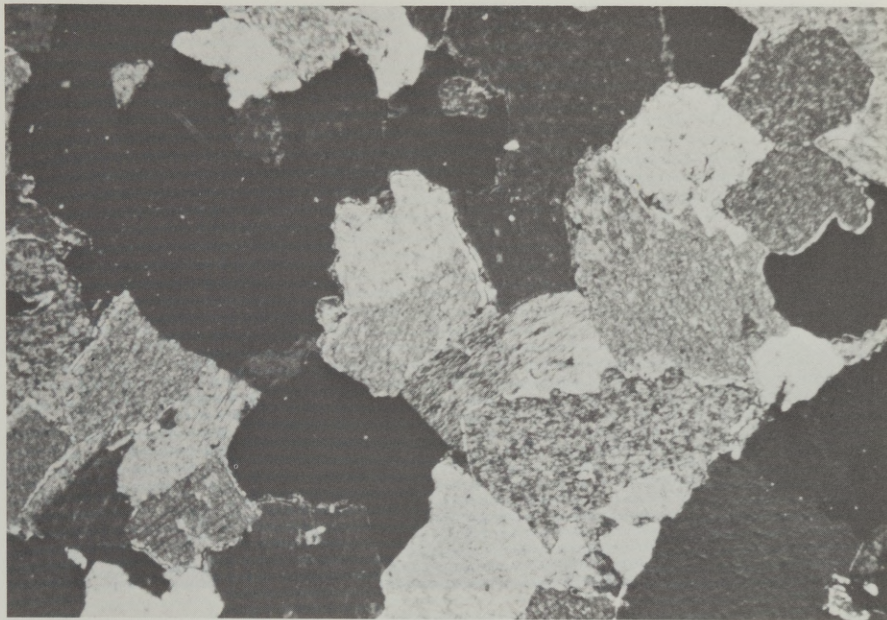
FIGURE 24. Tightly interlocking, xenoblastic crystals in anhydrite section of Oakwood cap rock; depth is 1,160 ft (353.6 m). Photo width is 2.6 mm; crossed nicols.

sample from 1,100 ft (335.3 m) is <0.01 md. Minor porosity is caused by solution of anhydrite and dolomite. A solution-enlarged fracture, oriented vertically, is present at 1,140 ft (347.5 m). No secondary mineralization occurs in the fracture. Small-scale faults, which are evident in the core, cause slight displacement of some anhydrite layers. Slickensides are present along some fault planes (fig. 26).

Anhydrite/Calcite Interface

Between 907 and 904 ft (276.5 and 275.5 m), the cap rock changes from predominantly anhydrite to predominantly calcite. Fine-grained calcite crystals (0.03 to 0.15 mm long) first appear at 926 ft (282.2 m), where they surround and corrode anhydrite grains (fig. 27). At 907 ft (276.5 m), part of the cap rock consists of a porous, open network of fine-grained calcite and pyrite (fig. 28). Where anhydrite remains, it is commonly surrounded by calcite or gypsum. The gypsum occurs either as poikilotopic cement surrounding anhydrite grains or as fibrous patches associated with fine-grained calcite (figs. 29 and 30).

At 905 ft (275.8 m), much of the porosity has been occluded by precipitation of additional fine-grained calcite. Residual dolomite rhombs from within the salt stock are common in the calcite, but some dolomite has been partially or completely dissolved. Kaolinite and celestite are present in pores, including secondary pores formed by dolomite dissolution. Quartz rosettes

TABLE 2. Porosity and permeability of Oakwood cap rock.

Depth (ft)	Porosity (percent)	Permeability (millidarcys)
720 C	1.3	<0.01
740 C	2.2	<0.01
760 C	3.1	0.04
780 C	3.8	0.02
800 C	9.1	43.0
820 VC	6.2	16.0
820 C	4.0	0.01
840 C	13.0	<0.01
880 C	5.1	<0.01
904 T	5.7	0.05
907 T	2.3	<0.01
907 VT	8.3	0.29
920 A	0.7	<0.01
940 A	0.7	<0.01
960 A	0.8	<0.01
1,040 A	0.9	<0.01
1,060 A	0.8	<0.01
1,080 A	0.8	<0.01
1,100 VA	0.9	<0.01
1,100 A	1.0	<0.01
1,120 A	1.3	<0.01
1,138 A	3.3	0.02
1,162 A	1.1	<0.01

C=calcite; A=anhydrite; VA=vertical analysis; T=transition zone.

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FIGURE 25. Contact between coarse- and fine-grained anhydrite layers in Oakwood cap rock; depth is 1,086 ft (331.0 m). Photo width is 2.6 mm; crossed nicols.
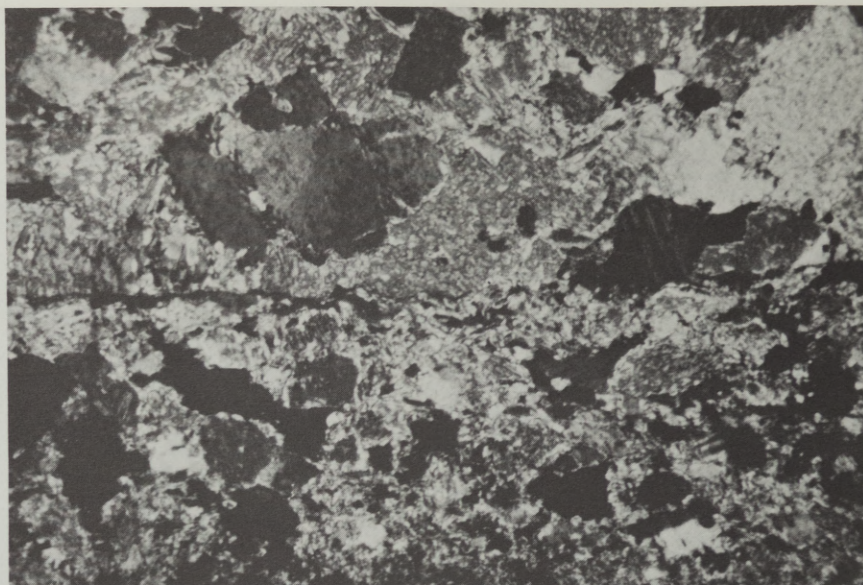
FIGURE 26. Fracture in Oakwood anhydrite cap rock with smooth, slickensided surface.
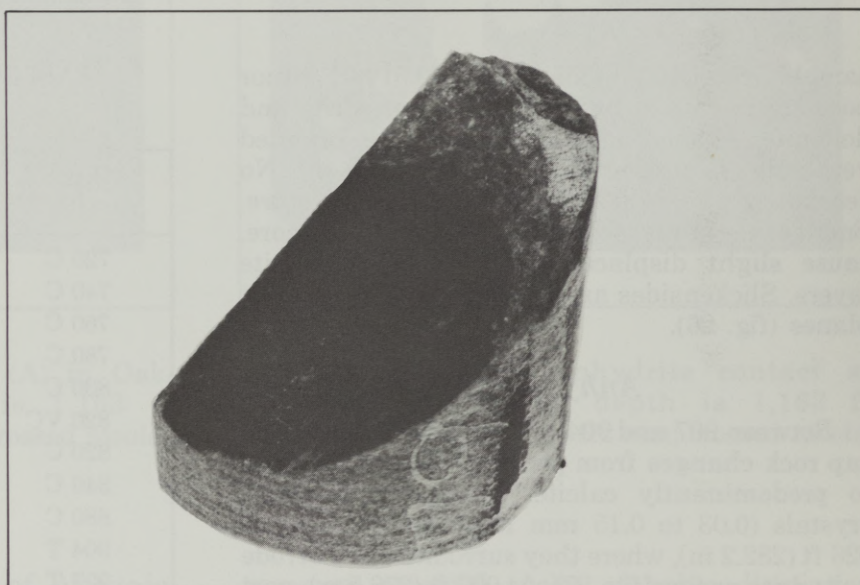
and doubly-terminated crystals also occur in the calcite and are probably residual minerals from the salt stock.

Calcite Section

Above 905 ft (275.8 m), no anhydrite or gypsum is present. From 904 to 881 ft (275.5 to 268.5 m) the cap rock (fig. 20) consists of brecciated pieces of dark-gray, fine-grained (0.03 to 0.25 mm long) calcite (fig. 28) separated by coarse-grained (1.5 to 5.0 mm long) white calcite (fig. 31). This light, coarse calcite appears to have grown into open pores and formed later than the fine-grained calcite. Above 861 ft (262.4 m), the fine and coarse calcite alternate in horizontal layers (fig. 20). Some layers are broken or disrupted, but in general the upper section is not brecciated.

Pyrite, dolomite rhombs, and quartz rosettes occur in the fine-grained calcite layers but were not observed in the coarse-grained calcite. No

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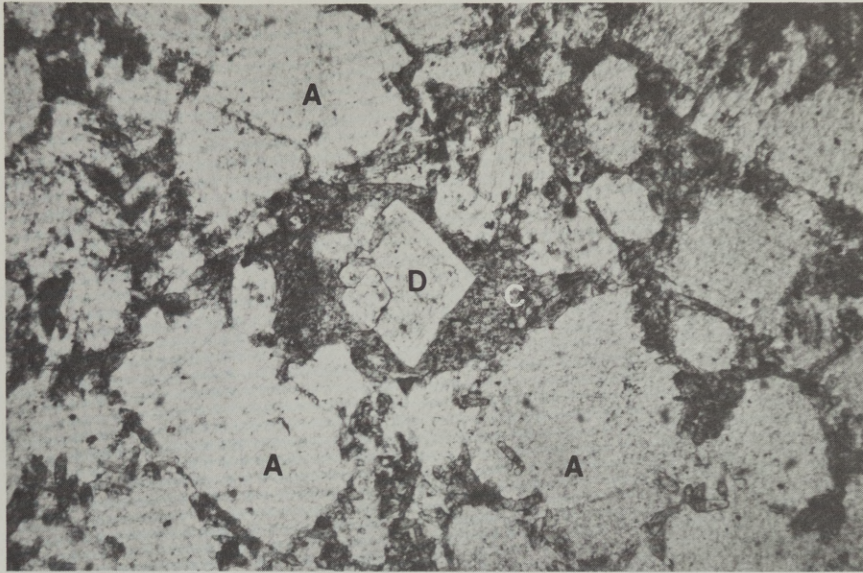
FIGURE 27. Calcite cement (C) corroding anhydrite (A) near the top of the Oakwood anhydrite cap rock. Note dolomite rhomb (D) in center of photo. Depth is 926 ft (282.2 m). Photo width is 2.6 mm; plane light.

FIGURE 28. Network of fine-grained, dark calcite (C) and pyrite surrounding large pores (P) in the Oakwood anhydrite-calcite transition zone; depth is 907 ft (276.5 m). Photo width is 2.6 mm; plane light.

sulfur has been observed. Celestite needles and baroque dolomite crystals (large, twisted crystals with undulose extinction) are present in coarse calcite layers and also fill fractures. Many of the coarse calcite and dolomite crystals show growth bands that record the growth stages of crystals as they precipitated into open pores (fig. 31). Under cathodoluminescence, the coarse calcite crystals showed at least 16 growth zones, with an overall trend toward greater luminescence at the outer (younger) margins of crystals (fig. 32). This suggests an increase in manganese content or a decrease in iron content as the crystals precipitated. Some of the celestite needles and rhombic and baroque dolomite crystals have been partly or completely dissolved. Partial dissolution commonly occurs along a particular growth band in several adjacent crystals of dolomite or calcite. Vuggy porosity is abundant in the calcite cap rock, and, in the upper part of the calcite cap rock,

FIGURE 29. Poikilotopic gypsum cement (G) and anhydrite (A) in anhydrite-calcite transition zone, Oakwood cap rock; depth is 906 ft (276.1 m). Photo width is 2.6 mm; crossed nicols.
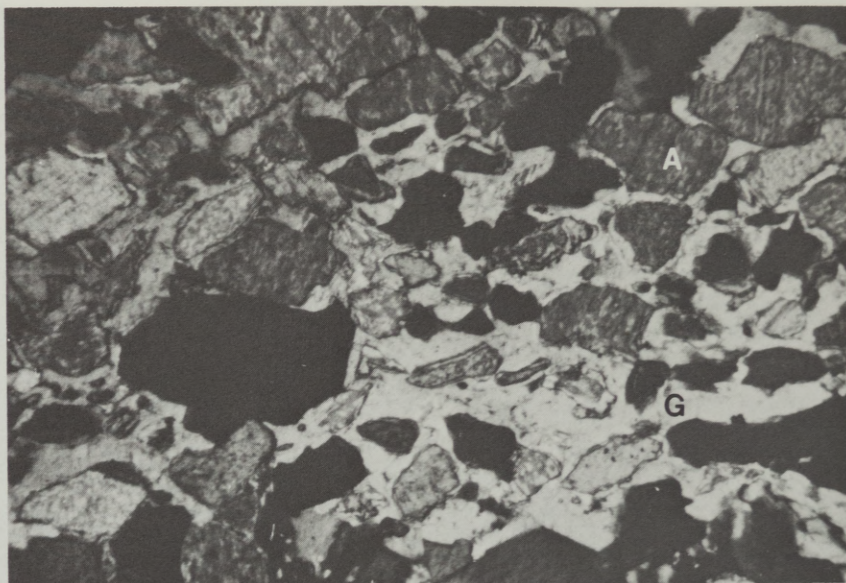
FIGURE 30. Fibrous gypsum (G) and fine-grained, calcite (C) in anhydrite-calcite transition zone, Oakwood cap rock; depth is 907 ft (276.5 m). Photo width is 2.6 mm; plane light.
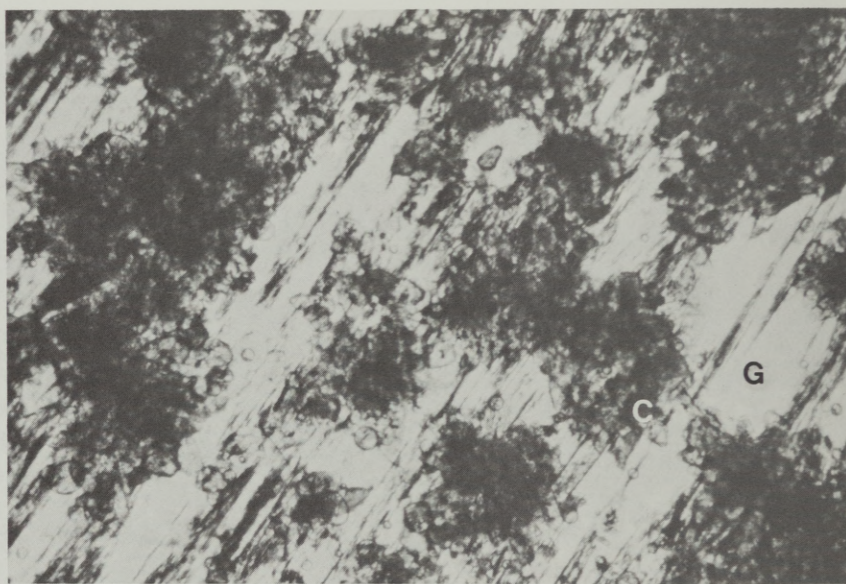
vugs are generally aligned horizontally. Most vugs are lined by coarse calcite or dolomite crystals.

The transition between cap rock and the overlying Wilcox sandstone occurs at 712 ft (217 m). Sandstone at the base of the Wilcox is cemented and partly replaced by calcite.

Porosity in the calcite cap rock occurs primarily in horizontal vugs. In sections of dark, fine-grained calcite, and where white calcite has completely filled vugs, porosity is generally low. Porosity that could be measured in 1-inch (2.54-cm) plugs ranges from 0.7 to 13.0 percent (table 2). Permeability varies between <0.01 and 43.0 md (table 2). Vertical permeability at 820 ft (249.9 m), in a typical banded calcite sample, is 16.0 md, whereas horizontal permeability is only 0.01 md. At 907 ft (276.5 m), in the transition zone, vertical permeability is 0.29 md, and horizontal permeability is <0.01 md. The reason that vertical
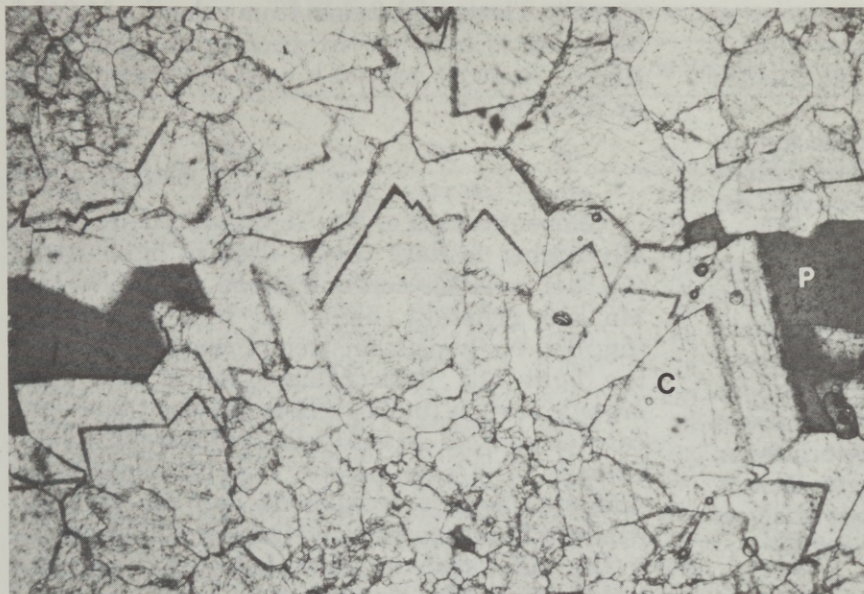
FIGURE 31. Coarsely crystalline, secondary light calcite (C) that grew into open pore space (P) in calcite section of Oakwood cap rock; depth is 757 ft (230.7 m). Photo width is 2.6 mm; plane light.
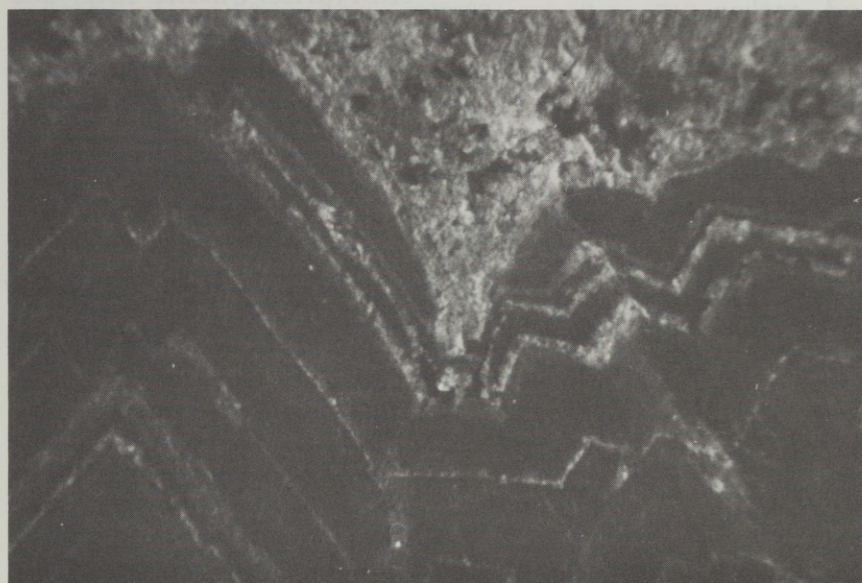
FIGURE 32. Coarsely crystalline, light calcite under cathodoluminescence, showing multiple growth zones. Sample from Oakwood cap rock at depth of 798 ft (243.2 m); photo width is 1.9 mm.

permeability in these samples is greater than horizontal permeability is not known.

Chemical Analyses

Samples of dark and light calcite were analyzed for the following elements by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES): Na, Mg, Ca, Al, Ti, Mn, Co, Cr, Cu, Ni, V, As, Cd, Mo, Pb, Sb, Se, Sn, Be, Sr, Ba, Zn, U, Th, and P. Only Na, Mg, Ca, Fe, Al, Mn, Sr, and Ba had concentrations significantly above threshold detection limits to be considered reliable. Potassium and iron were determined by atomic absorption. Chloride was determined by colorimetry (mercury-thiocyanate method). All samples used for elemental analysis were fused at high temperature and then dissolved in nitric acid. Similar procedures were followed for the

anhydrite samples. All chemical analyses were performed at The University of Texas at Austin, Bureau of Economic Geology Mineral Studies Laboratory.

Two calcite samples, one a light calcite sample (depth 894 ft; 272.5 m) and one a dark calcite sample (depth 904 ft; 275.5 m), were analyzed for gross C_{15+} composition. Saturated hydrocarbons (% sat), aromatic hydrocarbons (% arom), eluted NSO (nitrogen-sulfur-oxygen hydrocarbons), and non-eluted NSO and asphaltenes (% asph) were determined by standard liquid chromatographic techniques for hydrocarbons (Sassen, 1980). Gas-liquid chromatographic traces were made for the C_{15+} saturated hydrocarbons. Analyses were conducted by Dr. Roger Sassen, Getty Oil Company. Total organic carbon analyses were conducted by Geo-Strat, Incorporated.

Isotopic Analyses

Carbon dioxide for oxygen and carbon isotopic analysis was evolved from carbonates in the powdered whole-rock samples using 100 percent phosphoric acid (McCrea, 1950) at 78°F (25°C). Carbon dioxide samples were analyzed on a nuclide model 6-60 RMS mass spectrometer in the Department of Geological Sciences, The University of Texas at Austin. Oxygen isotopic values and carbon isotopic values of carbonates are reported relative to the Pee Dee Belemnite (PDB) standard. Oxygen and hydrogen isotopic analyses on a fluid inclusion (mean diameter 0.2 mm) in the salt at the salt/cap-rock interface were made by Paul Knauth, Department of Geology, Arizona State University. Oxygen analyses are considered accurate to ± 3 ‰. Hydrogen analyses are considered accurate to ± 1 ‰. Oxygen isotope samples were processed by vacuum volatilization and then fluorination, a method being developed by Knauth (P. Knauth, personal communication, 1982).

Geochemical Trends

Anhydrite Zone

Trace element concentrations of Na, Mg, Mn, and Ba in the anhydrite are routinely less than in the calcite samples (table 3). Aluminum has a concentration range similar to the dark calcites. Strontium concentrations range from 802 to 1,187 $\mu g/g$, the mean being approximately 1,000 $\mu g/g$. This mean value of Sr in the anhydrite cap rock is below the calculated value for the Sr in the anhydrite ($CaSO_4$) in the salt (~1,500 $\mu g/g$)

(fig. 33). The sample taken from a depth of 1,046 ft (318.8 m) is high in Na^+ because the anhydrite sample includes part of a halite inclusion found at that depth.

Calcite Zone

Concentrations of Na, Cl, Fe, and Al are generally higher in dark calcite than in light calcite (fig. 34), whereas concentrations of Mg, Sr, and Mn are generally higher in the light calcite (fig. 35). No consistent trends are seen between the light and dark calcites for K and total organic carbon (table 3). Both the light and dark calcites contain extensively biodegraded hydrocarbons. The samples are high in asphaltenes and saturated hydrocarbons and are strongly depleted in n-paraffins and isoprenoids. Organics in the dark calcite are more degraded than in the light calcite (fig. 36; table 4).

Anhydrite/Calcite Interface

In comparison to the trace element chemistry of the rest of the cap rock the elemental concentrations at the anhydrite/calcite interface are anomalously high in Na, Mn, Al, Sr, Cl, Ti, Cr, Cu, Ni, Zn, and Pb (table 5). Total organic carbon is also high.

Isotopic Trends

Calcite Zone

Carbon isotope data show three trends (fig. 37; table 6). (1) All the calcite samples are isotopically depleted in $\delta^{13}C$ (relative to PDB). These values are typical of calcite cap rock that has originated from the oxidation of hydrocarbon and the concomitant reduction of anhydrite. (2) Both the light and dark calcite become more depleted in $\delta^{13}C$ with depth. (3) The dark calcite is generally more depleted in $\delta^{13}C$ than is the light calcite from the same depth.

Two trends are observed in the oxygen isotopic data (fig. 38; table 6). All the calcite samples are depleted in $\delta^{18}O$ (relative to PDB), having a range of −9.0 to −11.4; most of the samples are between −9 and −10. There is a slight depletion in $\delta^{18}O$ with depth (1 δ unit). Most of the samples show a minimal isotopic difference between pairs of dark and light calcite samples taken from the same depth.

The transition zone from anhydrite to calcite at a depth of 900 to 905 ft (274.3 to 275.8 m) shows the greatest isotopic range for both oxygen and carbon (figs. 37 and 38). This is the same zone in

TABLE 3. Chemical analyses of cap rock, Oakwood salt dome ($\mu g/g$).

					Calcite Section						
Depth	Na	Mg	Ca	Al	Mn	Sr	Ba	K	Cl	TOC (wt %)	Fe
739.0 D	450	5290	329700	430	140	190	120	20	470	0.006	—
740.0 L	230	6470	320900	< 50	160	560	4180	40	460	0.008	—
772.0 L	502	4560	324300	520	82	320	1120	32	700	0.004	515
773.0 D	840	13300	322300	< 50	57	570	380	32	333	0.000	120
809.5 D	330	1850	332100	340	38	570	30	45	696	0.016	266
809.0 L	130	4360	321100	< 50	54	870	11100	35	463	0.004	110
831.8 D	170	3560	327400	*110	78	1030	17900	15	500	0.042	246
831.6 L	110	3630	325700	< 50	110	1130	8080	17	223	0.030	229
845.5 L	170	3100	338400	<100	78	1900	40000	12	376	0.398	160
845.5 D	150	2840	320300	190	33	1070	12700	5	356	0.042	263
861.0 D	230	1740	325400	300	54	450	40	7	707	0.004	380
861.0 L	180	3450	324900	< 50	58	820	1350	12	339	0.006	576
890.6 D	171	1450	324600	* 97	39	300	540	37	663	0.016	160
894.0 L	50	3730	322500	< 50	880	310	< 2.50	17	680	0.006	170
899.3 L	160	4290	323000	< 50	160	410	< 2.50	22	226	0.004	880
899.3 D	160	3700	325300	* 67	220	330	< 2.50	37	501	—	224
902.6 D	120	3420	324500	*115	466	250	< 2.50	15	463	0.000	629
902.6 L	50	3840	320400	< 50	610	310	< 2.50	10	269	0.002	311
905.0 D	150	3300	321000	* 53	1200	240	< 2.50	10	1019	0.008	905
905.5 PD	2900	2520	303800	3500	1800	2790	430	55	2096	0.264	6560
					Anhydrite Section						
913	< 25	330	251800	* 53	54	1190	< 1.25	44			
926	230	900	264600	210	530	1100	< 1.25	66			
938	280	60	247100	260	8	910	< 1.25	8.8			
949	* 40	367	248000	120	43	1060	< 1.25	130			
962	< 25	310	252000	140	48	1030	< 1.25	92			
1033	* 60	590	245000	86	62	1050	< 1.25	200			
1046	7800	170	194500	* 61	37	800	< 1.25	210			
1065	110	200	242000	124	19	1020	< 1.25	110			
1086	< 25	240	246100	98	18	1060	134	31			
1106	* 47	200	244400	74	13	910	< 1.25	31			
1126	< 25	230	242100	* 45	15	1010	293	42			
1142	< 25	260	246000	105	47	1180	< 1.25	26			
1152	260	260	241700	220	20	840	< 1.25	20			

D=dark calcite
L=light calcite
PD=porous dark calcite
*=approaching detection limit of ICP
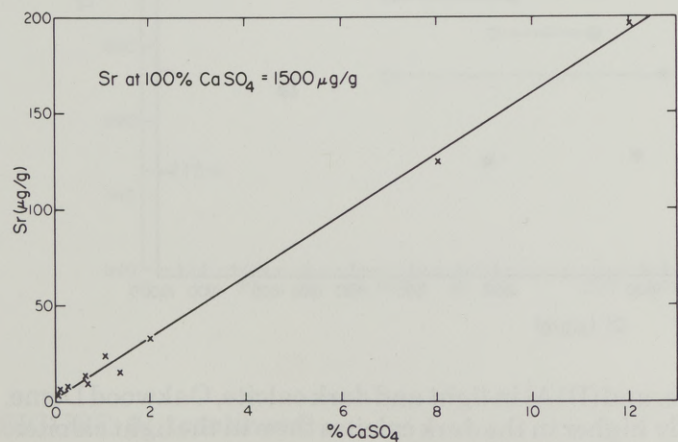
FIGURE 33. Strontium versus percent $CaSO_4$ in salt, Oakwood salt dome. If extrapolated to 100 percent $CaSO_4$, the Sr content would be 1,500 $\mu g/g$.
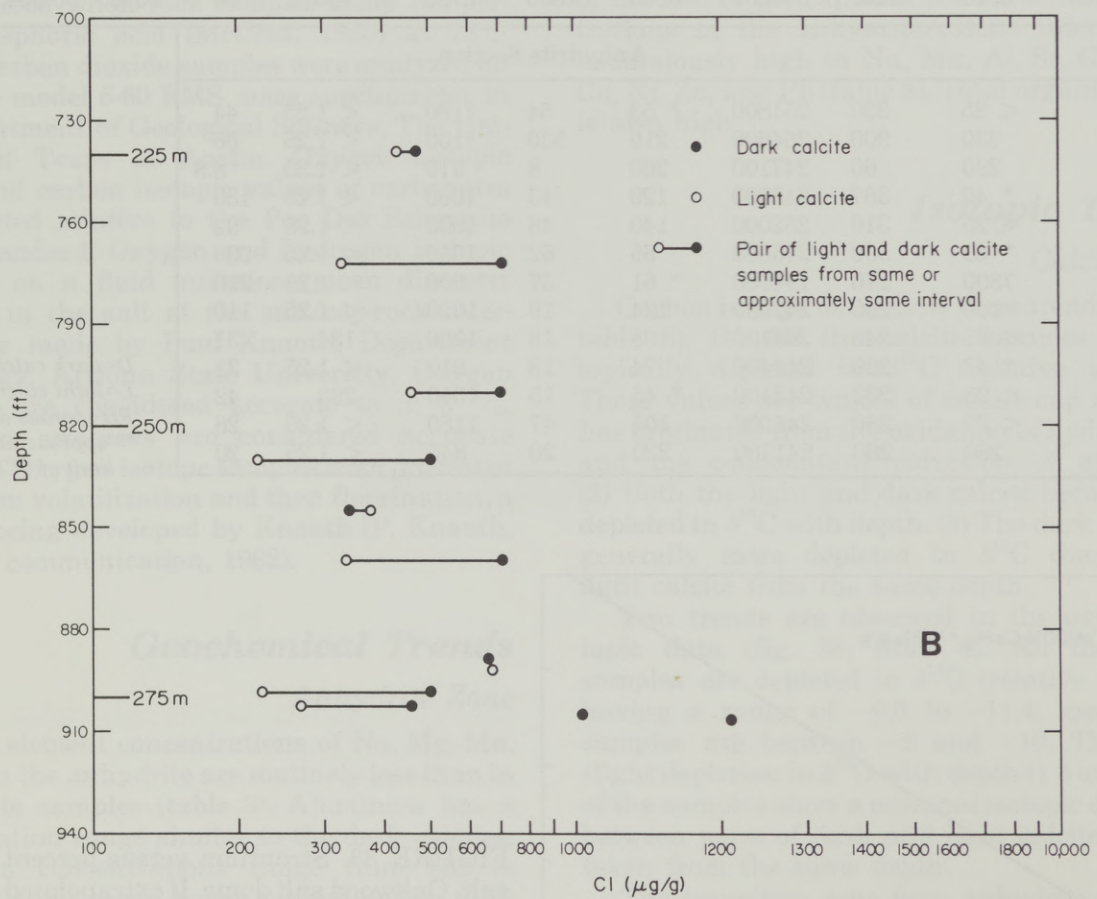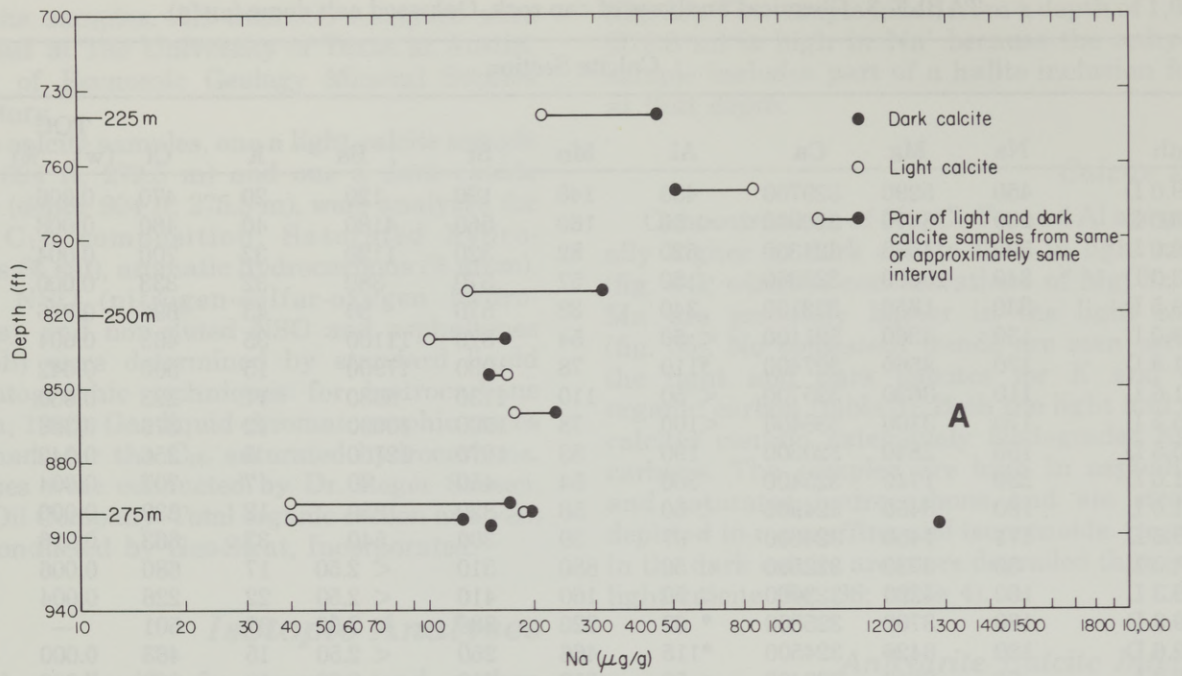
FIGURE 34. Concentrations of (A) Na, (B) Cl, (C) Fe, and (D) Al in light and dark calcite, Oakwood Dome. The concentrations of Na, Cl, Fe, and Al are generally higher in the dark calcites than in the light calcites.
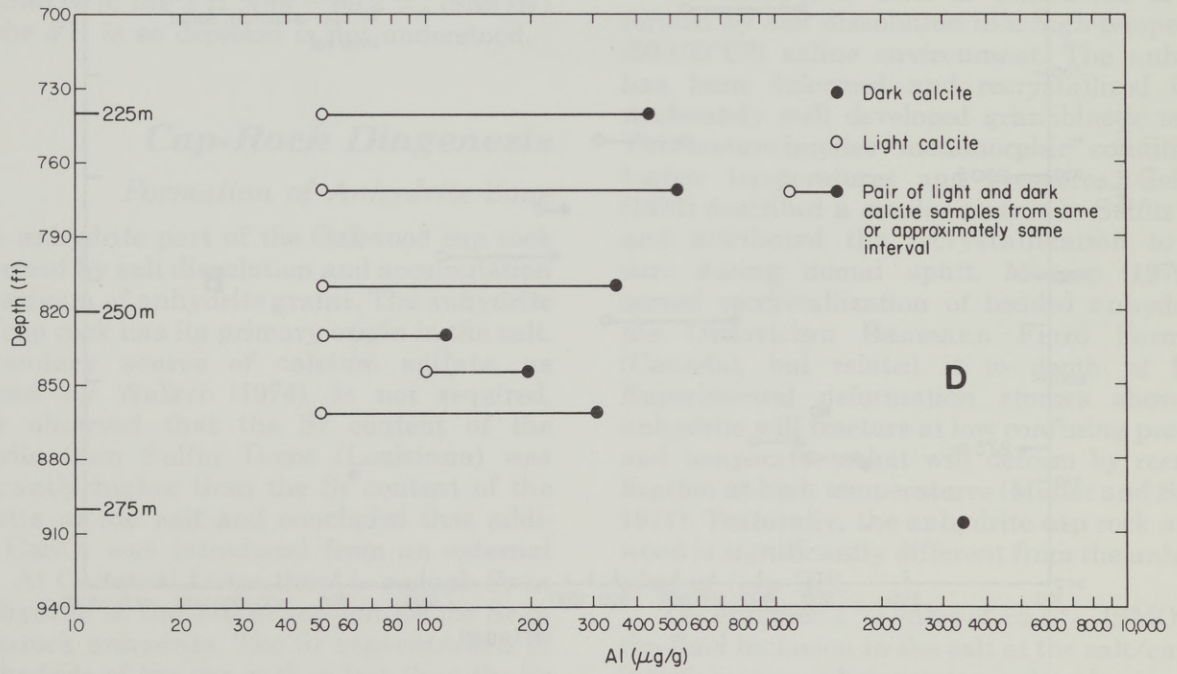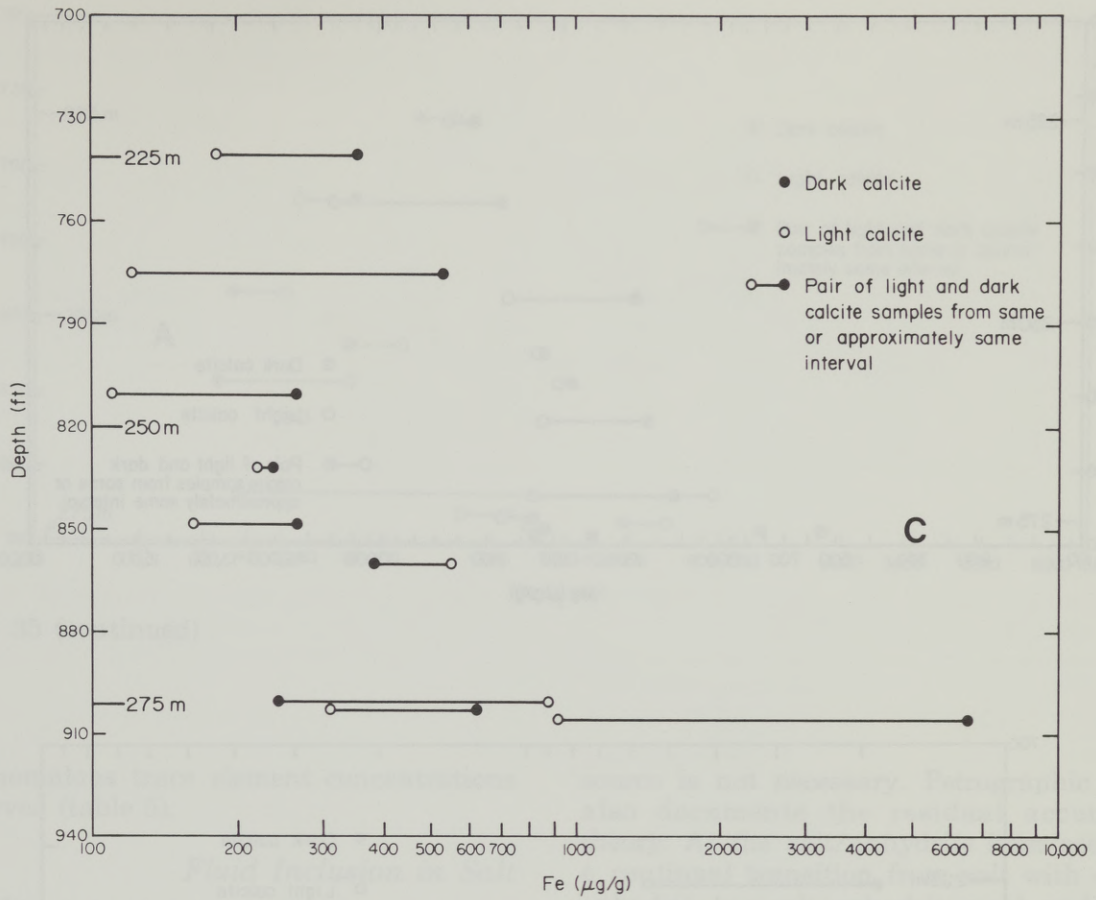
FIGURE 34 (continued)

35
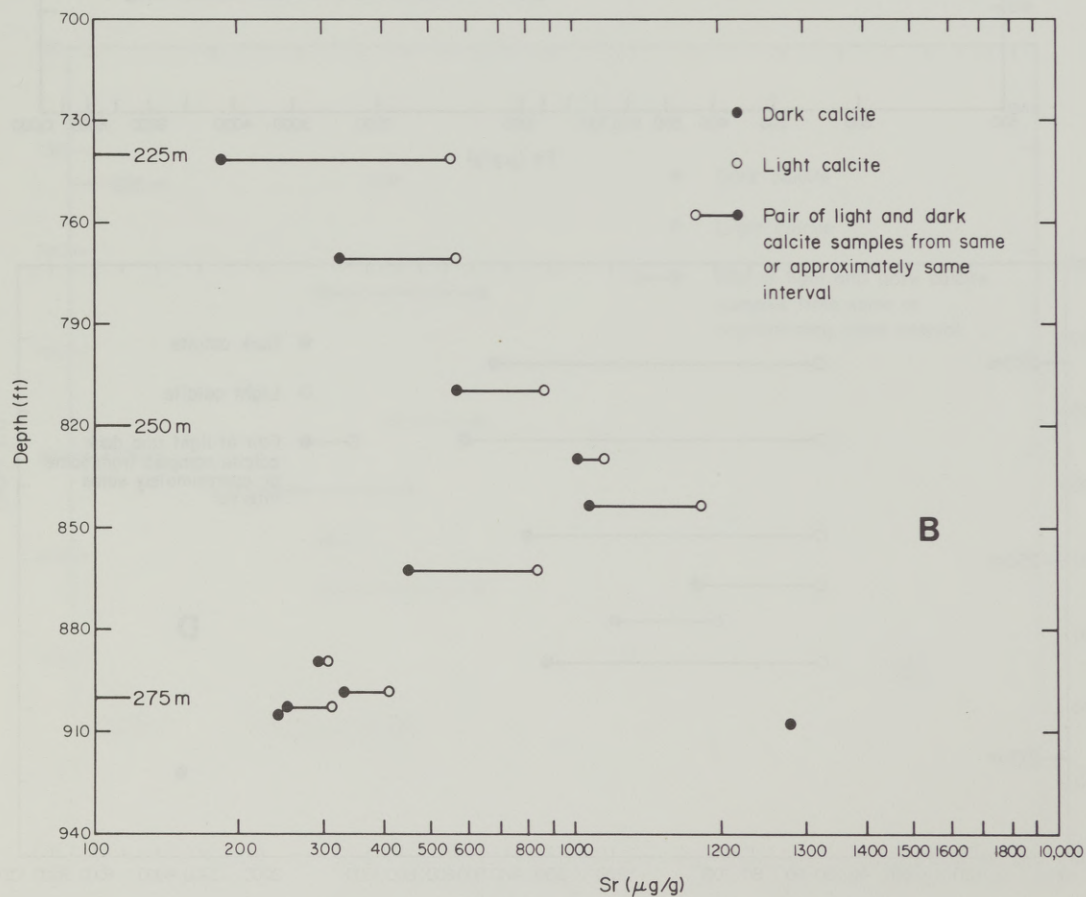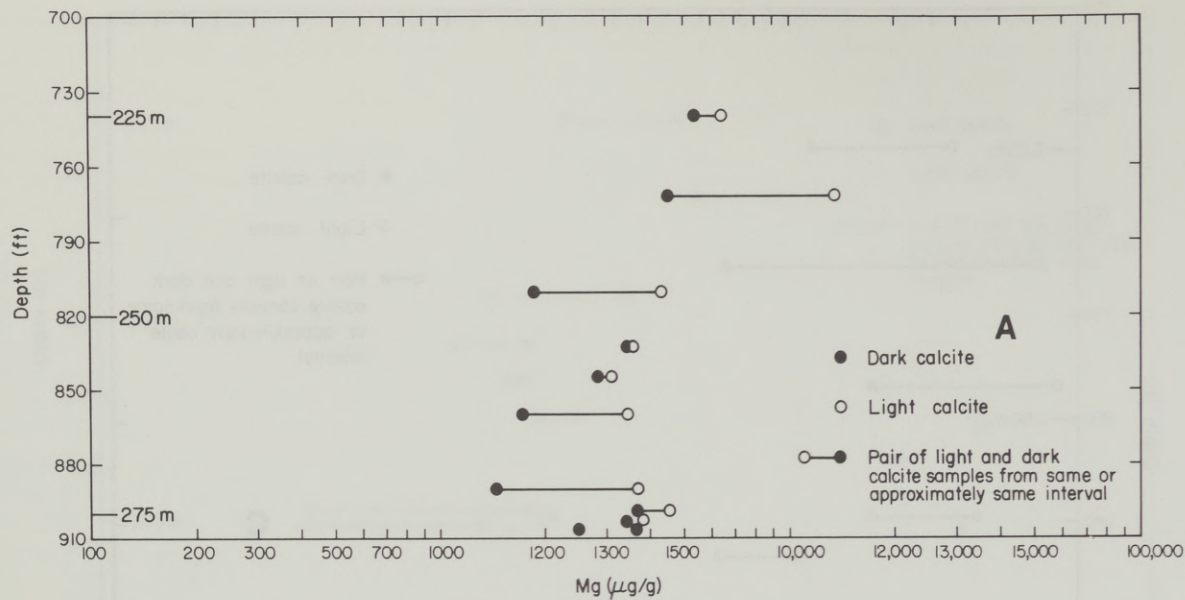
FIGURE 35. Concentrations of (A) Mg, (B) Sr, and (C) Mn in light and dark calcite, Oakwood Dome. The concentrations of Mg, Sr, and Mn are generally higher in the light calcites than in the dark calcites.
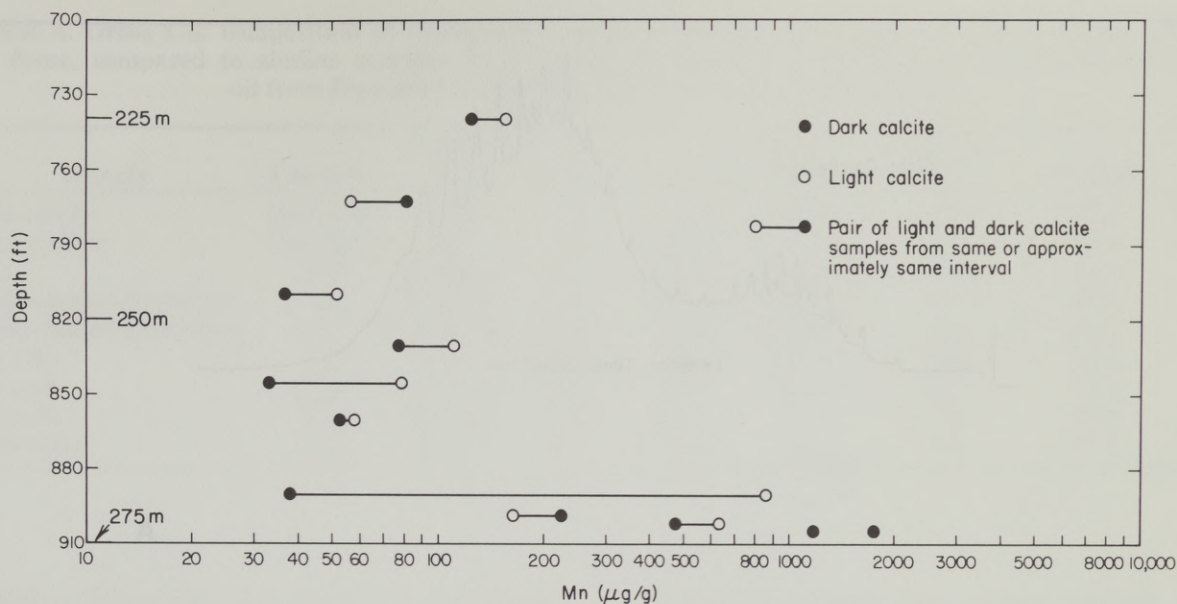
FIGURE 35 (continued)

which anomalous trace element concentrations are observed (table 5).

Fluid Inclusion in Salt

The $\delta^{18}O$ of the fluid inclusion analyzed was +5.4 ‰ (standard mean ocean water standard [SMOW]); the δ^2H was − 69.2 ‰ (SMOW). Why the δ^2H is so depleted is not understood.

Cap-Rock Diagenesis

Formation of Anhydrite Zone

The anhydrite part of the Oakwood cap rock was formed by salt dissolution and accumulation of a residuum of anhydrite grains. The anhydrite in the cap rock has its primary origin in the salt. A secondary source of calcium sulfate, as suggested by Walker (1974), is not required. Walker observed that the Sr content of the anhydrite from Sulfur Dome (Louisiana) was significantly higher than the Sr content of the anhydrite in the salt and concluded that additional $CaSO_4$ was introduced from an external source. At Oakwood Dome there is enough Sr in the anhydrite in the salt to account for the Sr in the cap-rock anhydrite. The Sr concentration of the anhydrite of the cap rock is less than the Sr concentration of the anhydrite in the salt (1,000 μg/g for anhydrite in the cap rock versus 1,500 μg/g for anhydrite in the salt). An external

source is not necessary. Petrographic evidence also documents the residual accumulation theory. At the salt/anhydrite interface there is a continual transition from salt with dispersed anhydrite to a salt/anhydrite mesh and finally to pure anhydrite (fig. 23).

The anhydrite zone is considered to have formed by salt dissolution in a high-temperature (50-100°C?) saline environment. The anhydrite has been deformed and recrystallized into a moderately well developed granoblastic texture. This texture implies "metamorphic" conditions of higher temperatures and pressures. Goldman (1952) described a similar texture in Sulfur Dome and attributed the recrystallization to pressure during domal uplift. Mossop (1979) observed recrystallization of bedded anhydrite of the Ordovician Baumann Fiord Formation (Canada), but related it to depth of burial. Experimental deformation studies show that anhydrite will fracture at low confining pressures and temperatures but will deform by recrystallization at high temperatures (Muller and Siemes, 1974). Texturally, the anhydrite cap rock at Oakwood is significantly different from the anhydrite zone at Gyp Hill.

The enriched $\delta^{18}O$ value of +5.4 ‰ (SMOW) for the fluid inclusion in the salt at the salt/cap-rock interface also substantiates a deep-basin, saline (rather than shallow, meteoric) source for the formation of the anhydrite cap rock. Dix and Jackson (1982), in their study of 57.3 m of salt

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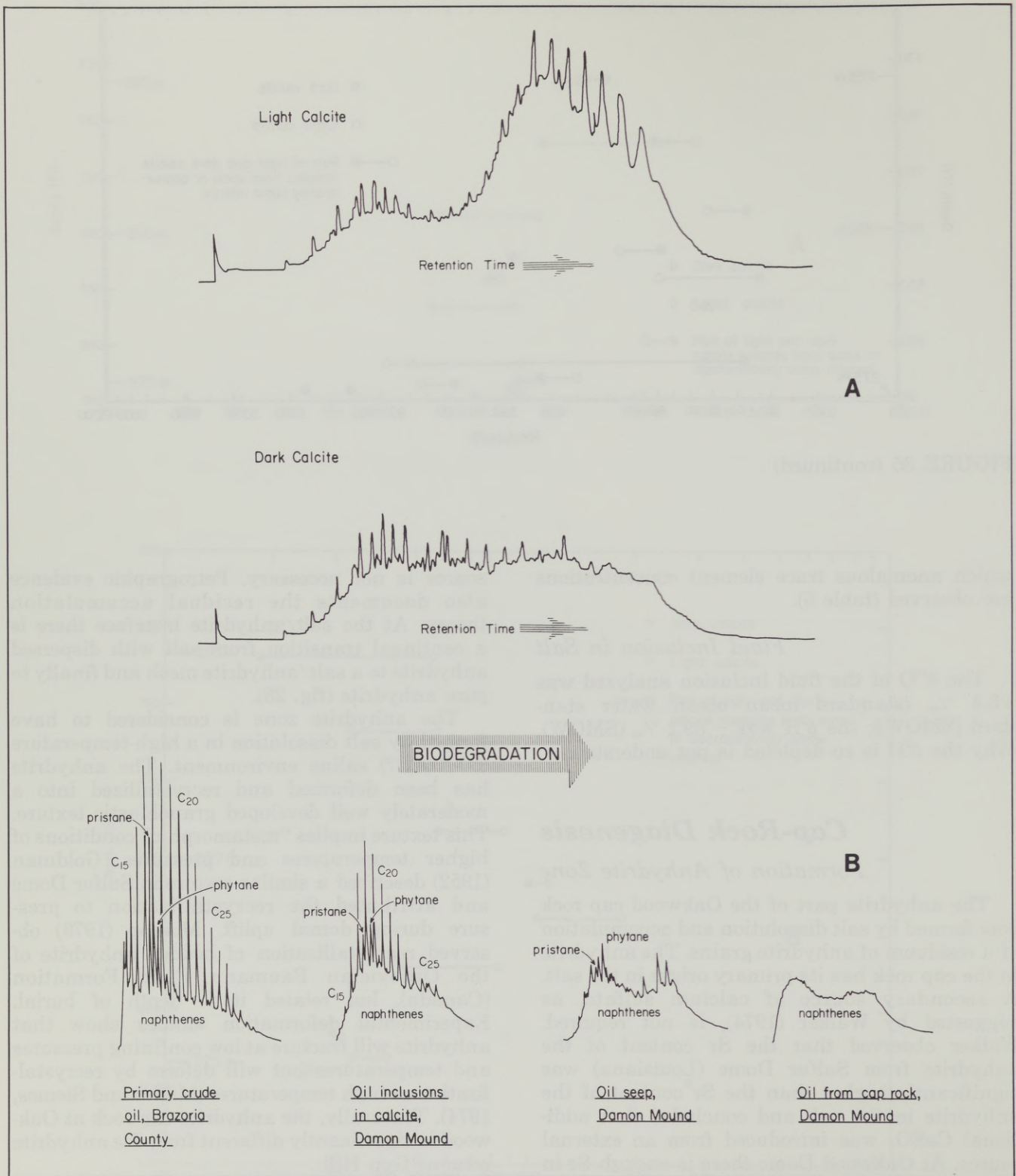
FIGURE 36. A. Gas-liquid chromatographic traces of light calcite (depth 894 ft; 272.5 m) and of dark calcite (depth 904 ft; 275.5 m) from Oakwood Dome. B. Gas-liquid chromatographic traces of biodegraded hydrocarbons, Damon Mound, Brazoria County, and unaltered crude oil, Brazoria County, Texas (Sassen, 1980). The Oakwood samples are similar to the biodegraded oil from the cap rock at Damon Mound but significantly different from the primary crude oil from Brazoria County.

TABLE 4. Gross C_{15+} composition of biodegraded crude oil samples from light and dark calcites, Oakwood salt dome, compared to similar samples from Damon Mound salt dome (DM) and nonbiodegraded crude oil from Brazoria County (BC), Texas. Data from Sassen (1980).

Sample	Location	Depth (ft)	% Sat	% Arom	% El. NSO	% Nonel. NSO	% Asph	Total C_{15+}
Dark calcite	Oakwood	844	1.0	6.7	4.9	0.6	88.4	1,300
Light calcite	Oakwood	894	7.5	12.9	11.0	5.2	63.5	1,000
Seep	DM	Outcrop	23.4	10.9	11.3	14.4	40.0	
Heterostegina limestone	DM	Outcrop	5.4	14.6	14.4	7.1	58.5	
Heterostegina limestone	DM	Outcrop	26.9	23.9	18.6	7.5	24.1	
Cap rock	DM	Outcrop	19.5	12.1	19.7	9.3	39.4	
Cap rock	DM	Outcrop	28.3	17.6	21.0	11.2	21.9	
Cap rock	DM	Outcrop	10.3	13.5	7.4	7.9	47.9	
Production	BC	9,000	56.1	20.4	3.3	9.0	11.2	

TABLE 5. Elemental concentrations in porous calcite from calcite/anhydrite transition zone (sample 905.5 PD), Oakwood salt dome.

Element	Concentration (μg/g)
Ti*	281.9
Cr*	21.7
Cu*	104
Ni*	17.2
Zn*	98.8
Pb*	166.4
Na	2809
Al	3463
Mn	1759
Sr	2792
Cl	2096
TOC	0.264†

*Concentrations of these elements in all other cap-rock samples from Oakwood Dome were below detection limit.

†Concentrations in weight percent.

TABLE 6. Carbon and oxygen isotopic values, calcite zone, Oakwood salt dome.

Sample Depth and Type*	$\delta^{18}O$ ‰†	$\delta^{13}C$ ‰†
739.0 D	-9.00	-10.68
740.0 L	-9.08	-14.65
772.0 D	-9.42	-24.80
773.0 L	-9.70	-24.61
809.5 D	-9.53	-36.74
809.6 L	-9.79	-31.48
831.6 L	-9.38	-34.04
831.8 D	-9.27	-36.71
845.5 L	-9.53	-38.35
845.5 D	-9.63	-43.20
861.0 L	-9.95	-41.51
861.0 D	-9.95	-42.99
890.6 D	-10.78	-49.22
894.0 L	-11.38	-40.29
899.3 L	-10.26	-31.76
899.3 D	-10.95	-35.70
902.6 L	-11.14	-35.70
902.6 D	-11.11	-32.79
905.0 D	-11.16	-30.91
905.5 PD	-10.79	-24.24
926.0 a	-10.15	-46.78
926.0 a	-10.25	-47.39

*D=dark calcite; L=light calcite; PD=dark porous calcite; a=calcite in anhydrite section
† relative to PDB standard

core in Oakwood Dome, observed that the top 2 m of salt has been recrystallized (in comparison to the highly deformed salt below) and that the recrystallized salt is filled with fluid inclusions. This recrystallization resulted from the last salt dissolution event. The fluid inclusions therefore represent the water that caused the last dissolution. The $\delta^{18}O$ value of +5.4 ‰ indicates a deep-basin origin for this water. This enriched $\delta^{18}O$ value is typical for saline formation waters in the Gulf Coast Basin (see Clayton and others, 1966; Kharaka and others, 1977; and Knauth and

others, 1980, for examples) but significantly different from continental meteoric water for this region. The $\delta^{18}O$ of Wilcox ground water (well TOH-2A) in the vicinity of Oakwood Dome was −4.87 ‰ (SMOW).

The anhydrite/salt contact is tight. At this location on the dome, salt dissolution is not
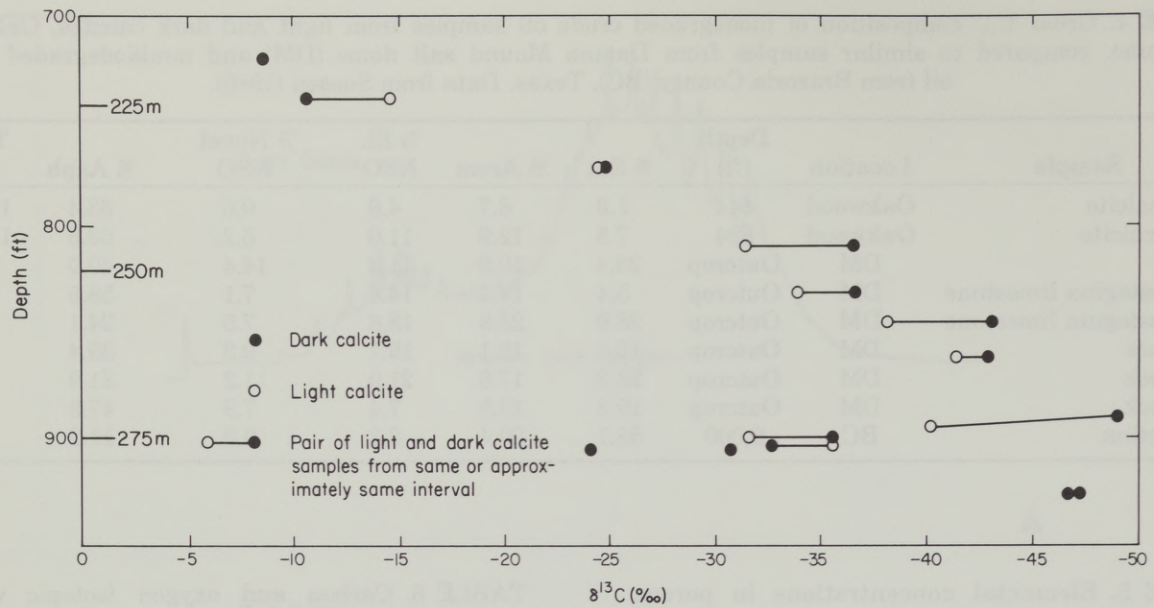
FIGURE 37. The $\delta^{13}C$ (relative to PDB standard) of calcites versus depth in Oakwood cap rock. All samples are depleted in ^{13}C and are in the isotopic range of hydrocarbon-carbon. The light calcites characteristically are more enriched in ^{13}C than are the dark calcites.
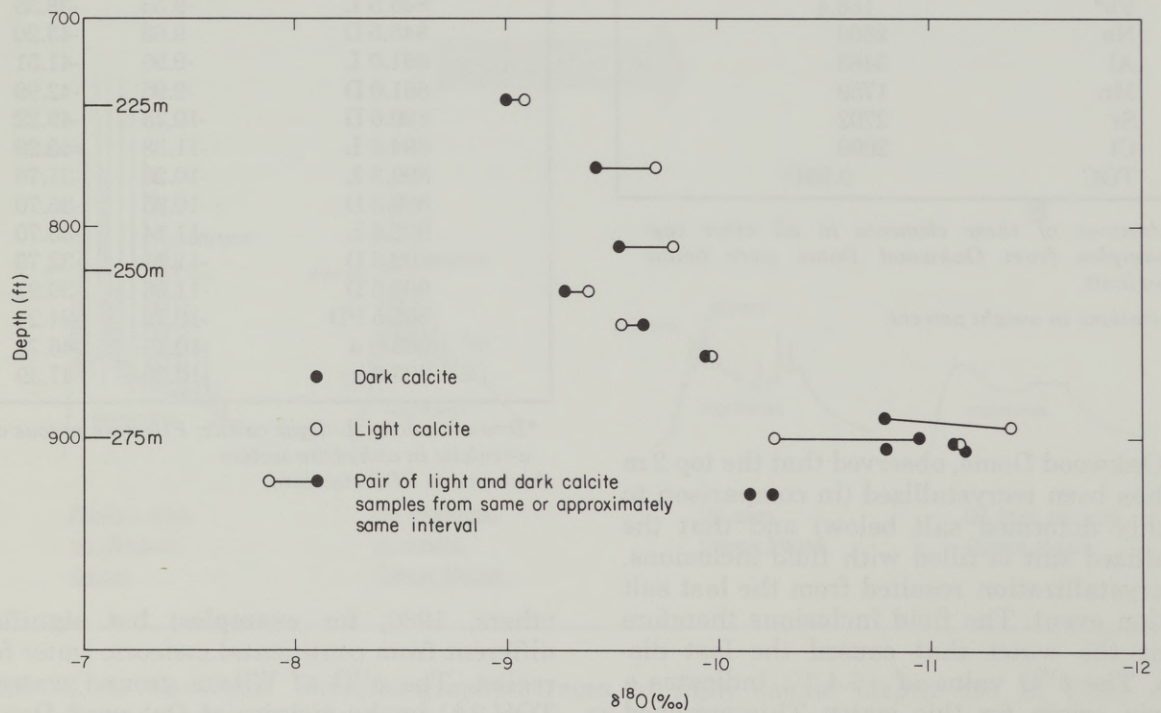
FIGURE 38. The $\delta^{18}O$ (relative to PDB standard) of calcites versus depth in Oakwood cap rock.

occurring. The mineralogy at the interface and throughout the entire anhydrite zone indicates that dissolution is not occurring and that no meteoric waters are presently moving through the anhydrite section. The anhydrite zone of the cap rock formed in a geochemical environment in which anhydrite, and not gypsum, was stable; that is, a relatively high-temperature and/or high-salinity environment.

An alternative to anhydrite cap-rock formation is an earlier gypsum-cemented anhydrite-type cap rock formed in a meteoric ground-water environment. The cap rock was later buried and recrystallized. Goldman (1952) identified a type of anhydrite that he called "regenerated anhydrite." He thought that regenerated anhydrite resulted from anhydrite crystallization from gypsum. The anhydrite in the Oakwood cap rock does not, however, appear to have recrystallized from gypsum. Regenerated anhydrite, according to Goldman, occurs as well-crystallized anhydrite in poikilotopic gypsum. In the Oakwood cap rock the morphology of the anhydrite crystals is very similar to the grain shape of the anhydrite in the salt. The crystals in cap rock are also approximately the same size as those in the salt (Dix and Jackson, 1982). Recrystallization has only altered the crystal shape at crystal-to-crystal boundaries; it has not changed the general size of the crystals. The narrow transition zone between salt and recrystallized anhydrite documents the entire anhydrite accumulation and recrystallization process. There is no need for an earlier gypsum phase.

Another alternative origin of the Oakwood anhydrite is dissolution in a shallow marine environment (in contrast to a continental meteoric environment) and subsequent burial. Analysis of unconsolidated cap rock from a shallow salt diapir in the Gulf of Mexico shows uncemented anhydrite crystals with no gypsum (see detailed discussion of this diapir, p. 52). If this shallow diapir were being flushed by marine waters having the salinity of seawater, then gypsum would be the stable phase, but the diapir is surrounded by a halo of saline, connate water. This saline halo prevents the formation of gypsum. The low-permeability marine muds surrounding the diapir prevent fluid flow and flushing of extremely saline waters. Later burial of the uncemented anhydrite could cause the recrystallization. This hypothesis is reasonable because many salt domes in their early growth history occur as either salt pillows or large salt massifs and were buried only to relatively shallow depths. This is true of domes in the shelf and of Gulf of Mexico slope deposits. This process still requires that the anhydrite cap rock be formed in a geological and geochemical environment other than the fresh, continental, ground-water aquifer in which many domes currently occur. Again, the sharp transition from salt to recrystallized anhydrite at the salt/cap-rock interface argues against this hypothesis. This sharp transition appears to require immediate compaction and recrystallization after salt dissolution.

Timing of Anhydrite Cap-Rock Formation

Assuming an origin by residual accumulation, most of the anhydrite cap rock at Oakwood Dome probably formed before deposition of the Glen Rose Group. The timing of cap-rock formation can be estimated by first calculating the volume of salt that must be dissolved to leave the necessary residuum of anhydrite and then determining when in the geologic history of the dome enough salt was extracted from the rim syncline to account for the salt that had to be dissolved.

In determining the age of the anhydrite cap rock at Oakwood Dome, the following assumptions were made. (1) The original anhydrite cap rock was 450 ft (140 m) thick. The 200 ft (60 m) of calcite that now overlies the anhydrite was originally anhydrite. (2) The average anhydrite content was 2 percent. After studying 328 ft (100 m) of salt core from Oakwood, Dix and Jackson (1982) concluded that the average anhydrite content is approximately 2 percent. (3) The source of salt in a diapir is from the surrounding mother salt, and the amount of salt that has flowed into the diapir can be approximated by the volume of the rim synclines surrounding a dome. Therefore, the volume of salt flowing into a diapir during any geologic time interval can be calculated by measuring the increased volume of sediment surrounding the dome for that period.

The volume of salt that had to be dissolved to form the Oakwood cap rock is approximately 11.7 mi^3 (50 km^3) (table 7). However, there are only 3.1 mi^3 (15 km^3) of salt in the rim synclines of the Glen Rose Formation and younger formations (table 8). Interpretation of geologic cross sections across Oakwood Dome based on seismic data (fig. 21) shows a massive rim syncline below the Glen Rose Formation in the Travis Peak and associated formations (Late Jurassic to

TABLE 7. Volume of salt dissolved from Oakwood Dome to form its cap rock.

Cap-rock thickness (anhydrite and calcite)	140 m
Cap-rock radius	1,500 m
Cap-rock volume	9.9×10^8 m^3
Anhydrite content of Oakwood salt dome	2%
Amount of salt dissolved	5×10^{10} m^3 (11.7 mi^3)

TABLE 8. Timing and volumes of rim synclines surrounding Oakwood Dome.

Stratigraphic Interval	Rim Syncline Volume*
Top of Cotton Valley to top of Travis Peak[1]	significant
Top of James to top of Glen Rose[2]	no closure
Paluxy[2]	no closure
Top of Kiamichi to top of Buda[2]	2.27 mi^3
Woodbine[2]	no closure
Base of Austin Chalk to top of Pecan Gap[2]	0.83 mi^3
Top of Pecan Gap to top of Midway[2]	no closure

*Volume of rim syncline is considered equivalent to the volume of salt that flowed into the dome and was lost by dissolution. Volume calculations by S. Seni.
[1] from seismic data
[2] from electric log data

Early Cretaceous time). The volume of this deep, Lower Cretaceous - Upper Jurassic rim syncline cannot be determined quantitatively because of the limited seismic data and lack of electric log control at this depth. This massive Lower Cretaceous - Upper Jurassic rim syncline is the only major rim syncline in the entire geologic section surrounding the dome; therefore, the Early Cretaceous - Late Jurassic is the only time interval when enough salt migrated into the diapir to be dissolved to form the cap rock. Consequently, the formation of most of the anhydrite cap rock at Oakwood Dome is

considered to have occurred either in Late Jurassic or Early Cretaceous time, that is, at least 100 million years ago.

Many authors (for example, Murray, 1961; Bodenlos, 1970; Martinez, 1975; and Overton, 1979) have had limited success in relating cap-rock properties, such as depth, thickness, and mineralogy, to modern, shallow geologic processes. Some cap rocks, however, formed millions of years ago (as is postulated for Oakwood Dome). Comparing general cap-rock properties to ongoing geologic processes may be of limited value. Future evaluations of cap rocks to determine their modes of origin must recognize the problem of differing diagenetic histories and the problem of timing.

Formation of the Calcite Zone

The calcite zone overlying the anhydrite zone results from oxidation of hydrocarbons and concomitant reduction of anhydrite to form calcite and reduced sulfur species (Equation 1):

$$CH_4 + CaSO_4 \rightleftharpoons CaCO_3 + H_2S + H_2O \quad (1)$$
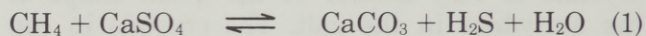
This reaction at Oakwood is documented isotopically, petrographically, and geochemically. The $\delta^{13}C$ of the calcite (fig. 37) is in the isotopic range for petroleum-derived calcites, which are isotopically very depleted in $\delta^{13}C$. These isotopically depleted calcites were initially observed by Feeley and Kulp (1957) and by others (Kirkland and Evans, 1976; Sassen, 1980) studying other calcites derived from the oxidation of hydrocarbons. The replacement of anhydrite by calcite can be observed (fig. 27) where anhydrite grains are surrounded and corroded by calcite cements. The isotopic composition of these cements is extremely depleted in $\delta^{13}C$ ($\delta^{13}C = -46\,°/_{oo}$), another indication of a petroleum source of carbon in the calcites.

The organic carbon incorporated in the light and dark calcites is biodegraded crude oil. The samples have low percentages of saturates and aromatic hydrocarbons and high percentages of asphaltenes and NSO's; chromatographs of saturated hydrocarbons (fig. 36) show a significant loss of n-paraffins and isoprenoids (Roger Sassen, personal communication, 1981). The Oakwood samples show significant biodegradation when compared with samples of unaltered crude oil (table 4). The Oakwood samples are also much more altered than the biodegraded hydrocarbons in the cap rock of Damon Mound, a shallow salt dome in the Texas

TABLE 9. Volume loss from conversion of anhydrite to calcite.

Mineral	Formula	Molecular Weight (g)	Density (g/cm³)
Anhydrite	$CaSO_4$	136	$2.89 - 2.98, \chi = 2.94$
Calcite	$CaCO_3$	100	2.72

reaction assumed in Equation 1 (p. 42)	ratio of molecular weights		ratio of densities	ratio of volumes
$\dfrac{1 \text{ mole calcite}}{1 \text{ mole anhydrite}}$	$\times$	$\dfrac{100\text{g calcite/mole calcite}}{136\text{g anhydrite/mole anhydrite}}$	$\times \ \dfrac{2.94\text{g anhydrite/cm}^3 \text{ anhydrite}}{2.72\text{g calcite/cm}^3 \text{ calcite}}$	$= \dfrac{0.79 \text{ cm}^3 \text{ calcite}}{1.0 \text{ cm}^3 \text{ anhydrite}}$

A chemical conversion of anhydrite to calcite, assuming reaction 1 (p. 42) in a closed system, results in an overall volume reduction. One cm³ of anhydrite yields 0.794 cm³ calcite. Assuming equal volume lost in the horizontal and vertical directions, a section of anhydrite 65 m thick converts to a calcite section 60 m thick. Assuming all volume loss is in the vertical direction, a section of anhydrite 76 m thick converts to a calcite section 60 m thick.

Coastal Zone. It is reasonable to speculate that the organics in the Oakwood calcites may be more degraded because they are much older than the hydrocarbons in the calcites now forming in the Damon Mound cap rock.

As discussed previously in this paper, there are two types of calcite, dark, fine-grained calcite and light, coarse-grained calcite. The dark calcite is primary and results from the reduction of anhydrite. The light calcite results from a secondary precipitation filling vugs or pores in breccia in the dark calcite. All the layers of light calcite formed later than the dark calcite. In contrast, Walker (1974) attributed the light and dark calcite layering to diffusion of trace elements and inferred a continual and rapid sequential precipitation of one band after another. Mineral textures, trace element distribution, and isotope chemistry imply a two-stage formation of dark and light calcite.

The light calcite precipitated as a coarse-grained secondary infilling around the highly brecciated dark calcites in the lower section of the calcite cap rock (fig. 20c, 898.2 to 903 ft). Similarly, the light calcite in the horizontally layered, shallower section of the calcite cap rock is coarse grained; crystals grew toward the center and commonly preserved horizontal vugular pores in the middle of layers (fig. 20). All these features are characteristic of secondary calcite that filled vugular pores.

The initial alteration of anhydrite to dark calcite may have resulted in increased porosity because of a loss in rock volume. Assuming a closed system, with a 1:1 molar conversion of anhydrite to calcite, 1 cm³ of anhydrite will form 0.79 cm³ of calcite (table 9). This volume loss can explain the deformation features observed in the calcite section (both in the deeper brecciated sections and in the shallower, less deformed, subhorizontal layering of dark and light calcite). Deformation in the calcite section is not related to continued solution of the salt dome because there is no evidence of deformation in the anhydrite zone; deformation must result from processes occurring in the calcite zone. With the development of porosity, a second solution was able to flow through the cap rock and precipitate the light calcite.

Anhydrite cap rock has a time-reversed stratigraphy; that is, the top of the cap rock is oldest and the bottom is youngest. The cap-rock material at the interface between salt and anhydrite is the most recent. The calcite section probably does not have a time-reversed stratigraphy. Two diagenetic events occurred: the first resulted in a massive alteration of anhydrite to calcite, and the second event caused dissolution of some of the dark calcite and precipitation of the light calcite. The first solution, which caused the precipitation of the dark calcite, was enriched in Na, Cl, Fe, and Al. The second solution may have had lower NaCl concentrations but higher Sr, Mg, Ba, and Mn concentrations, which resulted in the precipitation of dolomite and celestite as well as increased trace element content in the calcite. If every dark and light calcite band represented a separate diagenetic event, then multiple pulses of fluid would have had to pass through the cap rock, but each fluid associated with all the dark

bands would have had to have a similar chemical composition. Likewise, each fluid associated with each band of light calcite would also have had a similar chemical composition. It is simpler to envision that the dark calcite formed when hydrocarbons migrated as a pulse to the dome; the hydrocarbon-rich waters then altered approximately 200 ft (60 m) of anhydrite to calcite. A later subsurface fluid migrated through the porous dark calcite, dissolved dark calcite, and then precipitated the light calcite.

This second solution dissolved the primary dark calcite and reprecipitated the light calcite near the initial point of dissolution. All the $\delta^{13}C$ data show a progressive enrichment of ^{13}C in shallower samples, but each pair of light and dark calcite samples from similar depths has relatively similar $\delta^{13}C$ values (fig. 37). The light calcite for each pair is commonly 5 to 10 $°/_{oo}$ more enriched in $\delta^{13}C$ than is the dark calcite. Calcite has been dissolved and then reprecipitated nearby and an additional heavier carbon source has been added. Continual oxidation of hydrocarbons may provide the acid necessary for dissolving the dark calcites. The light calcites also contain biodegraded hydrocarbons.

Both the light and dark calcite precipitated at depth. The calcites are not forming in a shallow meteoric system, as is the case for calcites from Damon Mound, Texas Coastal Plain (Sassen, 1981) or calcites in the Limestone Buttes, Culberson County, West Texas (Kirkland and Evans, 1976). This conclusion is based on the depleted $\delta^{18}O$ values (-9 to -11 $°/_{oo}$) for the dark and light Oakwood calcites that imply a deep-basin origin (fig. 38). Similarly depleted $\delta^{18}O$ calcite (-8.6 to -10 $°/_{oo}$ PDB) was observed in the Vacherie cap rock (Smith and Kolb, 1981).

Oxygen isotopic compositions of calcite have been used to identify the origin of the water (meteoric or marine) and/or the approximate temperature of calcite precipitation. Water becomes isotopically depleted in ^{18}O the farther it is transported in the atmosphere from its oceanic source (Dansgaard, 1964). Meteoric ground waters therefore are depleted in $\delta^{18}O$ in comparison to seawater. Because of this isotopic shift, calcites precipitating in meteoric continental waters are also depleted in ^{18}O compared with marine calcites (Land, 1973).

The oxygen-isotope fractionation factor between water and $CaCO_3$ decreases with increasing temperature (O'Neil and others, 1969). At higher temperatures this reaction results in a greater depletion of $\delta^{18}O$ in the carbonates and a greater enrichment of $\delta^{18}O$ in the formation waters than in the shallower waters. The degree of oxygen isotopic shift depends upon whether the formation is open to fluid flow; if it is open, the molar ratio of oxygen in the water to that in the country rock will be large. Major oxygen shifts would then be observed in the recrystallized country rock as well as in the water. If the formation is very restricted, the molar ratio of the oxygen in the water to that in the country rock will be small. A major oxygen isotopic shift should be observed in the water but not in the country rock (Prezbindowski, 1981). By knowing the isotopic history of the carbonates and the water as well as the general geologic setting of the formation, it is possible to define the origin of the water and the temperature (depth) of crystallization.

An open system may exist in the deeply buried Frio Formation of the Texas Gulf Coast. Milliken and others (1981) observed a continual depletion of $\delta^{18}O$ in calcite cements with depth in the Frio Formation (fig. 39). Conversely, the $\delta^{18}O$ of Gulf Coast saline formation water becomes progressively enriched in $\delta^{18}O$ with depth (Kharaka and others, 1977, 1980). The $\delta^{18}O$ enrichment in the water and $\delta^{18}O$ depletion in rocks result from this extensive oxygen exchange with burial and increased temperature (Clayton and others, 1966).

In contrast to the Frio, the Edwards Formation in the Stuart City Reef Trend in South Texas appears to be a closed system. Prezbindowski (1981) observed a continual enrichment of $\delta^{18}O$ of the formation waters with depth, but the $\delta^{18}O$ of the calcite cements did not significantly change. Therefore, Prezbindowski concluded that the deep Edwards Formation was predominantly a closed system.

The $\delta^{18}O$ range of the calcite cap rock at Oakwood Dome is approximately -9 to -11 $°/_{oo}$. To understand the geochemical factors that caused these very depleted $\delta^{18}O$ values in the cap rock, the water source (marine or continental) and temperature of formation must be examined. The depleted $\delta^{18}O$ values are not the result of calcite formation at low temperature with meteoric water depleted in ^{18}O. The $\delta^{18}O$ of a calcite cement from the shallow, fresh-water Wilcox aquifer near the dome is -4.6 $°/_{oo}$ (PDB). The $\delta^{18}O$ (SMOW) of the meteoric water in the Wilcox aquifer of East Texas is -4.9 $°/_{oo}$. (The $\delta^{18}O$ of meteoric ground water over Vacherie Dome in the North Louisiana Basin was measured at -5.4 $°/_{oo}$ [Knauth and others, 1980].) If the depleted $\delta^{18}O$ of the Oakwood calcite resulted from equilibration with meteoric

Depth (ft)

3000
4000
5000
6000
7000
8000
9000
10,000
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000

-13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 +1

δ¹⁸O(‰)

Depth (m)

1000

2000

100°C

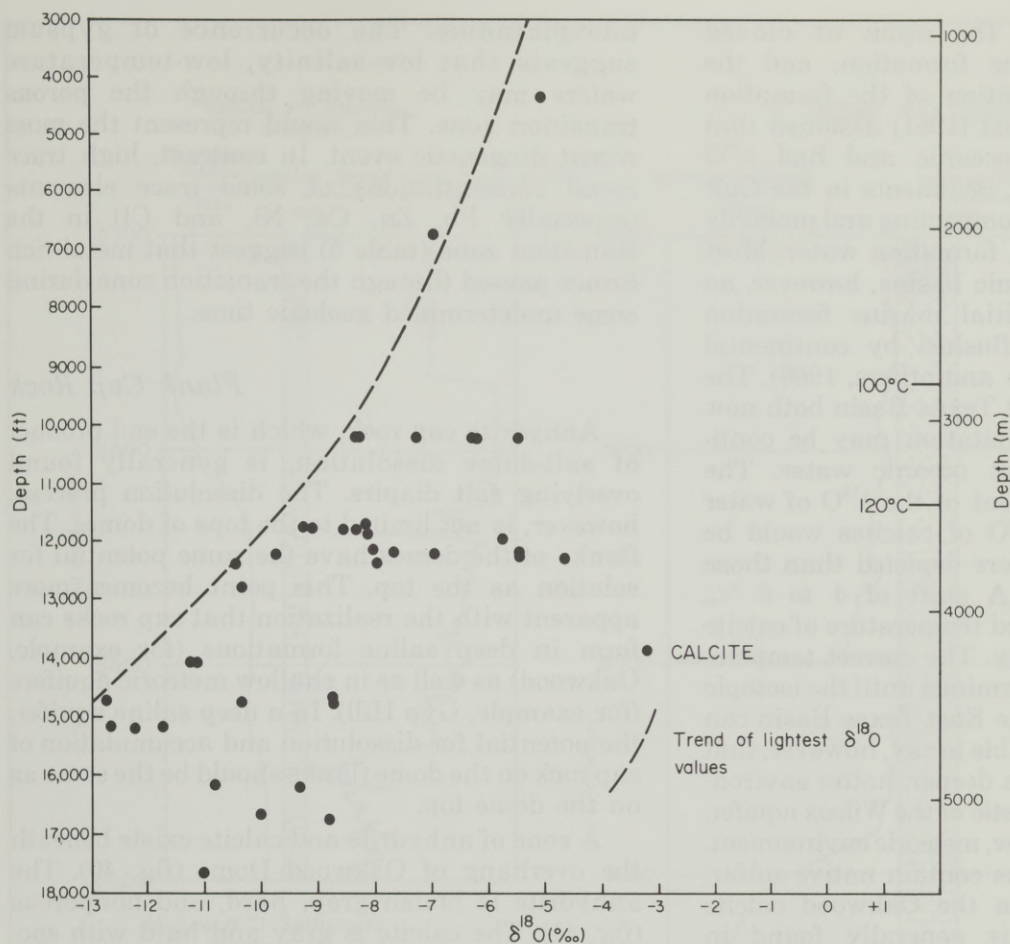120°C

3000

4000

5000

● CALCITE

Trend of lightest δ¹⁸O values

FIGURE 39. The $\delta^{18}O$ (PDB) trend of calcite versus depth and temperature, Frio Formation, Texas Gulf Coast Milliken and others, 1981. Note the depletion of $\delta^{18}O$ with depth.

Wilcox water, the $\delta^{18}O$ of these waters should be in the range of -8 to -11 $^o/_{oo}$ (SMOW), which was not observed.

The $\delta^{18}O$ of the meteorically altered calcite cap-rock boulders over Rayburn's Dome ranges from -3.9 to -8.3 $^o/_{oo}$, with heavier $\delta^{18}O$ values associated with the greater meteoric alteration (Smith and Kolb, 1981). If the Oakwood calcite cap rock formed in a fashion similar to the calcite boulders over Rayburn's Dome, then the $\delta^{18}O$ should have a similar range of approximately -4 to -8 $^o/_{oo}$. Thus, the Oakwood calcites have not precipitated from meteoric ground waters.

The depleted $\delta^{18}O$ values of the calcites from the Oakwood cap rock suggest a hot, and therefore a deep, origin. If conditions in the East Texas Basin were analogous to conditions in the Frio Formation in the Texas Gulf Coast (Milliken and others, 1981), the temperature of calcite formation at Oakwood Dome would have been greater than 212°F (100°C), corresponding to depths greater than 9,000 ft (2,800 m) (fig. 39). This high-temperature precipitation of Oakwood

cap-rock calcite, however, contradicts previous investigations and appears to be unrealistically high. Identification of possible bacterial remains in the calcite supports a biologic origin of the calcite precipitation (R. L. Folk, personal communication, 1981). Philippi (1977) concluded that the average maximum temperature for crude oil biodegradation (bacterially driven) is about 150°F (66°C). Roger Sassen (personal communication, 1981) concluded that the maximum temperature for survival of bacteria is approximately 160°F (70°C). Given an average geothermal gradient of 1.7°F/100 ft (31°C/1 km) for the East Texas Basin and 160°F (70°C) as the upper temperature limit for bacterially derived calcite, the maximum depth for cap-rock calcite to form would be about 6,000 ft (2,000 m). Our hypothesis, suggesting high temperature (>100°C) and deep depth of formation based on isotopic comparison to the Frio Formation, must be incorrect.

The depleted $\delta^{18}O$ values for the Frio Formation are controlled by the temperature of

calcite precipitation, the open or closed hydrologic nature of the formation, and the original isotopic composition of the formation water. Milliken and others (1981) assumed that the initial water was oceanic and had $\delta^{18}O$ values approaching zero. Sediments in the Gulf of Mexico Basin are still compacting and probably contain original, marine, formation water. Most marine deposits in cratonic basins, however, no longer contain their initial marine formation waters but have been flushed by continental meteoric waters (Clayton and others, 1966). The saline waters in the East Texas Basin both now and during calcite precipitation may be continental meteoric and not oceanic water. The initial point for enrichment of the $\delta^{18}O$ of water and the depletion of $\delta^{18}O$ of calcites would be shifted toward values more depleted than those assumed for the Frio. A shift of 4 to 6 $^{o}/_{oo}$ would lower the calculated temperature of calcite precipitation significantly. The correct temperature range cannot be determined until the isotopic history of the water in the East Texas Basin can be documented. It is possible to say, however, that these calcites formed in a deeper, hotter environment than that characteristic of the Wilcox aquifer, which has a cooler, shallow, meteoric environment.

Many calcite cap rocks contain native sulfur, which does not occur in the Oakwood calcite section. Native sulfur is generally found in shallow cap rocks of coastal salt domes in Texas and Louisiana and results from the oxidation of hydrogen sulfide. Feeley and Kulp (1957) originally argued that sulfate was the oxidant. Davis and others (1970) later noted that this reaction was thermodynamically improbable and that dissolved oxygen was a more logical oxidant. The lack of native sulfur at Oakwood can be explained by the following hypothesis. During the formation of dark and light calcite at Oakwood, geochemical conditions remained too reducing for the formation of native sulfur with an oxidant such as dissolved oxygen. In many domes, the native sulfur is associated with the light, secondary calcite. Conditions during the formation of the secondary calcite at Oakwood were reducing enough so that no native sulfur was formed. With time, the H_2S diffused into the formation waters and escaped.

Transition Zone

The transition zone has two distinct characteristics, the high concentration of metals and the only occurrence of gypsum in the cap rock. These two features are self-contradictory and at present unexplainable. The occurrence of gypsum suggests that low-salinity, low-temperature waters may be moving through the porous transition zone. This would represent the most recent diagenetic event. In contrast, high trace metal concentrations of some trace elements (especially Pb, Zn, Cu, Ni, and Cl) in the transition zone (table 5) suggest that metal-rich brines passed through the transition zone during some undetermined geologic time.

Flank Cap Rock

Anhydrite cap rock, which is the end product of salt-dome dissolution, is generally found overlying salt diapirs. The dissolution process, however, is not limited to the tops of domes. The flanks of the domes have the same potential for solution as the top. This point becomes more apparent with the realization that cap rocks can form in deep saline formations (for example, Oakwood) as well as in shallow meteoric aquifers (for example, Gyp Hill). In a deep saline aquifer, the potential for dissolution and accumulation of cap rock on the dome flanks should be the same as on the dome top.

A zone of anhydrite and calcite exists beneath the overhang of Oakwood Dome (fig. 40). The anhydrite is bluish gray, hard, and nonporous (fig. 41). The calcite is gray and hard with sporadic vugs containing oil. Its texture varies from finely crystalline to breccia-like. This calcite contains contorted laminations of darker calcite. Anhydrite thickness varies from 0 to 128 ft (0 to 39 m). Thickness of calcite rock varies from 18 to 195 ft (5 to 59 m). Thin sections of a core sample from the anhydrite zone of the deep ($\approx$1,500 m) flank cap rock exhibit oriented, recrystallized anhydrite (fig. 42). No gypsum cement is present.

This anhydrite rock is similar to the anhydrite observed in the cap rock overlying the dome. A sequence of dissolution of salt, accumulation of anhydrite, and recrystallization of anhydrite is considered to be the mechanism for its formation. The only observed difference between the flank anhydrite and the anhydrite on top of the dome is the strongly oriented fabric of the flank anhydrite. The oriented fabric may have developed because of shear forces at the salt diapir/sediment interface as the dome grew.

The anhydrite sample from beneath the overhang shows that the cap rock can form at depth in saline formations and further substantiates the hypothesis that the anhydrite cap rock on top of Oakwood Dome could also have formed at depth.
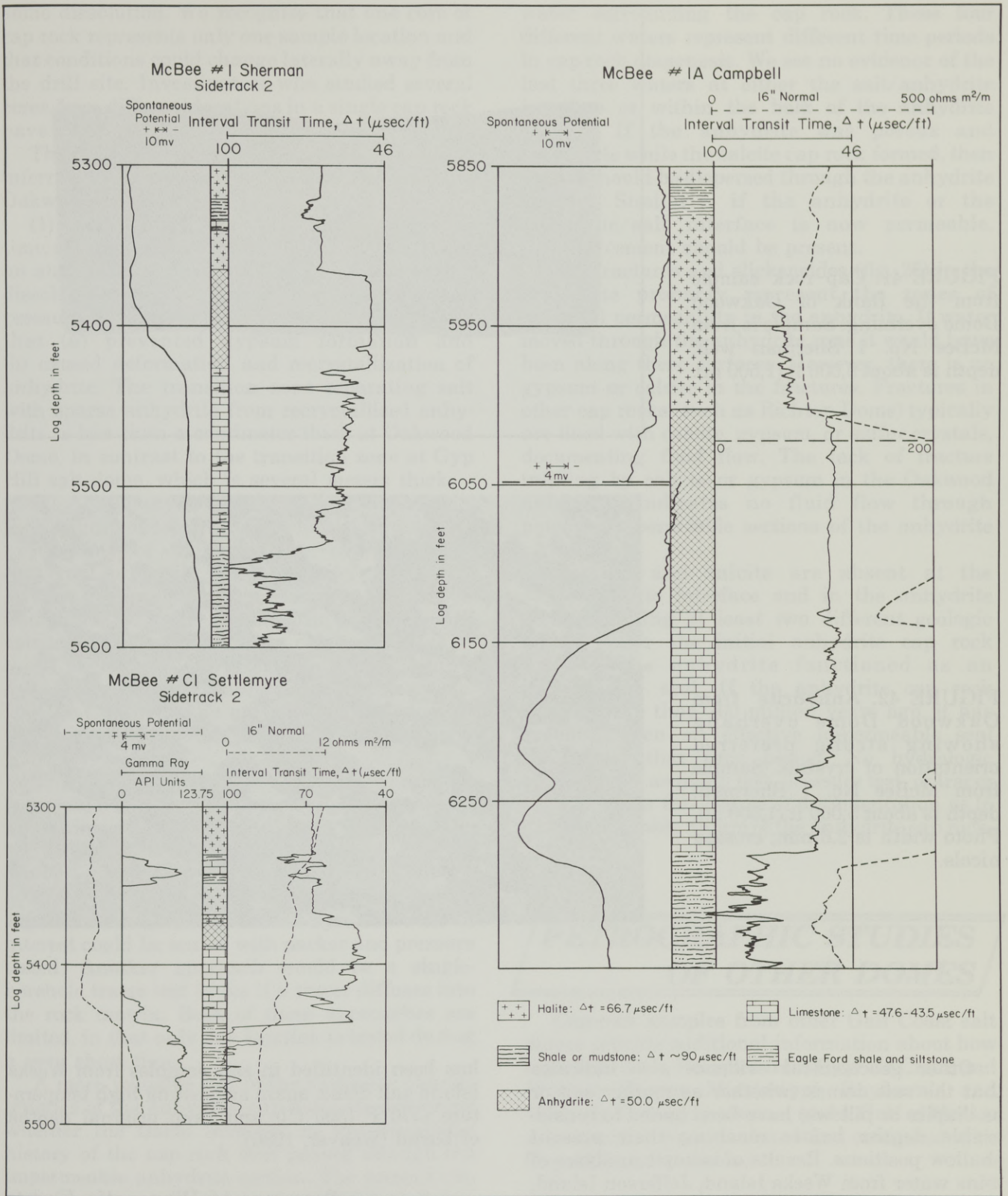
FIGURE 40. Anhydrite and calcite beneath overhang of Oakwood salt dome, based on electric log responses (from Giles and Wood, 1983).

FIGURE 41. Cap-rock sample from the flank of Oakwood Dome overhang. Sample is from McBee No. 1 Sherman well; depth is about 5,000 ft (1,500 m).
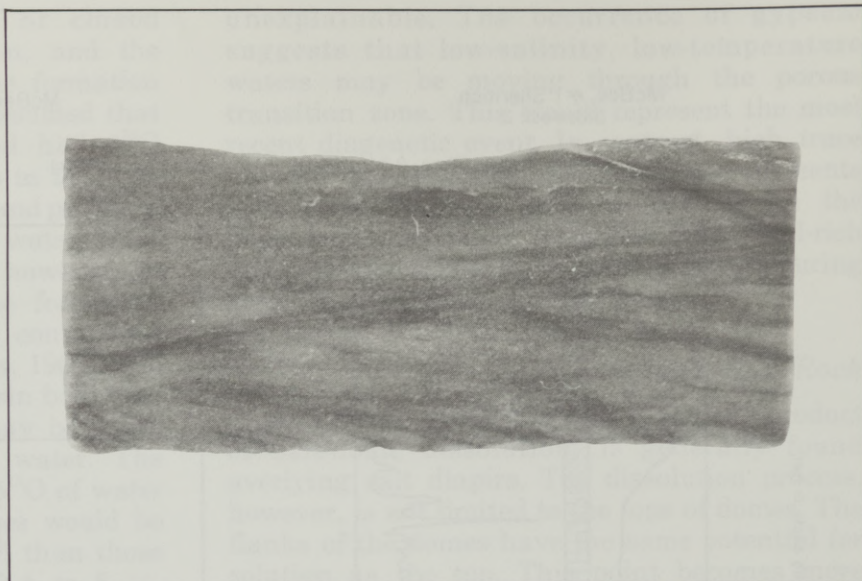
FIGURE 42. Anhydrite from Oakwood Dome overhang showing strong preferred orientation of crystals. Sample from McBee No. 1 Sherman; depth is about 5,000 ft (1,500 m). Photo width is 2.6 mm; crossed nicols.
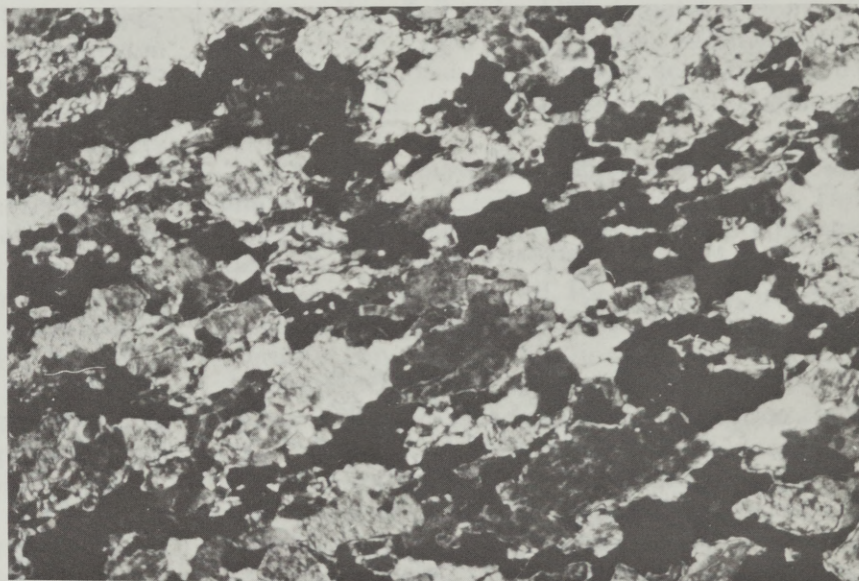
Other geochemical evidence also indicates that the salt domes (whether as mother salt or as diapirs or pillows) have been buried to considerable depths before reaching their present shallow positions. Results of isotopic analyses of mine water from Weeks Island, Jefferson Island, and Belle Isle salt domes (south Louisiana) suggest that these waters are formation waters introduced to the salt at temperatures of 300° to 360°F (150° to 180°C) or depths of 2 to 2.5 mi (3 to 4 km) (Knauth and others, 1980). Graphite

has been identified in salt samples from Weeks Island salt dome, again suggesting high temperature (570°F [300°C]) and deep original depths of burial (Weaver, 1980).

Sequence of Diagenetic Events

A series of diagenetic events through geologic time has resulted in the cap rock on Oakwood salt dome. This end product, cap rock, appears today as an impermeable seal, which is preventing

dome dissolution. We recognize that one core of cap rock represents only one sample location and that conditions could change laterally away from the drill site. Investigators who studied several cores from different locations in a single cap rock have found variations (Walker, 1974).

The following sequence of diagenetic events is inferred to have caused the formation of the Oakwood cap rock.

(1) During Late Jurassic to Early Cretaceous time, a large volume of salt was dissolved, leaving an anhydrite cap rock 450 ft (137 m) thick. This dissolution occurred in a hot, saline, high-pressure environment (deep sedimentary basin) that (a) prevented gypsum formation and (b) caused deformation and recrystallization of anhydrite. The transition zone separating salt with sparse anhydrite from recrystallized anhydrite is less than a centimeter thick at Oakwood Dome, in contrast to the transition zone at Gyp Hill salt dome, which is several meters thick.

(2) A hydrocarbon-rich, saline, deep-basin fluid migrated inward and downward through the upper zone of the anhydrite cap rock and converted anhydrite to dark calcite.

(3) Another hydrocarbon-bearing, deep-basin fluid, enriched in Sr, Mg, and Mn, dissolved dark calcite and precipitated light calcite.

(4) Recent meteoric ground water precipitated gypsum in the calcite/anhydrite transition zone. This last event is the only evidence of shallow meteoric water altering the cap rock in Oakwood Dome.

This sequence of events formed an impermeable rock in a nonmeteoric environment and indicates that the anhydrite section of the cap rock has been an impermeable seal through geologic time.

The hydraulic characteristics of the anhydrite cap rock can be tested three ways. The zone of interest could be sealed with packer and pressure tested. Another approach would be a single-borehole tracer test to see if a tracer diffuses into the rock matrix. Both of these approaches are limited, in that only one location is tested during a very short time.

A more valuable test of the hydraulic characteristics of the anhydrite cap rock is to determine whether the fluids involved in the diagenetic history of the cap rock ever passed through the impermeable anhydrite section. The present cap rock has been affected by four different fluids: (1) the water that dissolved the salt to form the anhydrite cap rock, (2) the water that formed the dark calcite, (3) the water that precipitated the light calcite, and (4) the present Wilcox meteoric

water surrounding the cap rock. These four different waters represent different time periods in cap-rock diagenesis. We see no evidence of the last three waters at either the salt/anhydrite interface or within the bulk of the anhydrite section. If the anhydrite was porous and permeable while the calcite cap rock formed, then calcite should be dispersed through the anhydrite section. Similarly, if the anhydrite or the anhydrite/salt interface is now permeable, gypsum cement should be present.

The fractures and slickensides (fig. 26) in the anhydrite probably represent the zones of potential permeability in the anhydrite. If water moved through the anhydrite zone it would have been along these surfaces. However, there is no gypsum or calcite in the fractures. Fractures in other cap rocks (such as Richton Dome) typically are lined with calcite, gypsum, or sulfur crystals, documenting fluid flow. The lack of fracture infilling by calcite or gypsum in the Oakwood anhydrite indicates no fluid flow through potentially permeable sections of the anhydrite cap rock.

Gypsum and calcite are absent at the salt/anhydrite interface and in the anhydrite section. During at least two different geologic periods after the initial anhydrite cap rock formed, the anhydrite functioned as an impermeable seal. If the anhydrite cap rock formed more than 100 million years ago, it has probably been an effective impermeable seal throughout that time period. No hydrologic testing (such as pump test, pressure test, or tracer test) can offer this degree of documentation as to the impermeable nature of the anhydrite cap rock.

PETROGRAPHIC STUDIES OF OTHER DOMES

Cap-rock samples from other Gulf Coast salt domes provide additional information about how cap rocks form. Samples from Cypress Creek and Richton Domes, Mississippi, Rayburn's and Vacherie Domes, Louisiana, and a Gulf of Mexico salt structure were analyzed and compared with Gyp Hill and Oakwood.

Rayburn's Dome

The cap rock from Rayburn's Dome closely resembles Gyp Hill cap rock. Samples of Rayburn's cap rock, taken from a hole drilled for

FIGURE 43. Patches of fibrous gypsum (G) in porous anhydrite sandstone, Rayburn's Dome cap rock; depth is 108 ft (32.9 m). Photo width is 0.5 mm; plane light.
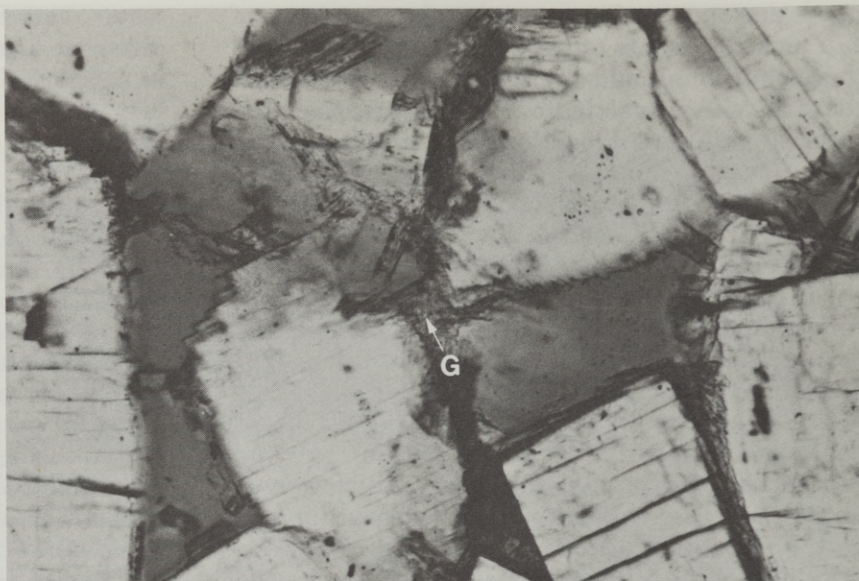

FIGURE 44. Poikilotopic gypsum cement (G) surrounding anhydrite crystals (A) in Rayburn's Dome cap rock; depth is 102 ft (31 m). Photo width is 2.0 mm; crossed nicols.

seismic tests (at a depth of 102.5 ft [31.2 m]), consist of porous anhydrite sandstone partially cemented by patches of fibrous gypsum (fig. 43). The cap-rock/salt boundary was not recovered during coring, and there may be a cavity containing loose anhydrite grains (Nance and Wilcox, 1979). No fine-grained anhydrite subgrains or interpenetrating grain boundaries were observed in the anhydrite section. In the sample from 102.5 ft (31.2 m), there are areas completely cemented by poikilotopic gypsum. Samples at 135 ft (41.1 m) still retain some

porosity at boundaries between poikilotopic crystals of gypsum (fig. 44). These samples of Rayburn's cap rock appear to represent an intermediate step in which the porous anhydrite is only partially cemented by gypsum, a step that is missing in the Gyp Hill section.

The upper part of the Rayburn's cap rock consists of medium- to fine-grained gypsum (fig. 45) that is similar to the gypsum section at the top of Gyp Hill. No anhydrite was observed in the cap rock above 80 ft (24.4 m). The enriched $\delta^{13}C$ and $\delta^{18}O$ values (Smith and Kolb, 1981)

FIGURE 45. Fine-grained gypsum from Rayburn's Dome cap rock; depth is 77 ft (23.5 m). Photo width is 2.0 mm; crossed nicols.
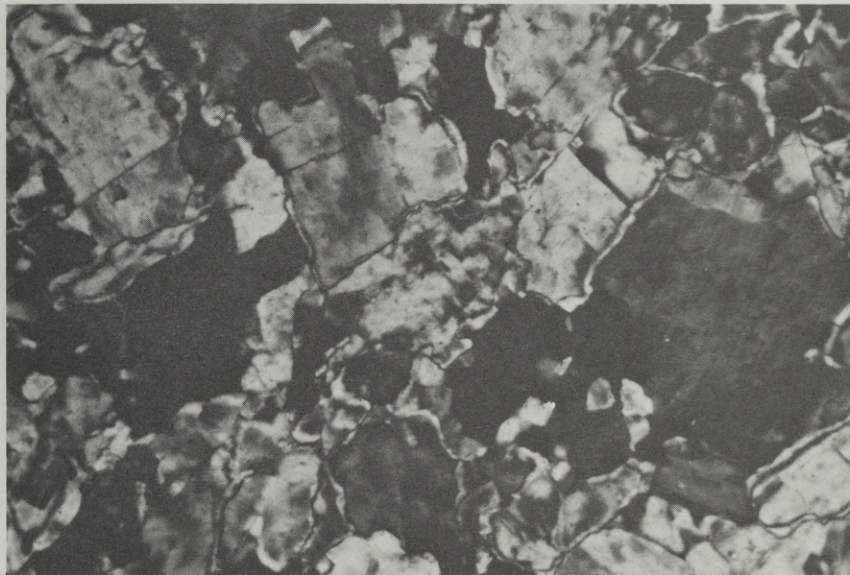

FIGURE 46. Tightly interlocking xenoblastic crystals of anhydrite in Vacherie Dome cap rock; depth is 750 ft (228.6 m). Photo width is 2.0 mm; crossed nicols.

observed in the calcite boulder zone overlying the calcium sulfate cap rock also reflect the influence of the meteoric water on the cap rock.

Vacherie Dome

In contrast to Rayburn's cap rock, Vacherie cap rock is very similar to cap rock on Oakwood Dome. It consists of a thick anhydrite section at the base (815 to 567 ft; 248.6 to 172.9 m below land surface) and calcite at the top (564 to 543 ft; 172.0 to 165.6 m), separated by a thin zone of gypsum

(567 to 564 ft; 172.9 to 172.0 m). The contact between salt and cap rock is a sharp, horizontal surface with no cavity (Nance and others, 1979). Anhydrite at the base of the cap rock (814.3 ft; 248.2 m) appears recrystallized, displaying a granoblastic texture (fig. 46) similar to Oakwood anhydrite (fig. 24). No gypsum was observed in the anhydrite section below 577.3 ft (176.0 m). One difference between Vacherie and Oakwood is that clasts of anhydrite occur in the salt stock at Vacherie, and discrete clasts can also be observed within the cap rock. In the Oakwood salt stock,

anhydrite occurs only as individual grains, although the grains may be concentrated in layers. Because there are no clasts in the salt stock, none occur in the cap rock.

Prominent banding in Vacherie cap rock is caused by the contact of layers of fine-grained (0.1 mm) anhydrite crystals with layers of coarser grained (1.0 mm) anhydrite crystals (fig. 47) throughout the anhydrite section. These bands occur at erratic intervals (Nance and others, 1979) ranging from 2.0 inches (5.1 cm) to 3.9 ft (1.2 m) apart.

The depleted $\delta^{13}C$ of the calcite cap rock (-20.1 to -28.4 $°/_{oo}$ PDB) indicates a hydrocarbon source (Smith and Kolb, 1981). The $\delta^{18}O$ values of the calcite (from Smith and Kolb, 1981) are depleted and similar to those at Oakwood, which indicates a deep-basin origin for these calcites.

Cypress Creek Dome

Cap rock from Cypress Creek Dome in Mississippi appears to represent an intermediate anhydrite texture between Oakwood and Gyp Hill cap rocks. Anhydrite at the base of Cypress Creek is tightly packed, but the crystals commonly retain their elongate, prismatic shape. They do not appear to be as highly recrystallized to the nearly equant, granoblastic texture that exists in Oakwood cap rock. However, in contrast to Gyp Hill cap rock, no porosity was observed, and gypsum is absent at the base of the cap rock. There is a sharp contact, with no cavity, between the salt and cap rock (fig. 48).

Richton Dome

Richton cap rock consists of light and dark calcite at the top (554 to 577 ft; 168.9 to 175.9 m) and anhydrite at the base (577 to about 764 ft; 175.9 to about 232.9 m). A cavity separates the salt from the cap rock, and loose anhydrite may be present in this zone (S. Fuerst, personal communication, 1980). The anhydrite section contains abundant gypsum-filled fractures, the deepest occurring at 740 ft (225.6 m) (fig. 49). Calcite and sulfur commonly occur in association with the gypsum veins. Anhydrite in the Richton cap rock is similar to that at Cypress Creek, having a texture intermediate between Gyp Hill and Oakwood (fig. 50). Fine-grained anhydrite is quite abundant, and much of this anhydrite may have originated as clasts in the salt. Vague outlines of clasts can be seen in some sections of the cap rock and similar fine-grained anhydrite clasts occur in the salt stock.

FIGURE 47. Contact between coarse- and fine-grained anhydrite layers in Vacherie Dome cap rock; depth is 588 ft (179.2 m). Photo width is 2.0 mm; crossed nicols.

Gulf of Mexico Salt Structure

Cap rock from a Gulf of Mexico salt structure (fig. 2) (Lehner, 1969) was sampled. Core hole 114-A penetrated 117 ft (35 m) of cap rock from 350 to 467 ft (106.7 to 142.3 m) below sea level. The samples that were recovered consist primarily of loose anhydrite grains, some of which show signs of dissolution (fig. 51). No gypsum is present. Clasts of halite and anhydrite were also recovered in the core (fig. 52). Some of the anhydrite grains have been cemented by pyrite or fibers of aragonite, which may indicate submarine cementation of the loose anhydrite. The lack of gypsum cements may be caused by pore waters that are undersaturated with respect to gypsum or by the NaCl halo (Manheim and Bischoff, 1969) that surrounds the dome and maintains the geochemical environment in the anhydrite stability field.
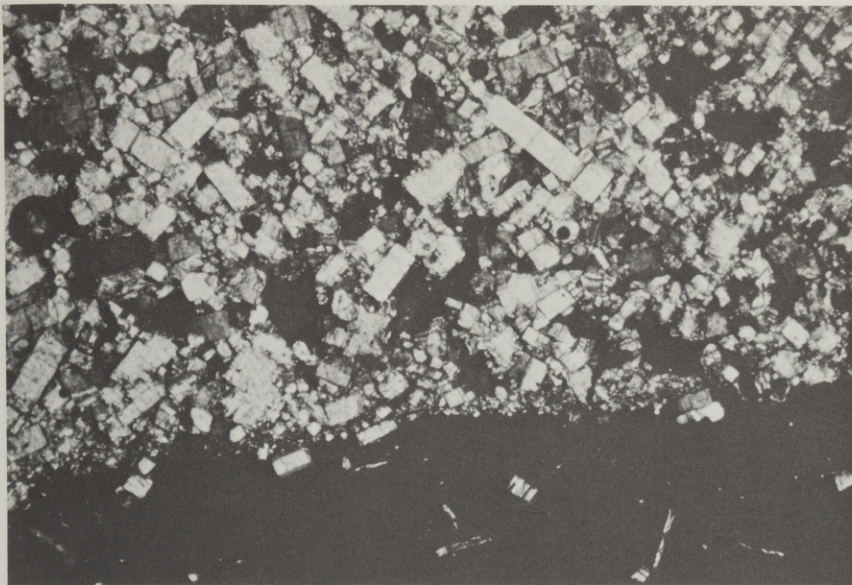
FIGURE 48. Sharp contact between salt and anhydrite cap rock at Cypress Creek Dome; depth is 1,386 ft (422.5 m). Photo width is 6.2 mm; crossed nicols.
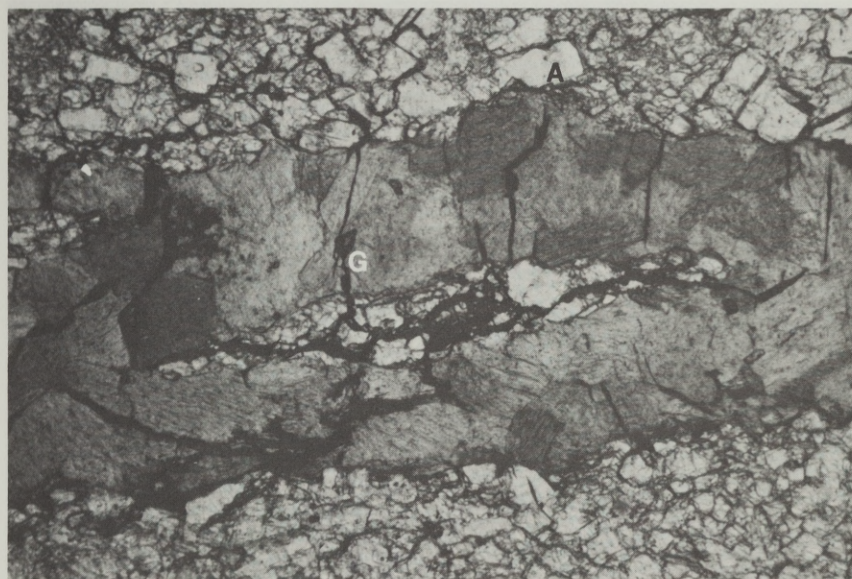

FIGURE 49. Gypsum-filled fracture (G) within anhydrite cap rock (A) at Richton Dome; depth is 634 ft (193.2 m). Photo width is 2.6 mm; plane light.

CAP-ROCK FORMATION: IMPLICATIONS FOR NUCLEAR WASTE ISOLATION

The cap rocks from Oakwood Dome and Gyp Hill Dome are significantly different in composition, texture, and mode and time of formation. Gyp Hill is composed entirely of calcium sulfate. The lower zone is a gypsum-cemented anhydrite rock. The anhydrite crystals are only mildly deformed and appear identical to the anhydrite in the salt. A cavity and uncemented anhydrite sand occur at the cap-rock/salt interface. This cap rock is considered to have formed and is still forming in a shallow, fresh-water aquifer. The gypsum cements precipitated in low-temperature, low-salinity waters. The minimal deformation of the anhydrite section of the cap rock indicates low overburden forces or low uplift forces, or both.

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FIGURE 50. Recrystallized anhydrite in Richton cap rock; depth is 634 ft (193.2 m). Photo width is 2.6 mm; crossed nicols.
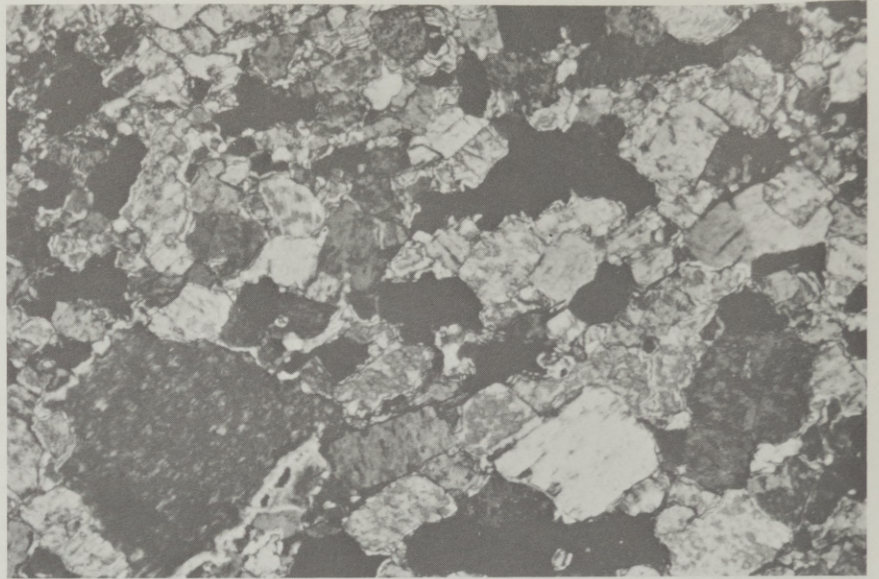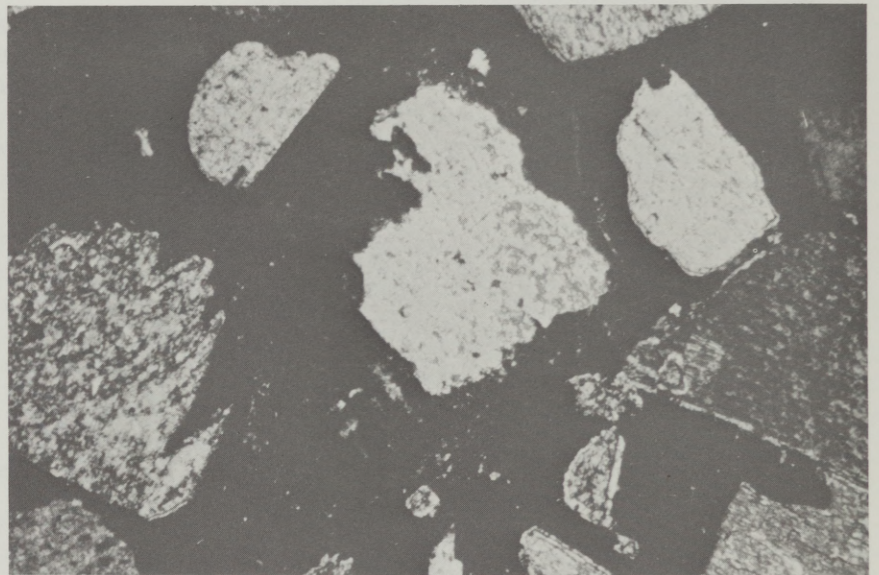

FIGURE 51. Partially dissolved anhydrite crystals from a Gulf of Mexico salt structure, well 114-A. The sample is from cuttings recovered at a depth of 1,320 to 1,321 ft (402.3 to 402.6 m). Photo width is 2.6 mm; crossed nicols.

Lithologically, Oakwood Dome cap rock is composed of a lower anhydrite zone and an upper calcite zone. The anhydrite zone is characterized by anhydrite recrystallized to a moderately well developed granoblastic texture. The contact between anhydrite cap rock and salt is very tight and extremely sharp. No gypsum is evident anywhere in the anhydrite section. The metamorphic texture of the anhydrite and the complete absence of gypsum indicate a relatively high-temperature, high-salinity, and high-

pressure environment. This anhydrite zone is considered to have formed by dissolution of the salt dome in a deep saline aquifer. The anhydrite cap rock appears to have formed during Late Jurassic and Early Cretaceous time. This conclusion is based on the fact that the only major rim syncline at Oakwood Dome formed before deposition of the Glen Rose Group.

The calcite zone overlying the anhydrite developed when hydrocarbon-rich waters passed over Oakwood Dome. Organic matter was
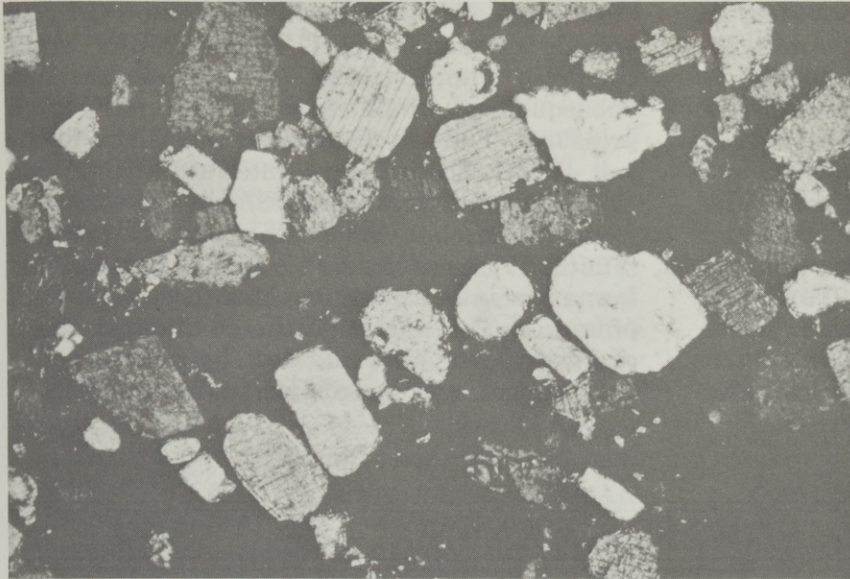
FIGURE 52. Halite-cemented anhydrite from a Gulf of Mexico salt structure, well 114-A. Dark zones are halite. Depth is 1,320 to 1,321 ft (402.3 to 402.6 m). Photo width is 6.2 mm; crossed nicols.

oxidized, the anhydrite was reduced, and dark calcite was precipitated. This process is confirmed by the extremely depleted $\delta^{13}C$ values of the calcites and the trace amounts of biodegraded hydrocarbons. Later, the dark calcite was partially dissolved and reprecipitated as light calcite. Both the light and dark calcite were precipitated in deep, hot, saline environments, as indicated by trace element and oxygen isotope data.

The Oakwood anhydrite cap rock, which formed more than 100 million years ago, appears to be an effective hydrologic seal. During the formation of the calcite section the anhydrite/salt interface was impermeable, as it remains today. In contrast, the Gyp Hill cap rock is still forming, and the salt dome is undergoing active dissolution; this cap rock is not an effective hydrologic seal. Salt domes being considered as nuclear waste repositories should have anhydrite cap rocks with the same characteristics as Oakwood Dome cap rocks and not those of Gyp Hill.

Gyp Hill and Oakwood Dome cap rocks may represent two end members of a spectrum of cap rocks forming in different hydrogeochemical environments during different geologic periods. Cap rock from Rayburn's Dome appears very similar to that at Gyp Hill, whereas the cap rock at Vacherie is very similar to that at Oakwood. Cap rocks for Cypress Creek and Richton are located between these extremes. The diagenetic

history of Richton appears more complex than that of either Oakwood or Gyp Hill. Many authors (for example, Murray, 1961; Bodenlos, 1970; Martinez, 1975; and Overton, 1979) have tried with varying success to relate cap-rock properties, such as depth, thickness, and mineralogy, to presently occurring, shallow geologic processes. Recognition of the different environments and times of formation invalidates this approach. Future evaluations of cap rocks must recognize these problems.

Petrographic analysis represents the most important approach to evaluating the permeability of the cap rock. The presence or absence of gypsum or calcite as either pore-filling cements or fracture-filling cements defines the past long-term hydrologic character of the anhydrite cap rock. The lack of gypsum or calcite in either the matrix (Goldman's [1952] "rim gypsification") or the fractures of the Oakwood anhydrite section documents the long-term impermeability of the cap rock. Fracture fillings of calcite, gypsum, barite, and sulfur in anhydrite sections (for example, Richton Dome), gypsum-cemented anhydrite (Gyp Hill Dome), or rim gypsification (Sulfur Dome) indicate a more permeable cap rock.

The presence of a recrystallized anhydrite cap rock does not guarantee that a salt dome is not dissolving today. It only indicates that the major dissolution, the one that caused the cap rock to form, occurred during the geologic past.

The impermeable nature of the cap rock must be evaluated further by petrographic and geochemical analysis and by hydrologic testing.

The existence of a cavity at the salt/cap-rock interface may or may not indicate ongoing dissolution. Two different types of voids are found at the interface: cavities containing normally pressured brine (for example, Gyp Hill) and cavities containing abnormally pressured brines (for example, Grand Saline Dome [Goldman, 1933]). Cavities with normally pressurized brines probably indicate current dissolution. Overpressured brine pockets may represent earlier dissolution events that were later followed by an episode of domal uplift. Dome growth would compress trapped fluids at the interface and subsequently would cause abnormally high pressures. The abundant fluid inclusions in the salt at the salt/anhydrite interface at Oakwood Dome (Dix and Jackson, 1982) may have resulted from this mechanism. Neither osmotic pressure (Smith, 1977) nor discharge from deeper basinal formation is needed to explain these high fluid pressures. The nature of the cavity and origin of fluids can be evaluated by petrographic, geochemical, and hydrologic testing.

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