

# Nature and Origin of Caprock Overlying Gulf Coast Salt Domes\*

Charles W. Walker

New Mexico State Bureau of  
Mines and Mineral Resources  
Socorro, New Mexico

## ABSTRACT

Caprock overlying Gulf Coast salt domes is an irregular complex of rocks: often composed of anhydrite, calcite, gypsum and occasionally celestite. Over half of the proved domes in the Gulf Coast area are known to have caprock, with the mantle more likely to occur and to be thickest over the shallow structures.

A study of caprock from 39 salt domes indicates large lithologic variations as well as variances in its chemical composition. Previous theories of origin cannot satisfactorily account for these variations in caprock and its relationship to the surrounding environment. The previous theories are: (1) residual accumulation and secondary alteration and (2) precipitation in place.

Neither of the two theories can account for all the known features of caprock: Great thicknesses of anhydrite caprock means that a tremendous thickness of salt would have had to be dissolved in order to accumulate thick residues. Minerals not found in the salt's less soluble residue are contained in caprock, and their presence cannot always be explained by secondary alteration. It is difficult to account for the large chemical differences between the salt anhydrite and caprock anhydrite by the residual accumulation theory. Precipitation alone of anhydrite can result in a thick caprock, but this process cannot account for the minor minerals included in the caprock which are so similar to those in the salt.

Since neither of the previous theories alone can satisfactorily account for all the known caprock features, it is proposed here that its origin may be explained by a combination of the two theories, with direct precipitation accounting for the bulk of the caprock overlying the shallow salt domes of the Gulf Coast region. The variability of caprock between domes and on any one individual dome would result from local controls and conditions. Structure would partially control fluid movement, along with permeability and osmotically derived pressures in the surrounding sedi-

ments. The composition of the associated brines would limit the type of minerals precipitated, and the geochemical environment would dictate the types of minerals which precipitate.

## INTRODUCTION

Caprock is an irregular complex of rock, predominantly anhydrite, which is present on the top, and occasionally on the sides, of many salt domes in the Gulf Coast area. Of the 329 proved domes, 181 are known to have caprock (Hawkins and Jirik, 1966). Both the shallow and deep seated domes are known to have this mantle, but it is more likely to occur and to be the thickest over the shallow structures. Thickness of caprock may vary from less than 10 to more than 1,500 feet.

A regional study of borehole data from 39 salt domes has indicated large variations in the character of caprock from dome to dome as well as on any single dome. These data were used to define lithologic variances of caprock and to determine if any qualitative and/or quantitative relationships exist between caprock and its surrounding environment.

Geochemical analytical methods were devised and employed to aid in the understanding of caprock genesis. These include major and trace element analyses of caprock and the salts' less soluble residue material, simulation of caprock growth and diagenesis in controlled laboratory experiments and solubility experiments on the salt-residue minerals. Caprock and salt-residue minerals have been characterized by use of thin sections, the transmission electron microscope and a scanning electron microscope.

Irregular zones of indurated sediments, commonly referred to as "false caprock" occur erratically above and

\*Research supported by the Institute For Saline Studies, Louisiana State University, Baton Rouge and the New Mexico State Bureau of Mines and Mineral Resources, Socorro.

adjacent to the true caprock of salt domes. These zones are cemented by various authigenic minerals which were derived from the true caprock and salt and then transported to surrounding sedimentary environments which favored their precipitation. An investigation of the false caprock has been most helpful in understanding the genesis of the true caprock.

#### Purpose of investigation

According to current concepts, caprock is believed to have formed from the accumulation of anhydrite as halite is dissolved from the uppermost part of the dome by circulating waters. Some anhydrite may subsequently alter to gypsum, calcite, sulphur and other minerals. This postulated sequence of events considered essential in caprock development is based on the rather limited information that was available during the early investigations and has not been experimentally tested except for the sulphur-isotope investigation by Feely and Kulp (1957).

The goal of this investigation was to develop a more thorough understanding of the origin of caprock and its relationship to the domal salt, the surrounding sediments and their contained fluids. In order to attain this goal a comprehensive study of all aspects of the nature of cap-

rock and its surrounding environment had to be considered.

Previous theories of caprock origin are analyzed to ascertain whether or not any of them, based on these above data, can satisfactorily account for the character of caprock and its relationship to the surrounding environment. This is followed by a modified theory of origin, which is postulated to account for all known facts. Finally, the sequence of events which may have taken place during the development of caprock is presented.

#### Salt domes studied

Figure 1 shows the location of salt domes for which information was available to the writer. Table I gives the name and location corresponding to the map numbers as well as the type of information obtained during the study.

### GENERAL GEOLOGY OF GULF COAST SALT DOMES

The Gulf Coastal region is underlain by great thicknesses of sediments and sedimentary rocks composed chiefly of sand, clay, marl, limestone, chalk and evaporites ranging in age from at least late Triassic to Recent. Semi-

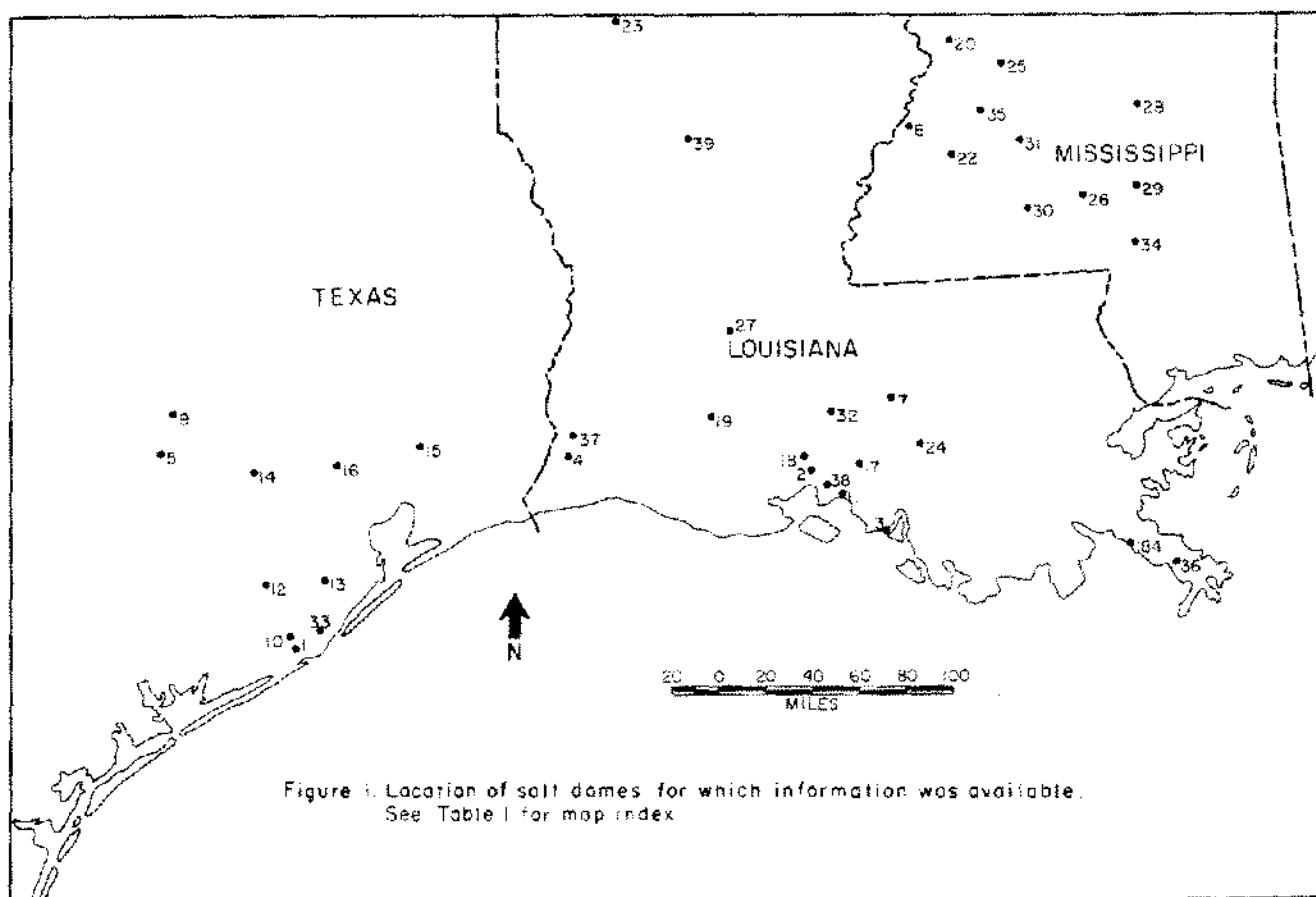


Figure 1. Location of salt domes for which information was available. See Table I for map index.

TABLE I

Map Index of Salt Domes for Which Information Was Available

Location					Type of Information Obtained						
Map Index	Dome	State	County or Parish	Survey or Sec. T.R.	Lithology Data	Samples	Thin Section	TEM	SEM	Chem. Analy.	Other*
1	Allen	Tex.	Brazoria	Alley	X	X	X			X	
2	Avery Island	La.	Iberia	39-13S-5E		X			X		
3	Belle Isle	La.	St. Mary	28-17S-10E	X	X			X		
4	Black Bayou	La.	Cameron	7-12S-12W	X	X	X				
5	Brenham	Tex.	Austin	Williams, A-110	X						
6	Bruinsburg	Miss.	Claiborne	13-11N-1E		X	X				
7	Choctaw	La.	Iberville	52-9S-11E		X	X		X	X	
8	Challenger	Abyssal Plain	Gulf of Mex.	23° 27.3'N, 92° 35.2'W							X
9	Clay Creek	Tex.	Washington	Perry							X
10	Clemens	Tex.	Brazoria	McNeel, A-92		X	X				
11	Cote Blanch	La.	St. Mary	23-15S-7E		X			X		
12	Damon Mound	Tex.	Brazoria	Millis	X						
13	Danbury	Tex.	Brazoria	Austin, A-14		X	X				
14	Hockley	Tex.	Harris	Coghill	X	X			X	X	
15	Hull	Tex.	Liberty	Devore	X	X	X			X	
16	Humble	Tex.	Harris	Adams	X						
17	Jeanerette	La.	St. Mary	37-13S-9E		X				X	
18	Jefferson Is.	La.	Iberia	59-12S-SE		X			X		
19	Jennings	La.	Acadia	47-9S-2W		X	X			X	
20	Kings	Miss.	Warren	39-17N-4E	X	X	X		X	X	
21	Lake Wash.	La.	Plaquemines	24-20S-26E		X	X				
22	McBride	Miss.	Jefferson	19-8N-4E	X						
23	Minden	La.	Webster	20-19N-8W	X	X	X	X	X	X	X
24	Napoleonville	La.	Assumption	41-12S-13E	X						
25	Oakley	Miss.	Hinds	27-5N-3W		X	X				
26	Oakvata	Miss.	Jeff. Davis	32-6N-19W	X						
27	Pine Prairie	La.	Evangeline	35-3S-1W	X						
28	Raleigh	Miss.	Smith	17-2N-8E		X	X				
29	Richmond	Miss.	Covington	20-6N-15W	X	X	X				
30	Ruth	Miss.	Lincoln	15-5N-9E	X						
31	Sardis Church	Miss.	Copiah	29-10N-9E	X						
32	Section 28	La.	St. Martin	33-9S-7E	X						
33	Stratton Ridge	Tex.	Brazoria	Groce	X						X
34	Tatum	Miss.	Lamar	14-2N-16W	X	X	X	X	X	X	
35	Utica	Miss.	Copiah	8-2N-4W	X	X	X		X	X	
36	Venice	La.	Plaquemines	26-21S-30E	X						
37	Vinton	La.	Calcasieu	33-10S-12W	X						
38	Weeks Is.	La.	Iberia	38-14S-6E		X			X		
39	Winnfield	La.	Winn	19-11N-3W	X						
Non-Gulf Coast Salt											
Hutchinson bedded salt, Kansas						X			X		
Pug Wash Salt Dome, Nova Scotia, Canada						X			X		
Whisky Island Mine, bedded salt, Michigan Basin						X			X		
Zechstein 2, Germany						X			X		

TEM = Transmission electron microscopy, SEM = Scanning electron microscopy, \* includes water analyses, pressure and temperature data, etc.

cylindrical masses of salt have thrust their way upward through these sediments, and have resulted in the well-known salt domes or salt plugs which are characteristic of the region. As of 1966, three hundred and twenty-nine of these structures had been proved to exist in the states of Texas, Louisiana, Mississippi and Alabama (Hawkins and Jirik, 1966). The presence of salt domes has since been established in the Sigsbee Deep area of the Gulf of Mexico (Leg 1, Glomar Challenger Project, 1968).

#### Salt dome minerals

Halite and the water-insoluble residue minerals which were identified during this investigation will now be examined in the order of their abundance.

Halite was found to constitute about 89 to 92 percent of the salt samples studied, and has been reported by various authors to range from 80 to 98 percent. The halite which is found in the domes is generally euhedral, with individual crystals ranging in size from near submicroscopic to as large as 5 centimeters. The color of the mineral, dependent upon the abundance of inclusions, ranges from almost colorless to dark brown. Inclusions occur within the individual salt crystals (Fig. 2) apparently in much the same relationship as when originally precipitated (Taylor, 1938). They are scattered throughout all of the salt crystals with greater concentrations along dark bands.

These inclusions were removed from the salt of several domes by dissolving the salt and recovering the water-insoluble residue. A size analysis of the residue from one dome, plus the major mineral components in each rock size class is shown in Table II. Chemical analyses of the water-insoluble residue obtained from four salt domes are displayed in Table III. These analyses indicate small

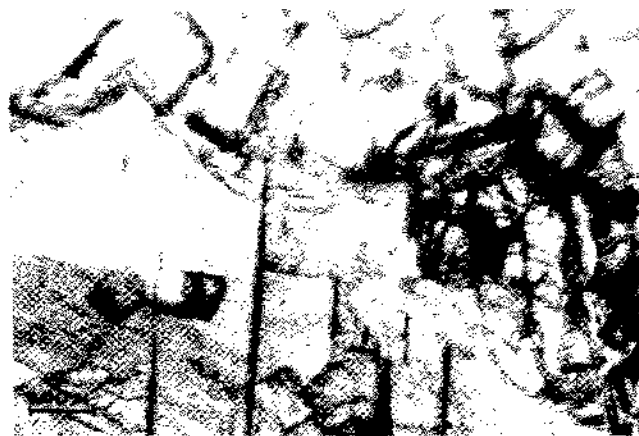


Figure 2. Thin-section of salt showing that the inclusions occur within the individual crystals, apparently in much the same relationship as when originally precipitated, AEC salt core, Tatum Dome, Mississippi, 1513 feet. Optical micrograph, nicol prisms removed.

chemical variations in the insoluble residue between domes.

Anhydrite constitutes approximately 99 percent of the water-insoluble residue. It ranges in size from minute cleavage fragments to about 5 mm (Table II), and has been reported to be as large as 14 mm (Taylor, 1938). The mineral occurs in two major morphologies; tabular crystals and "stem-shaped" (Taylor, 1938; used to designate a morphology having striations similar to those of a plant stem) crystals. The stem-shaped variety, apparently the most common type, is occasionally long and slender, but is generally stubby and often complexly twinned (Fig. 3). The mineral may contain inclusions of smaller anhydrite crystals, pyrite, dolomite, sulphur, fluid and possibly carbonaceous matter.

TABLE II

Water-Insoluble Residue: Size and Mineralogical Analysis  
Tatum Dome, Miss., AEC Well, 1947 feet

Sieve Size (mm)	Wt. retained on(g)	% retained on	Mineralogy
1.0	3.77	1.43	Anhydrite
0.5	95.06	36.15	Anhydrite
0.25	127.81	48.60	Anhydrite some dolomite
0.125	33.42	12.71	Anhydrite, dolomite
0.063	2.66	1.01	Anhydrite, dolomite
Pan	0.27	0.10	Anhydrite, dolomite, quart plagioclase

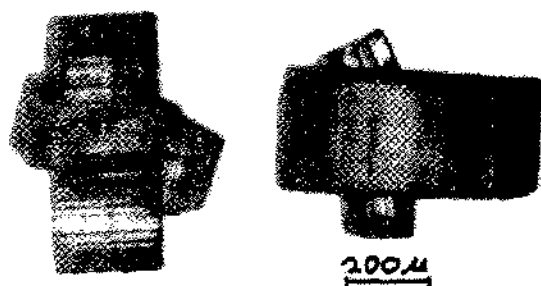


Figure 3. Water-insoluble residue, Tatum Dome, Mississippi. Twinned, "stem-shaped" anhydrite crystals. AEC well, 1513 feet. Optical micrograph, reflected and plane polarized light.



Figure 4. Water-insoluble residue, Tatum Dome, Mississippi. Twinned dolomite rhomb. AEC well, 1513 feet. Scanning electron micrograph.

Dolomite is the next most abundant residue mineral found, and has been reported to be in all of the domes in quantities up to several percent (Taylor, 1938). It occurs as well developed rhombohedral crystals, often twinned, which range in size from 0.05 mm to as large as 1.3 mm (Fig. 4). Many of the rhombohedrons contain a nucleus of a white or dark substance, probably carbonaceous material. The crystals are usually pale brown, but a few are colorless.

Quartz, following dolomite in abundance, occurs as well-developed individual crystals and as rosettes. The rosettes are very distinctive in appearance, containing nuclei of a white opaque substance, similar to that found in some of the dolomite rhombs. The individual crystals are generally about 0.02 mm in length and very rarely as large as 1 mm (Fig. 5). Most of the rosettes are about 0.1 mm in size.

Other less common occurring minerals include sulphur, barite, feldspar and a host of very rare minerals. The reader is referred to Taylor (1938) for a comprehensive list and description of the rare minerals obtained from Louisiana and Texas salt residues.

### THE CAPROCK

Caprock is an irregular complex of rocks which is present on the top, and commonly the sides, of approximately half the known salt domes in the Gulf Coast region as well as on the Sigsbee domes in the Gulf of Mexico. Both the shallow and deep seated domes have recognizable caprock, but it is more likely to be present and to be thickest over the shallower domes. The average depth to the salt on those domes having caprock is about 2,325 feet ranging from near surface to greater than 10,000 feet deep. The depth to the top of the caprock averages approximately 1,970 feet. Thickness of caprock is very variable, but averages about 420 feet.

TABLE III

Chemical Composition of Residue Anhydrite \*

	CeO(%)	S(%)	Si(ppm)	K(ppm)	Fe(ppm)	Zn(ppm)	Sr(ppm)
Min.	37.62	23.21	0	5	57	445	357
Max.	39.54	23.55	35	65	125	475	390
Mean	39.32	23.41	7	21	83	463	371
S.D.	0.26	0.03	1.77	10.50	14.70	2.57	6.81
C V (%)	0.66	1.13	5.89	48.92	17.87	0.57	1.86

\* Composition of four salt domes residues, ten samples.

Salt domes are: Tatum, Kings, Allen, Hull

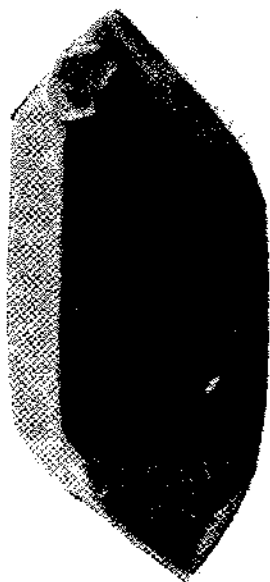


Figure 5. Water-insoluble residue, Tatum Dome, Mississippi. Double terminated quartz crystal. AEC well, 1513 feet. Scanning electron micrograph.

The caprock commonly consists of three or four different types of lithologies. These lithologies are predominantly monomineralic, and contain as their major minerals, anhydrite, gypsum, calcite and less commonly celestite. The term "limestone" is not used because of its genetic implications. Minor minerals include sulphur, pyrite, dolomite, barite and others. The anhydrite portion of the caprock is generally the thickest; followed in thickness by calcite, gypsum and celestite. Interbedded layers of salt and/or sediments are noted in caprock.

The upper portions of the caprock on many of the domes have been highly fractured and brecciated, and these features have been attributed to the pressure exerted on the caprock during upward movement. The calcite cap is commonly very cavernous with the cavities ranging in size from minute voids to over a quarter of a mile in length (Taylor, 1938). Hanna and Wolf (1934) noted that cavities can comprise up to 50 percent of some caprock. Most of the hydrocarbons and sulphur found in caprock are contained in these cavities.

The shape of caprock is highly variable. Generally, it overlies the upper surface and extends down the flanks of the salt dome, with the top of the cap nearly paralleling the salt surface. Numerous exceptions to this generalization can be found. For example, caprock extends beyond the edge of the salt at Barbers Hill Dome, Texas, Allen Dome, Texas and Tatum Dome, Mississippi. Caprock may be thickest over the central portion of the dome or it may be well developed over only a portion of the dome such as at Belle Isle Dome, Louisiana, Winnfield Dome, Louisiana and Brenham Dome, Texas. Caprock may ex-

tend down the flanks of the dome for several thousand feet such as at Winnfield and Lake Washington Domes, Louisiana.

### Lithology

The basis of the following discussion is derived from lithology data of all wells on each dome for which information was available to the writer. Most of this information is borehole data obtained from the files of Freeport Sulphur Company. Since all of the domes studied are considered shallow (generally less than 4,000 feet to the top of the salt), this description of caprock is only pertinent to the shallow domes, as the deep-seated dome caprock may be considerably different. However, general statements can be made about caprock of the shallow domes with the assumption that the domes studied are representative of all shallow salt domes. The lithology data from all wells on each dome is listed in Table IV.

The lithology data (Table IV) were averaged for each dome in order to characterize the caprock on each dome and to determine if any similarities or variations exist between domes (Table V). From this table it can be seen that the lithology of the caprock of the 24 domes listed is quite variable. Table V displays information obtained from a statistical analysis of the average lithology data. The coefficient of variation (standard deviation/mean  $\times$  100) was used to quantify differences in each variable between the 24 salt domes. The coefficient ranges from 51.18 percent for the depth to the top of salt to as high as 219.59 percent for the anhydrite to gypsum ratio.

As seen in Table V, the top of caprock best correlates with the top of salt, as one would expect, and there is a fair negative relationship between it and the gypsum thickness. Calcite thickness does not strongly correlate with any of the variables, but does show a slight relationship with the top of salt. Gypsum thickness is negatively related to the top of salt and somewhat to the anhydrite and calcite thickness. Anhydrite best compares to the total caprock thickness which indicates this is the most abundant lithology. There is a very poor relationship between caprock total thickness and the top of salt, indicating that caprock thickness is not a function of depth for this particular set of shallow domes. The total sulphate (anhydrite + gypsum) to carbonate ratio relates slightly to the total thickness and exhibits a weak negative trend when compared to the top of salt. The anhydrite to gypsum ratio also shows a slight relationship with total thickness.

The sequence of lithology from the top of the caprock to the base in each well examined is illustrated in Figure 6. Flank wells and centrally located wells in the caprock have also been differentiated in the figure. As summarized by Murray (1966), a mature caprock would consist of a calcite-gypsum-anhydrite-salt, top to bottom, sequence of lithology. This complete sequence is found in only 22 percent of the wells examined with a greater part of these

wells being centrally located. Six percent of the wells have lithologies which are not in this sequential order: calcite-anhydrite-gypsum-salt, in which gypsum is overlying anhydrite. Anhydrite-gypsum-salt sequence and the gypsum-calcite-salt distribution. The remaining wells have one or two rock types missing, but the sequence remains valid. A calcite-gypsum-salt sequence is the most common distribution present. It is interesting to note the large percentage of wells having only calcite caprock with most of these wells located on the flanks.

From the foregoing discussion it can be seen that caprock is quite variable in lithology and lithologic sequence. Furthermore, variability of lithologies are even much greater when the caprock is studied in more detail. Figure 7 displays columnar sections of boreholes drilled through the caprock of ten salt domes. Note the celestite zones in wells 9 and 10 as this mineral has not been previously noted in this great abundance. The sequence of lithology types is not as simple as most of the literature suggests. Columnar sections showing the lithologic variability of caprock on a single dome is illustrated in Figure 8.

The triangular diagram of Figure 9 which illustrated calcite-gypsum-anhydrite thickness relations for each dome listed in Table IV is plotted in a manner to differentiate the domes of each state. The three components of the diagram are in feet units. Measures of the three components were added, converted to percentages, and plotted as points within the triangle. The diagram shows quite a scatter of points, indicating thickness variability of the three components. Mississippi caprock points do not scatter as much as the other two states since gypsum thickness in this state is always less than 20 percent of the total thickness.

The character of caprock is very complex on a megascopic examination. The complexity increases as caprock is studied in greater detail: The variety of lithologic banding and variable nature of the boundaries between the bands, the presence of relatively large concentrations of celestite in Mississippi caprock, variable thicknesses of sediments and salt in caprock, crystal morphology, the chemistry of the minerals, stress effects and a host of other features all add to this complexity.

TABLE IV  
Average Lithology Data from all Wells on Each Dome

Dome	TC	CT	GT	AT	TT	TS	TCO <sub>3</sub>	TSO <sub>4</sub>	SO <sub>4</sub> CO <sub>3</sub>	Anhy Gyp	TSed	#Wells
Allen, Tex.	995	51	246.7	166.3	420	1394	51	376.7	7.39	0.7	18	15
Belle Isle, La.	859	283	120.3	10*	339.8	1199	283	130.3	0.46	0.1	3	7
Black Bayou, La.	1054	76.3	66	800*	942*	2000*	76.3	866	11.35	12.1	—	7
Brenham, Tex.	1523	74.8	—	363	459	2253	74.8	363	4.85	—	5	7
Damon Mound, Tex.	220	131.9	278.9	—	377	562	131.9	278.9	2.11	—	—	28
Hockley, Tex.	452	128.2	110.7	419	671	1124	128.2	502	3.91	3.8	54	4
Hull, Tex.	418	72.5	225.2	86.8	323.1	787	72.5	255	3.50	0.4	42	7
Humble, Tex.	1181	60.2	—	66.2	126.4	1307	60.2	66.2	1.10	—	—	5
Kings, Miss.	3593	155	22	75	252	3845	155	97	0.62	3.4	—	1
McBride, Miss.	2095	95.5	—	—	95.5	2190	95.5	—	—	—	—	4
Minden, La.	1175	144	—	586	730	1905*	144	586	4.07	—	—	2
Napoleonville, La.	580	104.7	113.5	27.5	151.2	773	104.7	112.6	1.07	0.2	8	10
Oakvale, Miss.	1648	94.6	—	702	826	2396	94.6	702	7.42	—	—	7
Pine Prairie, La.	173	169.3	157.8	18.8	356	530	169.3	168.1	0.99	0.1	91.8	12
Richmond, Miss.	1717	34	20	196.5	228	1950	34	216.5	6.37	9.8	—	3
Ruth, Miss.	2331	402.2	—	37*	439	2700*	402.2	37	0.09	—	—	4
Sardis Church, Miss.	1210	667	23*	400*	1110	2300*	667	423	0.63	17.4	30	8
Section 28, La.	1753	20	—	—	31.5	1785	20	—	—	—	10	2
Stratton Ridge, Tex.	1391	133.7	108.6	131.7	374	1633	133.7	240.3	1.80	1.2	—	8
Tatum, Miss.	1134	108.2	35	194.2	348	1520	108.2	223	2.06	5.5	—	9
Utica, Miss.	2641	494	—	—	494	3135	494	—	—	—	—	1
Venice, La.	1875	381.5	—	744*	1125	3000*	381.5	744	1.95	—	—	6
Vinton, La.	528	104	231.7	83	419	968	104	315	3.03	0.4	4	5
Winnfield, La.	100	160	60	140	360	460	160	200	1.25	2.3	—	4

Depth to tops is feet below sur. Thickness given in feet. — indicates none recovered. \* indicates value from published data. TC = top of caprock, CT = Calcite thickness, GT = gypsum thick., AT = anhydrite thick., TT = total thickness, TS = top of salt, TCO<sub>3</sub> = total carbonate, TSO<sub>4</sub> = total sulphate, TSed = total sed in cap.

Taylor (1938) states "that the top of the caprock often must be estimated because of the false caprock which grades into it, and because of the broken or brecciated condition of the caprock itself." The term "false caprock" may be applied to those sediments, above or around the true caprock, which have been indurated and often replaced by authigenic cement derived from true caprock (Walker, 1968).

The upper portions of the caprock on most of the domes have been highly brecciated, with brecciation generally decreasing downward toward the salt. The breccia clasts in the calcite cap are usually dark in color and range in size from minute particles to 20 centimeters or greater in their long dimension. The clasts can commonly be fitted together, show little contact with each other, and appear to "float" in a matrix of a white to yellow secondary calcite.

The upper surface of the salt, upon which caprock usually forms, is quite variable from dome to dome. It ranges from a near flat surface to a highly rounded surface, or may be very irregular and asymmetrical. Since caprock can form on any of the above surfaces, a "solution table" or flat surface is not a requirement for its formation.

Generally, the caprock-salt interface is somewhat gradational; characterized by undissolved salt at the bottom, grading upward into a zone of friable anhydrite sand, and finally grading into the hard anhydrite caprock. It has been reported (Taylor, 1938) that when the interface is

encountered in drilling at Jefferson Island and Lake Washington Domes, Louisiana, a cavity of from a few inches to several feet is found. The caprock may also rest directly on the salt with no intervening anhydrite sand, such as at Hockley Dome, Texas (Teas, 1931). Some domes have either calcite or gypsum in contact with the salt, for example; Damon Mound, Texas and McBride, Mississippi.

Taylor (1938) remarked that the leached condition of the unconsolidated sediments close to the flanks of salt domes is probably due to the upward movement of ground waters, and that the sediments frequently contain water-insoluble residue minerals from the salt. He further indicates that the shale from near the flank of Darrow Dome, Louisiana, contains solution-worn anhydrite grains at a depth of nearly 8,000 feet.

#### Circumjacent sediments

Figure 10 illustrates an idealized salt dome and its surrounding sediments. Kerr and Kopp (1958) observed brecciation in deep (?) shale sections surrounding salt domes. They report that the brecciation extends laterally at least for several thousand feet, with an apparent roughly circular but somewhat asymmetric ground plan which may expand in depth. The clasts and matrix are mineralogically similar, and some fragments can be pieced together. They concluded that the mechanism of formation for these breccias may be a result of domal movement

TABLE V

Statistical Analysis of Average Lithology Data  
Correlation Matrix

Variable	TC	CT	GT	AT	TT	TS	TSO <sub>4</sub>	S/C	A/G
TC	1.000	0.254	-0.643	0.014	-0.006	0.942	-0.202	-0.177	0.169
CT	0.254	1.000	-0.254	0.072	0.091	0.406	-0.005	-0.421	0.064
GT	-0.643	-0.254	1.000	-0.310	-0.073	-0.670	0.015	0.148	-0.389
AT	0.014	0.072	-0.310	1.000	0.811	0.300	0.945	0.659	0.718
TT	-0.006	0.091	-0.073	0.811	1.000	0.241	0.832	0.546	0.679
TS	0.942	0.406	-0.670	0.300	0.241	1.000	0.089	-0.028	0.357
TSO <sub>4</sub>	-0.202	-0.005	0.015	0.945	0.832	0.089	1.000	0.739	0.623
S/C	-0.177	-0.421	0.148	0.659	0.546	-0.028	0.739	1.000	0.261
A/G	0.169	0.064	-0.389	0.718	0.679	0.357	0.623	0.261	1.000

Variable	Mean	Std. Deviation	Coeff. of Variation
TC = Top of caprock	1276.9	847.7	66.4
CT = Calcite thickness	172.7	159.7	92.6
GT = Gypsum thickness	75.8	91.4	120.0
AT = Anhydrite thickness	218.6	256.9	117.5
TT = Total thickness	416.6	272.6	65.4
TS = Top of salt	1738.2	889.7	51.2
TSO <sub>4</sub> = Total sulphate	287.6	243.9	84.8
S/C = SO <sub>4</sub> /CO <sub>3</sub>	2.8	2.9	105.8
A/G = Anhydrite/Gypsum	10.6	23.3	219.6



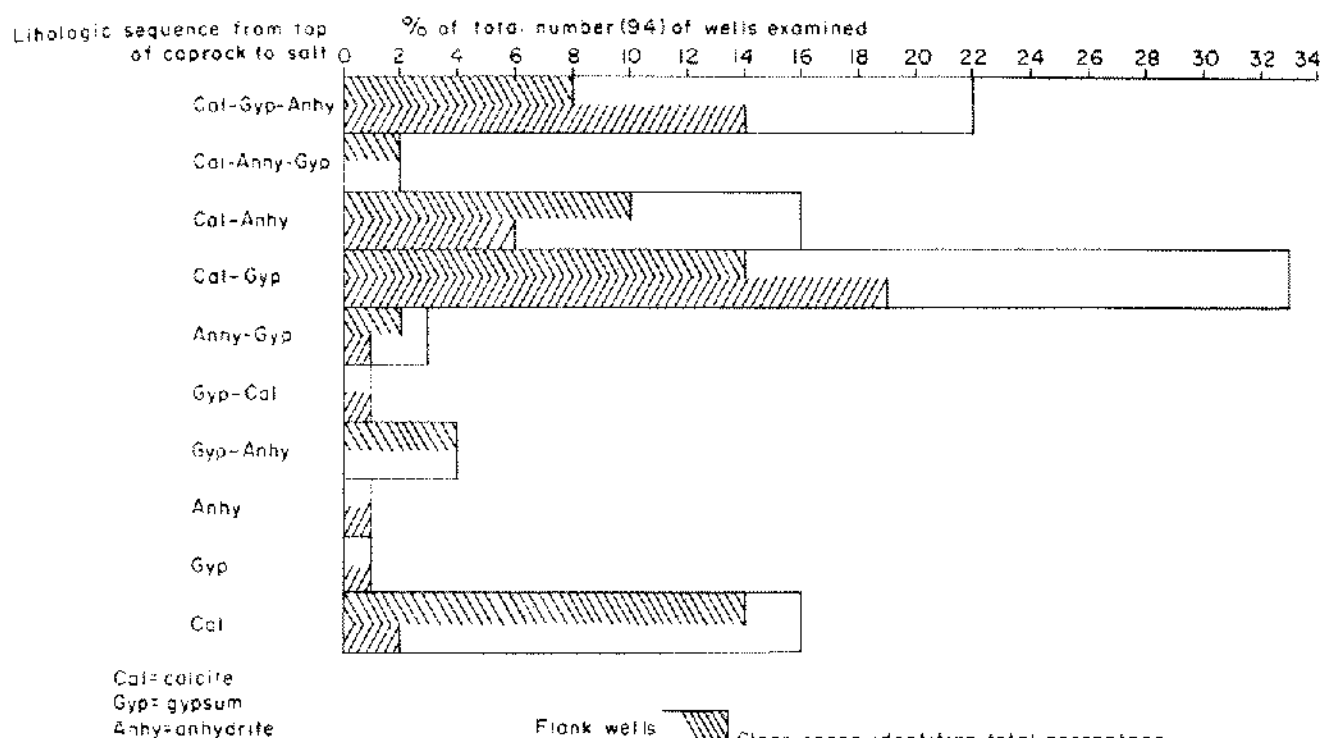


Figure 6  
Generalized lithology with Depth  
Segments omitted for simplification

Figure 6. Generalized lithology with Depth.

exerting an upward and outward pressure which exceeds the pressure of overburden.

An alternate idea is the possibility of osmotically derived fluid pressure, which could exceed the pressure due to the weight of the overburden, could result in brecciation of the shale. Osmotic pressure is generated when two aquifers of different salinity are separated by a semi-permeable membrane, which would be geologically, a fine-grained sediment (White, 1965). As a result, gradients in hydraulic head develop, in the direction of the more saline aquifer. The term "geopressure" is applied to abnormally high subsurface fluid pressure, and has been defined as "any pressure which exceeds the hydrostatic pressure of a column of water containing 80,000 mg/l (milligrams per liter) total solids" (Dickinson, 1953).

Adjacent to the flanks of many salt domes are found shale sheaths composed of fine-grained clayey material. The gouge shale, or sheath, (Fig. 10) is quite variable in age and thickness (Murray, 1966), probably resulting from the material being dragged high above the immediate position of the undisturbed equivalent bed during domal movement (Hanna, 1953). This shale sheath could possibly behave as a semi-permeable membrane, due to its

fine-grainness, permitting selective movement of water toward the salt and the development of osmotic pressure.

## CAPROCK MINERALOGY AND GEOCHEMISTRY

The major minerals of the caprock framework are sulphates and carbonates. Other associated minerals include sulphides, arsenides, halides, silicates, oxides and a number of pure elements. A list of minerals which have been identified by various students of caprock is presented in Table VI. This table also tabulates the occurrence for each mineral. Of the thirty minerals listed, only nine or ten are found in significant quantities.

A somewhat detailed discussion of the more common minerals will follow. This discussion will include such aspects as spatial distribution, abundance, age relations, crystal morphology, stress effects, alteration and replacement features, geochemistry, banding and the association with other minerals and sediments. The order in which the minerals are discussed is based on a typical sequence through the caprock from top to bottom. A few of the rarer minerals are briefly discussed at the end of the sec-

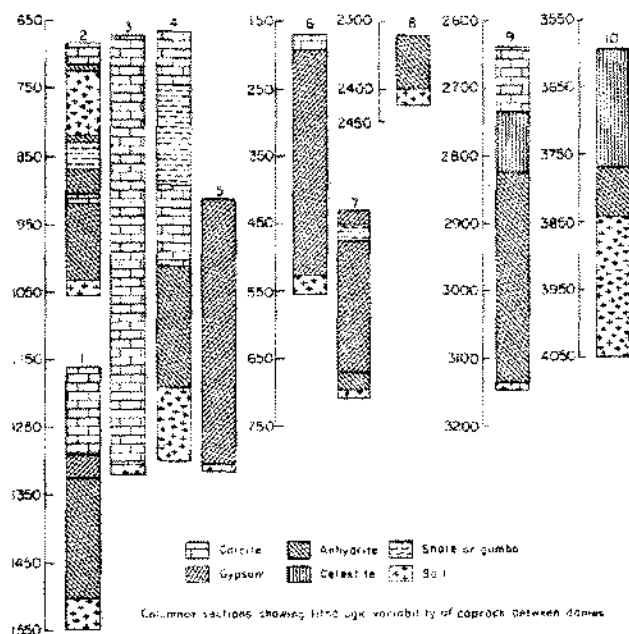


Figure 7.

- 1—Tatum Dome, F.S. Co. Well No. 9
- 2—Hull Dome, F.S. Co. Well No. 4
- 3—Bell Isle Dome, F.S. Co. Well No. 2
- 4—Hockley Dome, F.S. Co. Well No. 6
- 5—Stratton Ridge Dome, Tolar Well No. 1
- 6—Pine Prairie Dome, F.S. Co. Well No. 8
- 7—Napoleonville Dome, F.S. Co. D&L Well No. 1
- 8—Minden Dome, Hudson Well No. 2
- 9—Utica Dome, L. Little Well No. 1
- 10—Kings Dome, Hall Well No. 1

tion, as well as the sediments found within the caprock. A total of 118 samples from 9 salt domes were analyzed by x-ray fluorescence to determine major and trace element concentrations of Ca, S, Si, K, Fe, Zn, Sr, Ti, Mg and Na.

### Calcite

This mineral is second in abundance to anhydrite. All of the caprock studied contain large amounts of calcite, and it is the major cementing mineral of the false caprock. It is most abundant in the upper zones of caprock and is occasionally (16% of wells examined) the only major mineral constituent of caprock, such as at McBride and Utica Domes, Mississippi. Calcite may be found as a minor component in any of the lithologies, and constitutes from less than 1 percent to somewhat more than 98 percent by weight of the individual specimens as determined by acid-insoluble tests. The crystals vary in size from near submicroscopic to over 12 mm in the maximum dimension. The size of the individual crystals is apparently indicative of relative age relationships: The finely crystalline variety is generally the oldest generation calcite because it is never found to be cutting other minerals and is generally the

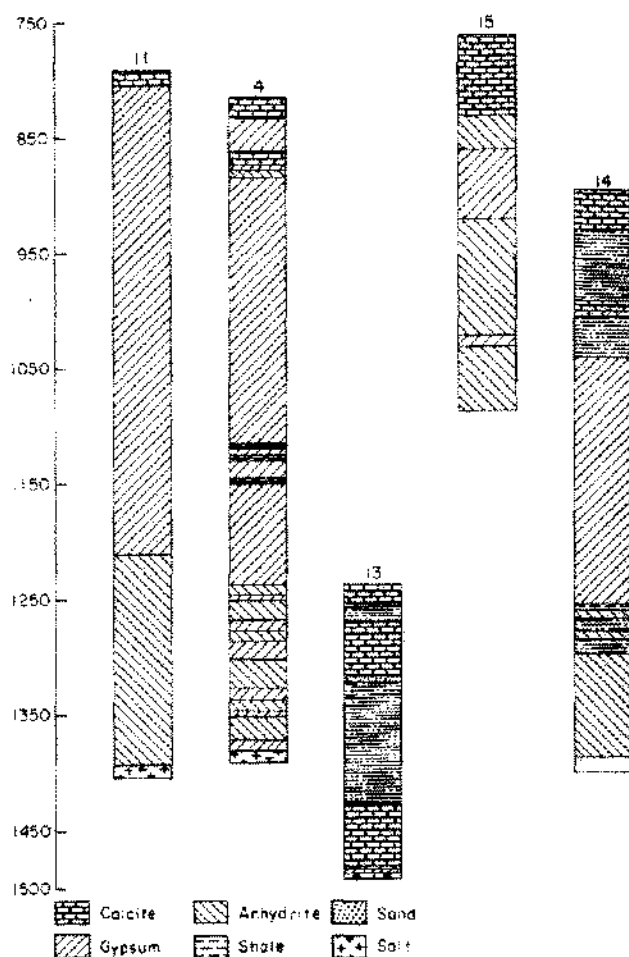


Figure 8. Columnar sections showing lithologic variability of caprock on a single dome, Allen Dome, Texas.

most deformed; the coarsely crystalline calcite is associated with the recementation of fractures which may cut either of the other two types; an intermediate to coarsely crystalline calcite may be either older or younger than the recementing calcite because of recrystallization at the expense of either of the above mentioned varieties.

Calcite replaces all of the common caprock minerals except the sulfides to varying degrees, and is occasionally replaced by sulphur.

The concentrations of trace elements in calcite is quite variable. As the calcite zone is not completely monomineralic, the trace element distribution is a function of both solid solution and other minor phases present. It is believed that most of the silica is in the form of quartz, iron in pyrite, sulphur as the native element and in pyrite, and magnesium in dolomite. Other trace elements occur predominantly as interstitial impurities in calcite as in trace minerals or in solid solution. The calculated coefficients of variation indicate that calcium, iron and sodium remain fairly constant, whereas the other elements are quite vari-

TABLE VI  
Caprock Minerals

Mineral	Composition	Habit	Occurrence*
Anhydrite	CaSO <sub>4</sub>	Prismatic, radiating, fibrous, "sterm shaped"	XXXXXX
Barite	BaSO <sub>4</sub>	Radiating, tabular, rosettes, prismatic	XXX
Celestite	SrSO <sub>4</sub>	Radiating, fibrous, massive, tabular	XXXX
Gypsum	CaSO <sub>4</sub> ·2H <sub>2</sub> O	Prismatic, tabular, fibrous, massive	XXXXX
Calcite	CaCO <sub>3</sub>	Rhombohedral, scalenohedral, equant to bladed	XXXXXX
Aragonite	CaCO <sub>3</sub>	Tabular, prismatic	XX
Dolomite	(Ca, Mg)(CO <sub>3</sub> ) <sub>2</sub>	Rhombohedral	XXXX
Strontianite	SrCO <sub>3</sub>	Acicular	XX
Siderite	FeCO <sub>3</sub>	Not reported	X
Smithsonite	ZnCO <sub>3</sub>	Not reported	X
Pyrite	FeS <sub>2</sub>	Cubes, pyritohedral, octahedral	XXXXX
Marcasite	FeS <sub>2</sub>	Not reported	X
Galena	PbS	Cubes	XX
Sphalerite	ZnS	Earthy	XX
Hauerite	MnS <sub>2</sub>	Octahedral	X
Alabandite	MnS	Tetrahedral	X
Realgar	As <sub>2</sub> S <sub>2</sub>	Prismatic	X
Chalcopyrite	CuFeS <sub>2</sub>	Massive	X
Chalcocite	Cu <sub>2</sub> S	Massive	X
Enargite	Cu <sub>3</sub> AsS <sub>4</sub>	Prismatic	X
Halite	NaCl	Cubes	XXXX
Fluorite	CaF <sub>2</sub>	Cubes	X
Hematite	Fe <sub>2</sub> O <sub>3</sub>	Earthy	XX
Quartz	SiO <sub>2</sub>	Terminated xls., rosettes, chalcedonic	XXX
Kaolinite	Al <sub>2</sub> O <sub>3</sub> ·2SiO <sub>2</sub> ·2H <sub>2</sub> O	Tabular, fibrous	XX
Tourmaline	Mg rich	Rhombohedral, prismatic	X
Sulphur	S	Orthorhombic xls, massive	XXXXX
Arsenic	As	Colloform	X
Gold	Au	As inclusions (?)	X
Silver	Ag	As inclusions (?)	X

\*XXXXXX very common; XXXXX common; XXXX fairly common; XXX fairly rare; XX rare; X very rare

able, with silica and titanium being the most variable.

Banding in the calcite caprock is a very common feature. One of the most distinctive properties of this banding is the rhythmic alteration of colors (Fig. 11). The thickness of any one band may range from about 0.25 mm to 40 mm or thicker. In the lesser disturbed portions of the cap the banding is generally horizontal or at a small angle from the horizontal. The bands are limited in horizontal extent as they terminate either by pinching out or by truncation. When viewed closely, the bands show many irregularities and contortions. Under the microscope the bands appear to grade into one another and a sharp contact cannot be found. Cavities lined with drusy calcite are characteristic of the light bands while the dark bands are usually more dense and may contain considerable pyrite.

The dark bands are somewhat harder (a greater resistance to abrasion) than the white bands as indicated by the fact that when the banded rock is polished, the light bands are undercut leaving the dark bands protruding.

White bands have an anomalously high concentration of titanium (up to 3800 ppm) but are generally low in sulphur and iron. Darker bands are characterized by high iron, sulphur and often silica but are low in titanium. Calcite is usually the only mineral in the white bands. Sulphides (predominantly pyrite) and sometimes organic matter generally constitute minor phases in the dark banded calcite.

Brown in 1931 attributed this banding to diffusional movement. Since that time, little attention has been given to the subject. A possible mechanism of diffusion during

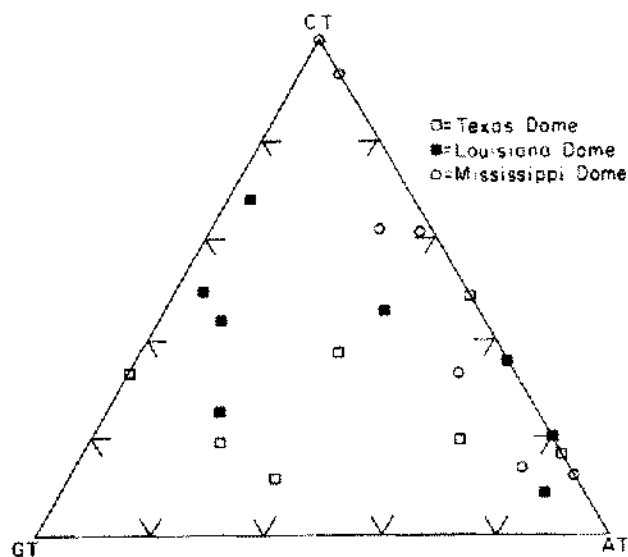


Figure 9. Triangular diagram illustrating calcite-gypsum-anhydrite thickness for each dome. Data from Table 4.

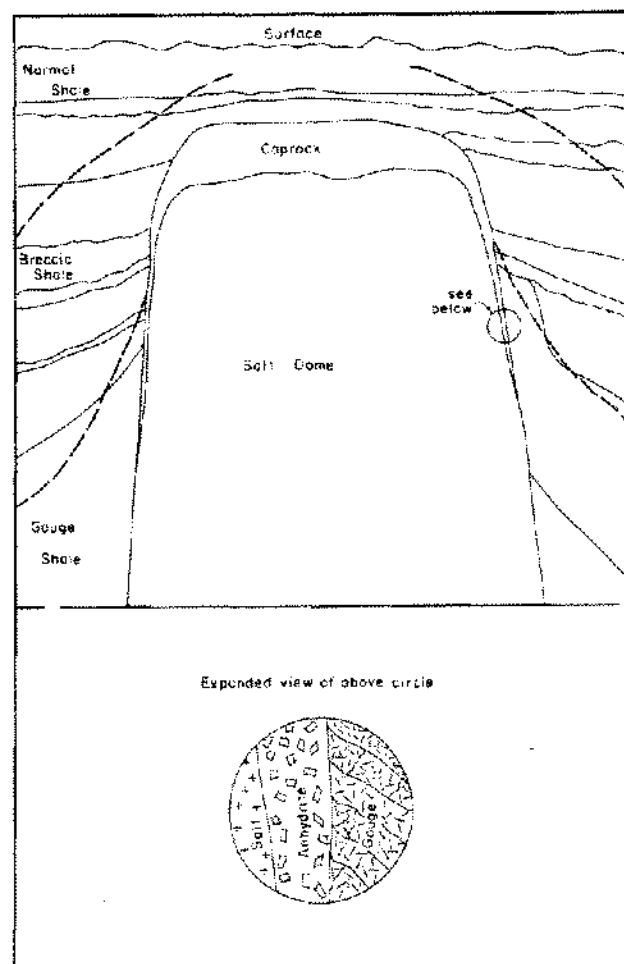


Figure 10. Idealized section of a salt dome and circumjacent sediments. (Modified from Kerr and Kopp, 1958 and Hanna, 1953)

early diagenesis would be that dissolved sulphide is capable of diffusing out of organic rich material. Diagenetic models, supported by experimentation, display factors affecting the migration of iron and sulphur within anaerobic sediments (Berner, 1969). The model which appears to best explain calcite caprock banding features contains from four-tenths to ten times the reactive iron concentration over the initial concentration of reducible sulphur. In this situation the  $H_2S$  is able to diffuse out of the organic rich layer only after solubilizing species have begun to build up fairly high dissolved iron concentrations. Under these conditions there may be steep and approximately equal gradients of both  $Fe^{++}$  and  $H_2S$  perpendicular to the organic rich layer resulting in the iron diffusing upward and the sulphide downward. Berner adds that due to the fairly high insolubility of iron sulphide, the concentration product of the interdiffusing iron and sulphide will exceed the solubility product to a sufficient degree so that iron sulphide will precipitate at some point below the organic rich layer, giving rise to a dark liesegang band. Alternating bands may then result from repeated increases of interdiffusing iron and sulphide concentrations succeeded by relief of supersaturation by precipitation. Berner (1971) lists three principal factors that limit the amount of pyrite which may form: (1) concentration and reactivity of iron compounds, (2) the availability of dissolved sulphate and (3) the concentration of organic material which can be utilized by sulphate-reducing bacteria to produce  $H_2S$ .

The interface between calcite and gypsum or calcite and anhydrite is somewhat gradational. Taylor (1938) states that "in most cases the anhydrite is not in sharp contact with the calcite zone, but grades into it through a transition zone of variable thickness." McLeod (1960) believes that there is a "rather complete separation of the calcite layer from the anhydrite zone." Unfortunately, only seven samples of this interface from six domes were available to the writer, resulting in that a generalization may not be statistically reliable. All of the samples did show some gradation, but the transition zone never exceeded 12 centimeters in vertical distance and averaged approximately less than 2 cm. The sequence of alteration observed is the anhydrite grading upward into a zone where calcite appears along cleavage traces in the anhydrite. Farther upward the amount of calcite increases to a degree at which about 40 percent of the original anhydrite remains. At this point there is a fairly abrupt change in which anhydrite almost completely disappears and only calcite is present. Upward from this point there is no evidence of any anhydrite. Alternating sequences of anhydrite-calcite caprock in one bore hole (Hull Dome, Tex.) showed a similar phenomenon.

#### Dolomite

Dolomite was noted in each caprock investigated. It comprises up to about 60 percent of some zones of caprock

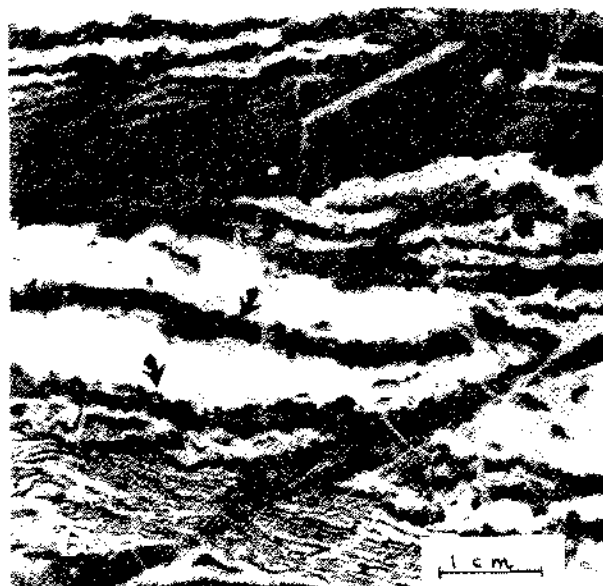


Figure 11. Core sample, Jennings Dome, Louisiana. Polished surface of calcite caprock illustrating the rhythmic banding which is distinctive of this lithology. The banding is most surely developed by diffusional processes as indicated by their orientation with respect to each other. The bands are limited in horizontal extent as they terminate either by pinching out or by truncation. Cavities lined with drusy calcite are characteristic of the light bands while the dark bands are usually more dense and may contain considerable pyrite (arrows).

and is only a minor constituent in others. It ranges in size from less than 0.1 mm up to occasionally as large as 1.0 mm, and always displays its characteristic rhombohedral form.

The mineral is one of the major constituents in the caprock in a 200 foot section of the Utica Dome, Mississippi and in a 160 foot section of the Kings Dome, Mississippi. Here dolomite is associated with calcite and/or celestite. Dolomite as a minor constituent in caprock is very common.

Textural evidence indicates that dolomite replaces calcite to varying degrees and possibly celestite and barite to a very small degree. It is replaced by calcite and seldom by gypsum and barite.

#### Celestite

It is believed by the writer that this is the first time that celestite has been recognized as a major caprock mineral. Previous literature (Taylor, 1938; Brown, 1931; Hanna and Wolf, 1934; et al) indicates the presence of this mineral, but only in minor quantities. The large concentrations of celestite are found in the caprock overlying Mississippi domes, where it constitutes over 90 percent in some portions of the caprock.

Celestite was identified in this study both optically and by x-ray diffraction analysis. The mineral is usually associated with either calcite or dolomite or both. When it is one of the major minerals, it is generally fibrous or in

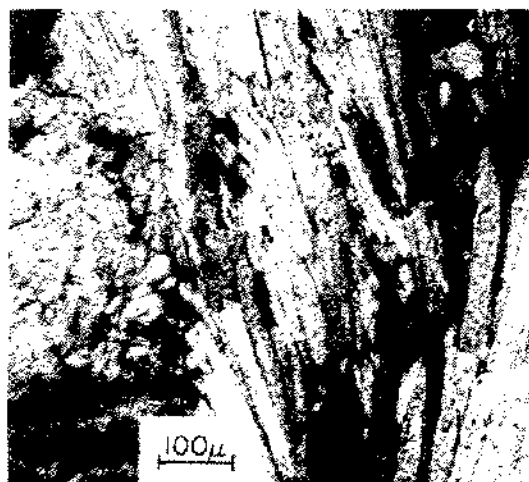


Figure 12. Core sample, thin section, Utica Dome, Mississippi. Radial clusters of bladed celestite. Some of the celestite has been partially replaced by calcite. Lee Little No. 1 Well, 2795 feet. Optical micrograph, crossed nicols.

radiating blades (Fig. 12). Disseminated throughout any of the lithologies, celestite appears as radiating blades or as tabular crystals. Celestite is generally thought to occur as a coprecipitate of the associated minerals. This relationship is based on such textural features as: commonly curved boundaries between celestite and other minerals, the tendency for the angles of intersection between three crystals to be  $120^\circ$  and the alternation of bands of celestite with associated mineral. Celestite is infrequently replaced by calcite, dolomite and sulphur and it slightly replaces anhydrite, gypsum and calcite.

The distribution of this mineral, as previously stated, is largely restricted to caprock of Mississippi domes. Figure 13 illustrates the concentrations of five elements associated with celestite in one of these domes. The mineral is generally characterized by fairly low Si and K concentrations and is commonly associated with dolomite. Two questions can be asked concerning the presence of this mineral in fairly large quantities: (1) Why are large amounts of celestite restricted to the caprock of Mississippi domes? and (2) What is the source of strontium?

The following explanation is offered as an answer to both of these questions: Mississippi domes are unique because the mother salt is overlain by a series of carbonate and evaporite facies which range in age from Upper Jurassic to Lower Cretaceous. The carbonates are composed of materials which range from oolites to quiet water dolomitic beds. Recent carbonate analogues of the above facies contain large concentrations of strontium: Bahama oolites contain about 10,000 ppm; reef coral aragonites contain around 8,000 ppm; algal aragonites contain about 9,000 ppm  $\text{Sr}^{++}$  (Kinsman, 1969).

During diagenesis of these recent aragonites, the  $\text{Sr}^{++}$  content decreases with increasing age of the rocks. Waters

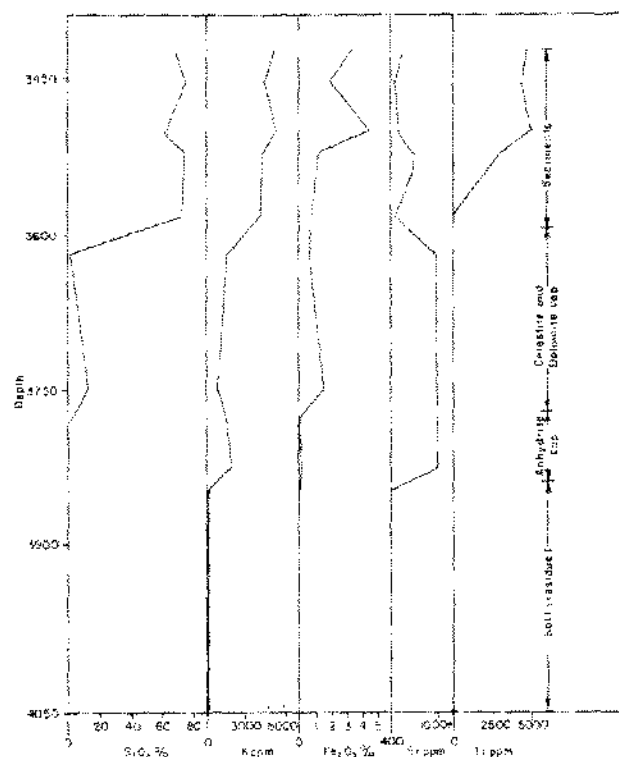


Figure 13. Kings Dome, Hall No. 1 Well, Depth vs. Si-K-Fe-Sr-Ti in sediments, caprock and salt residue.

moving through these carbonate rocks progressively dissolve the aragonite and precipitate calcite, which would result in the ratio ( $\text{Sr}^{++}/\text{Ca}^{++}$ ) in solution progressively increasing. When the solubility product of celestite is reached, in the caprock forming environment, it will begin precipitation. The strontium to calcium ratio will decrease during precipitation of celestite to a point where the ratio will reach the equilibrium value, and then either  $\text{CaCO}_3$  or  $\text{CaSO}_4$  will begin to precipitate.

Celestite and calcite are quite commonly noted in alternating bands in the caprock of Mississippi domes. The bands alternate from a dark gray to white, each averaging approximately 1.5 mm in width. These bands were observed in the caprock of Oakley, Clemons and Utica Domes, Mississippi, with the banded intervals sometimes exceeding 100 feet.

The darker bands consist mainly of finely-crystalline calcite; the dark color resulting from organic staining and/or a greater abundance of sulphides. White bands are composed mainly of bladed and somewhat radiating celestite crystals. The boundaries between these bands are not very distinct as the celestite and calcite gradually grade into one another. The accessory minerals associated with the banded caprock include quartz in about equal amounts of euhedral crystals and rosettes, dolomite rhombs

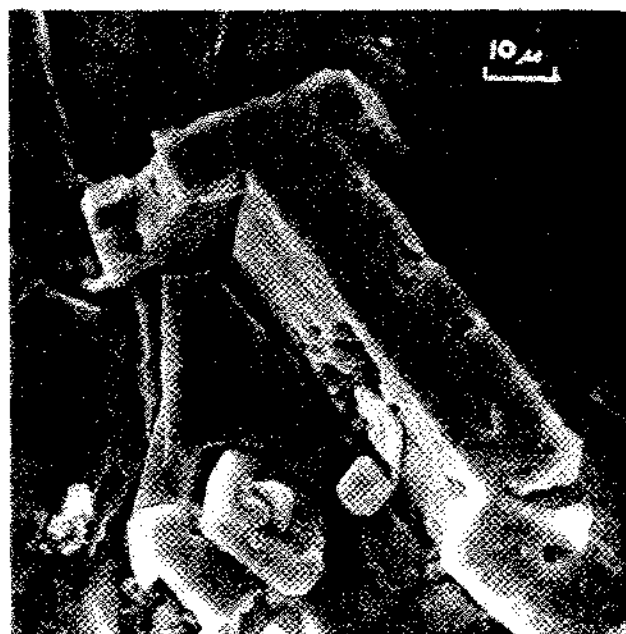


Figure 14. Core sample, polished and etched surface, Minden Dome, Louisiana. Calcite caprock, barite cutting across growth lines which indicates that it has replaced calcite. Jones No. 1 Well, 1284 feet. Scanning electron micrograph.

which have been partially replaced by calcite, pyrite, gypsum and anhydrite.

The alternating bands of celestite and calcite are probably due to differences in their solubility, diffusion of strontium out of calcite in the presence of dissolved sulphate and the periodic build up of strontium by this diffusion alternating with a lowering of the strontium concentration by precipitation.

The interface between celestite and anhydrite is gradational. This contact was examined in detail in the caprock of Utica Dome, Mississippi. The features, going down section, are as follows: At 2795 feet only celestite was observed; at 2805 feet celestite is still the major mineral and calcite, dolomite and quartz appear in minor quantities; at 2812 feet anhydrite was first noted and continued to increase in abundance downward to a depth of 2825 feet where no celestite could be found; at 2825 feet and downward, the anhydrite contains an anomalous amount of strontium when compared to the other analyses of caprock anhydrite.

#### Barite

Barite was noted in small amounts in many of the caprock samples. It occurs predominantly as tabular to prismatic crystals (Fig. 14), sometimes as radiating blades and rarely as rosettes. The crystals vary in size from 0.1 mm to large blades over 1.5 mm in their long dimension.

Barite is generally associated with the carbonate minerals and has been found to be associated with celestine in gypsum and anhydrite rocks (Goldman, 1951). Taylor (1938) states that tabular crystals of barite in anhydrite caprock are of the same age as the anhydrite, dolomite, quartz and celestine, apparently indicating the mineral is of residual origin. Barite was identified during this study in both syngenetic and epigenetic relationships with the carbonate minerals. The mineral can replace or be replaced by calcite, dolomite, sulphur, or gypsum.

### Sulphur

This mineral, in economic quantities, is largely restricted to local areas in the caprock. Small amounts of sulphur are disseminated throughout the carbonate and gypsum zones and occasionally in the anhydrite caprock. The sulphur ore zones are invariably associated with either calcite or gypsum. The ore zone sulphur deposits consist of orthorhombic crystals which range in size from very small to over 18 mm in length, and have been reported to be as large as 3 cm in length (Taylor, 1938).

Sulphur is thought to be an alteration product from the reduction of anhydrite (Feely and Kulp, 1957). The reducing agent in the alteration process may be hydrocarbons or dead organic matter, aided by sulphate-reducing anaerobic bacteria. One type of sulphate reduction reaction may be



in which methane is used only for simplicity. Elemental sulphur may later be formed by the  $\text{H}_2\text{S}$  produced in the above equation being reoxidized.

### Gypsum

Gypsum is found on only a little over half of the domes studied. The thickness of gypsum is quite variable, having a coefficient of variation of 120 percent, considerably greater than the coefficient for calcite thickness and somewhat greater than the coefficient for anhydrite thickness. Gypsum thickness generally increases from an east to west direction with Texas domes having the greatest amount of the mineral. The mineral comprises less than 15 percent of the total caprock thickness on any Mississippi dome, while Louisiana and Texas domes may have gypsum thicknesses comprising from 0 to 75 percent of the total thickness.

Gypsum occurs as prismatic, tabular and fibrous crystals. The tabular selenite variety is the most common form with the crystals ranging in size from less than 1 mm to 8 mm in their long dimension. Minerals associated with gypsum include calcite, which is usually noted to be replacing the gypsum and sometimes in an apparent syngenetic relationship with gypsum, aragonite, barite, sulphur, plus a few rarer minerals.

The largest percentage of gypsum resulted from the direct alteration from anhydrite with a smaller amount of the mineral resulting from direct precipitation. The hydration of anhydrite to form gypsum rarely proceeds at depths greater than 1820 feet (MacDonald, 1953). Gypsum thickness shows a fairly good inverse relationship with both the depth to the top of caprock and top of salt (Table V) which indicates that the process of hydration with depth is increasingly less effective.

### Anhydrite

Anhydrite is the most abundant mineral with respect to the total number of domes which have caprock, however, a few domes with caprock do not contain this mineral in any of the wells examined (Table IV). Anhydrite thickness averages approximately 220 feet thick on the domes listed in Table 4, but the thickness is quite variable from dome to dome as well as on any one single dome. Anhydrite is most commonly found in the lower portions of caprock, although it is not restricted to this area, and is occasionally found in relatively smaller quantities associated with other major minerals.

Anhydrite occurs in a number of forms; prismatic, radiating, fibrous and "stem shaped." The prismatic variety is characteristic of most of the massive anhydrite caprock, often referred to as "saccharoidal" (Taylor, 1938) or "pile-of-brick" structure (Brown, 1931). The "stem-shaped" anhydrite was noted by the writer to be only present in the caprock-salt interface, both in the salt and directly above the salt, and a search of the literature did not reveal any mention of this form in the massive anhydrite.

The massive anhydrite caprock is characterized by prismatic crystals which vary in size from about 0.05 mm up to 2.1 mm in their long dimension. The color of the mineral in thin-section varies from nearly colorless to a light brown. The anhydrite crystals form an interlocking mosaic, resulting in low porosity, and exhibit a slight preferred orientation trending in a horizontal direction. Coalescence of crystals has resulted in fairly indistinct boundaries when a fractured surface of the rock is examined.

Anhydrite is associated with a host of rare occurring minerals. These minerals can be dispersed throughout the anhydrite cap or can be found in concentrated zones which normally parallel the banding. A list of the rarer minerals, accompanied by a brief description follows: calcite, usually finely-crystalline and found along cleavage traces and grain boundaries, coarsely-crystalline in veins; dolomite, ranges in size from minute inclusions up to 0.8 mm, generally contain, in this zone, small nuclei; quartz, occurs as small terminated crystals and rosettes as inclusions within anhydrite grains; pyrite, minute inclusions; sulphur, minute inclusions in both anhydrite and dolo-



mite; barite, small bladed crystals; celestite, occurs as small radiating clusters and rarely as rosettes; and a number of very rare minerals. Barnes (1933) studied samples containing metallic minerals collected from the mine dump at Winnfield Dome, Louisiana. He indicates that the samples are probably from the basal portion of the anhydrite caprock.

Trace element concentrations in anhydrite caprock vary considerably with depth in each dome analyzed. An abnormally high strontium content in the anhydrite of Utica Dome, Mississippi, appears to be related to the celestite caprock which overlies it. This probably indicates that  $\text{Sr}^{++}$  was present during anhydrite formation. The strontium is diadochically included in the anhydrite. The greatest amount of  $\text{Sr}^{++}$  included is 0.125 percent, while the average strontium content of worldwide anhydrite deposits, in the absence of celestite, is about 0.2 percent (Braith, 1971). The German Zechstein anhydrites range in strontium content from 0.11 to 0.43 percent, whereas a recent gypsum deposit in Trapani, Sicily contains 0.28% strontium.

Generally two somewhat different types of banding are common to the massive anhydrite caprock. One type is composed of irregular and usually horizontal dark bands, about a millimeter in width, alternating with thicker, lighter colored bands (Taylor, 1938). The second type of banding, referred to by Goldman (1933; 1952) as "katatectic" banding, is characterized by near parallel layers, generally horizontal or dipping at low angles, which alternate between a band of a centimeter or less of fine-grained anhydrite and a thicker band of coarse-grained anhydrite.

Anhydrite displays characteristic features which indicate whether the mineral is undergoing dissolution or precipitation. The solubility of anhydrite is slightly different for each of the three crystal faces (Brown, 1931), resulting in the peculiar, but diagnostic, shapes formed during either of the two processes. Diagnostic dissolution features are (1) protruding plates and needles which represent the less soluble faces and, (2) a very irregular surface on all crystal faces. The features most diagnostic of precipitation are (1) pronounced growth lines and, (2) differential growth rates resulting in platy type structures.

A comparison of morphological features with trace element content, with decreasing depth, in the Tatum Dome is as follows: The top of the solid salt is at a depth of 1510 feet. The water-insoluble residue from this depth primarily consists of anhydrite. The only anhydrite habit noted was the "stem-shaped" crystals and no dissolution features were found. At a depth 1509, just above top of salt, the anhydrite sand is "stem shaped" (Fig. 15) and shows dissolution features. The concentration of Si, K and Fe in the anhydrite caprock has increased while Zn and Sr decreased with respect to the anhydrite in the salt. The

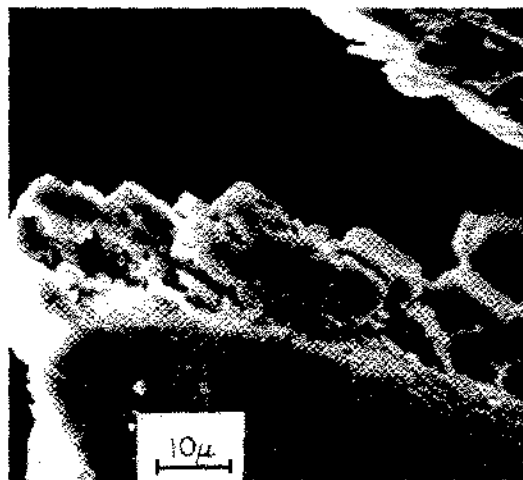


Figure 15. 1509 feet. The crystals show a fairly high degree of dissolution and they are all of the "stem-shaped" variety. Fractured core, scanning electron micrograph.

"stem-shaped" variety and dissolution features still predominate at 1507 feet (Fig. 16). At this point, no silica was detected and both K and Fe content decrease by about a factor of two, with zinc and strontium remaining almost unchanged. At a depth of 1506 feet, crystals abruptly display a prismatic habit and only precipitation features are noted (Fig. 17). The crystals at this depth again increase in Si and K; while Fe, Zn and Sr remain fairly constant. Above 1506 feet, smaller variations in concentration occur except at four different depths, each separated by approximately 100 foot intervals, where both silica and potassium decrease and iron slightly decreases.

The dissolution features of the anhydrite sand just above the salt indicates that the interstitial water in this zone is undersaturated with respect to anhydrite. The sudden increase in Si, K and Fe above the salt is not fully understood. The decreased concentrations of Zn and Sr probably mean that they are being lost to the water during the dissolution of anhydrite. Above the depth 1506, at which only precipitation features are found, smaller trace element concentration variations exist. This may indicate that fairly uniform water quality conditions were present during the formation of the anhydrite section. The four abrupt changes in concentration at about 100 foot intervals result from environmental variations at the time of anhydrite formation. One possible explanation of this variation would be the upward movement of the salt dome.

Figure 18 illustrates Si-K-Fe concentrations in the entire  $\text{CaSO}_4$  caprock and in the salt residue anhydrite for each dome analyzed. It can be noted from the figure that all but one salt residue points plot toward the bottom of the diagram, and caprock points plot toward the silica apex. The residue point which groups with the caprock is



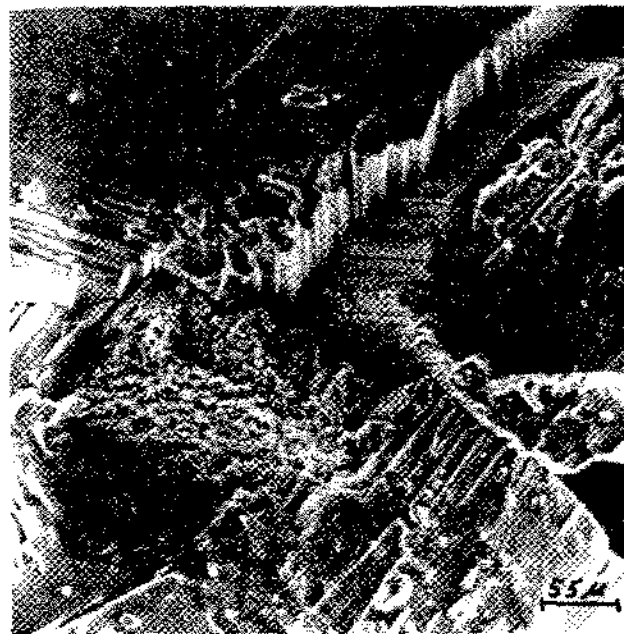


Figure 16. 1507 feet. The friable rock consists of "stem-shaped" anhydrite crystals which show dissolution features. Fractured core, scanning electron micrograph.

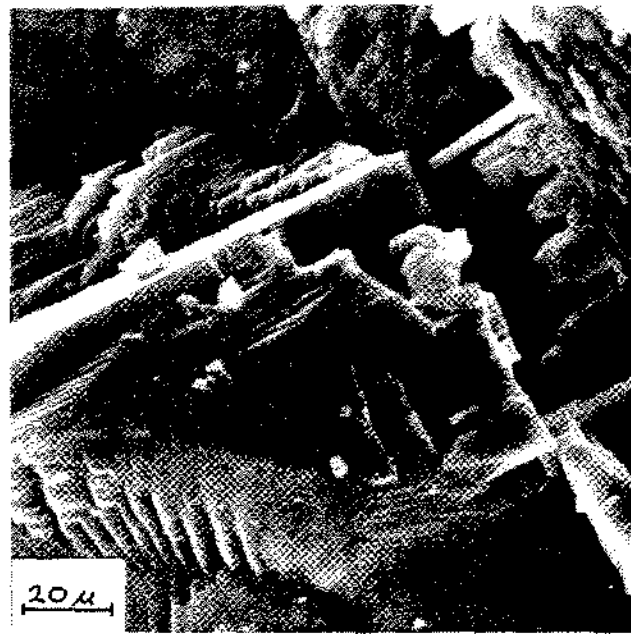


Figure 17. 1506 feet. The rock is only slightly friable, crystals show a prismatic habit and only precipitation features are present. Fractured core, scanning electron micrograph.

a sample brought up in a brine well on the Choctaw Dome, Louisiana, and left on the surface for an undetermined amount of time. The anomalously high silica was probably introduced at the surface. The caprock point isolated in the center of the diagram represents the Minden Dome, Louisiana.

The triangular diagram (Fig. 19) illustrating Si-K-Fe in anhydrite caprock immediately overlying the salt and in the average salt residue also indicates fairly large differences between the two anhydrites. This difference is largely due to the enrichment of silica with respect to the other two elements in the caprock  $\text{CaSO}_4$ .

Figure 20 displays Si-K-Fe-Zn-Sr average concentrations in both caprock and salt residue anhydrite for five domes. Silica, potassium and strontium show the largest variations in caprock  $\text{CaSO}_4$  between domes, while concentrations of iron show less variation and zinc remains fairly constant. The most striking feature of this figure is the uniformity of the trace elements in the anhydrite salt residue, since the domes listed are located in two different states. This could possibly mean that the salt and included anhydrite were precipitated contemporaneously in one large basin or that conditions were very similar in several smaller basins. Further evidence is the work done by Feely and Kulp (1957) in which they show that the  $\text{S}^{32}/\text{S}^{34}$  isotope ratios of anhydrite salt residues from a number of Gulf Coast domes vary just slightly, even less than the ratios of modern sea water sulphate.

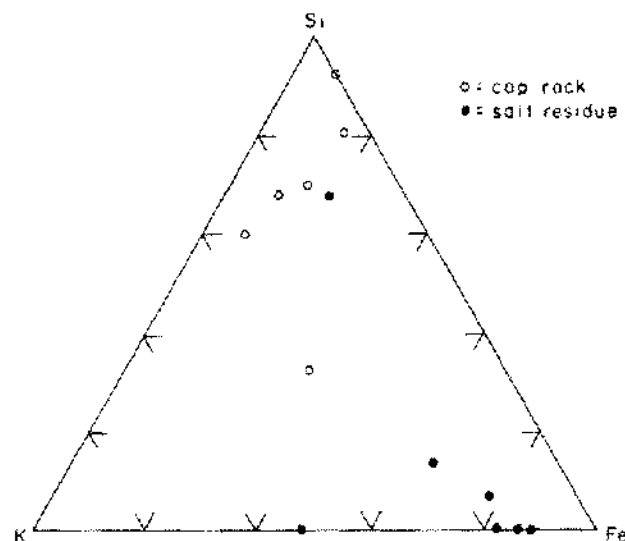


Figure 18. Triangular diagram illustrating average Si-K-Fe in entire  $\text{CaSO}_4$ . Caprock and salt residue for each dome analyzed.

Feely and Kulp (1957) indicate that the  $\text{S}^{32}/\text{S}^{34}$  ratios of anhydrite caprock vary much more widely than do the ratios of anhydrite salt residues from all domes. They further state that enrichment of  $\text{S}^{32}$  in caprock may indicate original variations in the isotopic composition of anhydrite salt residue, based on inclusions of bedded anhydrite rock in the salt. This does not appear likely, since the "bedded anhydrite" is probably a locally high

concentration zone of the mineral and should have the same isotopic composition as the more dispersed anhydrite. Isotopic analysis of Spindletop Dome sulphate compounds by Feely and Kulp show that the  $S^{32}/S^{34}$  ratio of anhydrite caprock is different from that of the salt residue, but is very similar to the ratio of bleedwater sulphate.

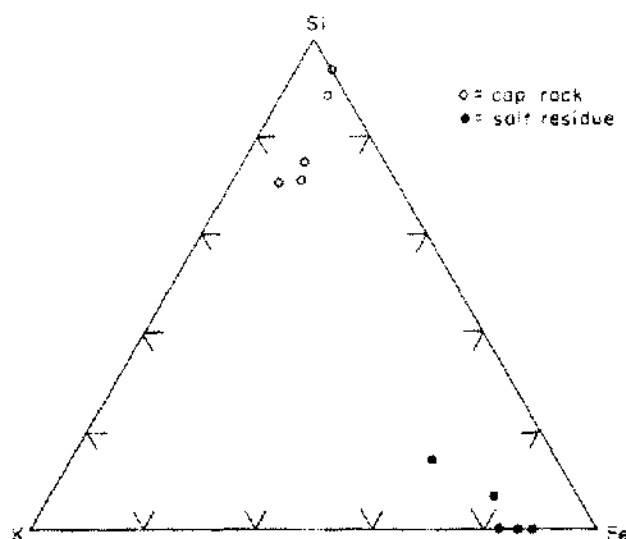


Figure 19. Triangular diagram illustrating Si-K-Fe in  $CaSO_4$ . Caprock immediately overlying salt and in average salt residue.

Great thicknesses of anhydrite caprock means that a tremendous amount of salt would have had to be dissolved off the top of the domes to accumulate thick residues. Accompanying this dissolution of salt should be tremendous collapse areas over the top of the domes if the salt did not move up as fast as the dissolution rate. Collapse features, however, are not found above all domes that have caprock. The surface area available to dissolution at the top of the dome is quite small in relation to its entire surface area. Waters moving past the top would soon approach saturation which would result in a reduced rate or possibly even halting of the dissolution process. Anhydrite is not insoluble, therefore, a portion of the residue anhydrite may go into solution. Two models are now presented to illustrate two different processes of obtaining anhydrite for caprock formation. The first model only considers residual accumulation of anhydrite and the second model illustrates how another process can result in a source of the anhydrite. This second model assumes that both halite and anhydrite are dissolved from the flanks of the dome and that anhydrite can later be reprecipitated.

**Model I:** A hypothetical salt dome; one mile in diameter, with the shape of a cylinder, containing 5 percent of evenly dispersed anhydrite impurity. 20,000 feet of this salt would have to be dissolved off the top of the dome in order to accumulate 1,000 feet of anhydrite (Assuming that none of the anhydrite is dissolved).

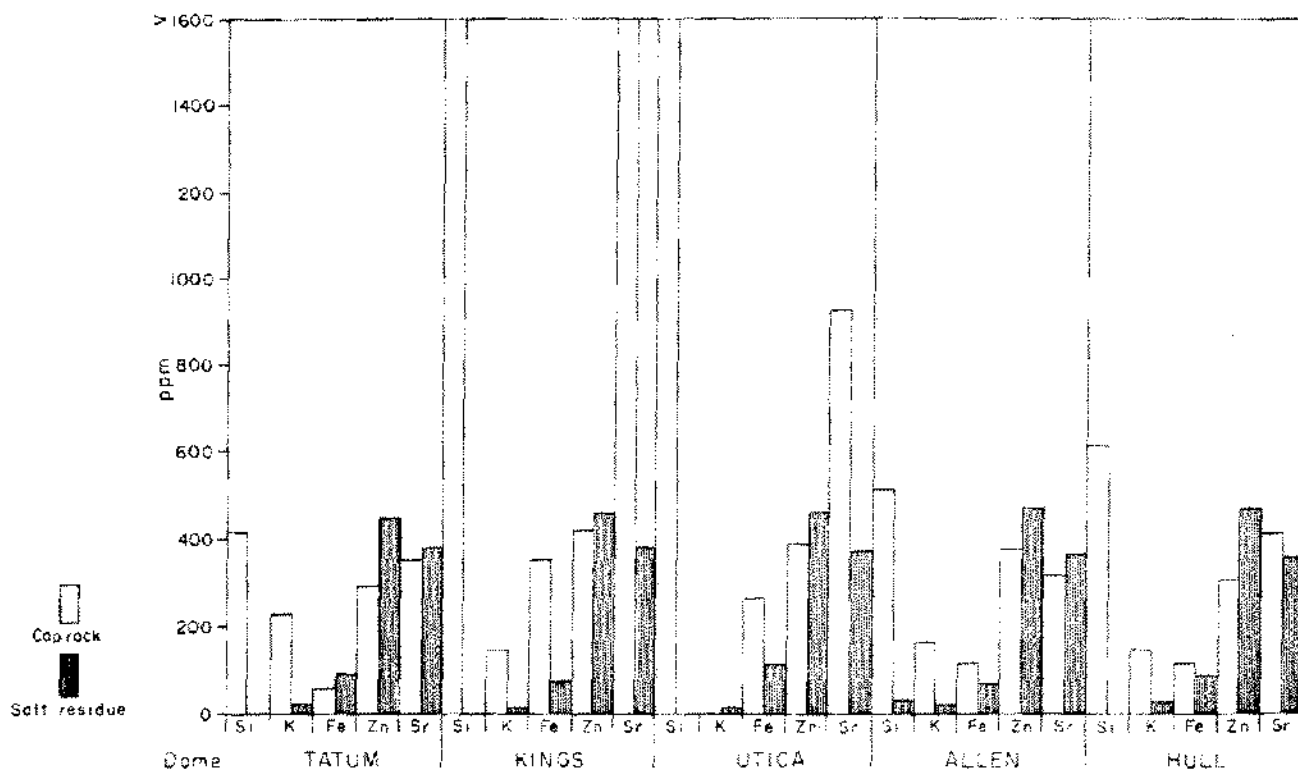


Figure 20. Si-K-Fe-Zn-Sr average concentrations in cap and salt residue  $CaSO_4$ .

**Model II:** The same hypothetical dome as above. For a caprock 1000 feet thick and one mile in diameter its volume would be  $21.9 \times 10^7$  cubic feet of anhydrite. If only 40 feet of salt were dissolved by upward moving waters on the flanks of the dome for a distance of 10,000 feet,  $32.9 \times 10^7$  cubic feet of anhydrite would be available, or approximately 33 percent more anhydrite than necessary for a 1000 foot thickness.

#### Less common caprock minerals

**Pyrite.** This mineral occurs in varying amounts in all lithology types, but its largest concentrations are in the calcite zone. Pyrite ranges in size from nearly submicroscopic to as large as 2.4 mm, with many of these crystals being euhedral and having the form of cubes, pyritohedrons or octahedrons. Pyrite replaces sulphur and gypsum to a small degree; it is replaced by none of the other minerals.

**Quartz.** This mineral is usually dispersed in small amounts throughout the caprock, although quartz is occasionally found in higher concentrations in shear zones. Quartz is commonly noted as terminated crystals or rosettes, with both forms being generally small in size. The rosettes often contain dark nuclei similar to those in the dolomite crystals. Quartz is replaced only by calcite, and it replaces none of the other minerals.

**Halite.** This mineral is probably disseminated throughout many of the interstitial voids and cavities of the caprock, but due to its high solubility it is probably dissolved in the drilling process. Halite also forms as discontinuous beds, or lenses, in any part of the caprock and can separate other lithology types. One well drilled into the caprock of the Hull Dome, Texas, encountered salt 40 feet into the cap and had to drill 100 more feet to reach its base. The salt in this well is both overlain and underlain by anhydrite. The presence of a small lens of pure salt (no water-insoluble residue was recovered) in the anhydrite caprock at Hockley Dome, Texas has been reported (Teas, 1931).

#### Sediments within caprock

Detrital minerals, either disseminated or in bedded deposits, within the caprock is much more common than the literature would lead one to believe. Sediments have been observed in all lithology types and are chiefly composed of quartz, clay and feldspar detrital minerals. Clastics were often noted filling fractures in the caprock. Napoleonville Dome, Louisiana has considerable clay dispersed through gypsum; Hull Dome, Texas contains both sand and clay dispersed in anhydrite; and Vinton Dome, Louisiana contains quite an abundant amount of disseminated sand in the calcite caprock.

The following is a list of examples of caprock which contain more or less bedded sediments and a short de-

scription of their associations: (Data from F. S. Co. lithology logs)

Allen Dome, Tex.	Lenses of sandy clay, up to 111 feet thick, are found throughout most of the calcite cap. One well displays a sandy shale alternating with anhydrite in beds about 10 feet thick.
Hockley Dome, Tex.	A shale bed, which may be continuous from one side of the cap to the other side, separates the calcite zone in one well and separates the massive anhydrite at the same depth but on the other side of the dome.
Hull Dome, Tex.	A lens of shale and gravel about 50 feet thick separates anhydrite.
Napoleonville Dome, La.	A fairly continuous bed of shale about 25 feet thick is located within the gypsum caprock.
Pine Prairie Dome, La.	In one well a 450 foot section of shale separates the gypsum cap from the calcite cap, and in another well a 20 foot section of sand separates the same lithologies.

#### False caprock

The origin of false caprock in the Gulf Coast region is directly related, and therefore very similar, to that of the true caprock of the region. The cementing materials of the rock are the same as the major minerals of the true caprock. The form and size of false caprock will be discussed. A large percentage of the information concerning false caprock in this section was obtained from a thesis by Walker (1968).

All of the samples which were studied are cemented by calcite to some degree, and the majority contain only calcite as the cementing agent, with the amount of the mineral, by weight, ranging from 1.8 to 73.8 percent of the samples. A smaller percentage of the samples are cemented by other authigenic minerals to varying degrees. In a few of the wells, and very locally, gypsum is the major



Figure 21. Core sample, thin-section, Black Bayou Dome, Louisiana. Clastic grains which have been partially to almost completely replaced by the calcite cement. F.S. Co. Watkins No. 5 Well, 1132 feet. Optical micrograph, crossed nicols.

cementing agent. Anhydrite also locally cements some of the sediments, but never exceeds four percent of the cement in any of the specimens. Pyrite was occasionally noted as a cementing mineral, but it is most commonly found as disseminated crystals cemented in either calcite or gypsum.

The average false caprock sample contains about 60 percent clastic material and 40 percent authigenic material. These authigenic minerals were found as individual crystals, in clusters and as the cementing agent. The samples also contain fragments and individual grains from the true caprock, and false caprock fragments from other areas adjacent to the dome. When the rocks are highly fractured, mylonized materials are likely to be found. It was noted that many of the samples had contained organic matter during the time of precipitation. Thus, the constituents which make up the false caprock are numerous and they vary greatly from one area to another.

The primary properties of the indurated sediments were found to be practically absent in most of the examined samples. Original form and size of grains were often destroyed by various physical and chemical changes. Very few of the samples contain any primary porosity and the largest percentage of pore space was a result of dissolution of the cement. The secondary features alter the sediments to an extent where differentiation between the true caprock and the false caprock becomes impossible. The first major secondary feature to occur was the cementation of the sediments by authigenic minerals derived from migrating fluids. A prerequisite to the induration was environmental factors which were favorable to authigenic mineral precipitation, but were apparently unfavorable to the stability of the major clastic minerals, with the result of the replacement of the clastics by the stable authigenic minerals (Fig. 21).

## THE GEOCHEMICAL ENVIRONMENT

The geochemical environment associated with the caprock must be quite complex, as shown by the large number of mineral species and their variable distribution. Trace element analysis of the minerals themselves has also indicated this complexity. A more thorough understanding of caprock genesis requires knowledge of the interaction between the solid-water phases in the environment. This knowledge must include information on the geochemistry of interstitial waters, both in the caprock and in the circumjacent sediments. Water movement in the surrounding sediments is also discussed in this section.

### Geochemistry of sediment interstitial waters

Oil field brines associated with salt domes contain concentrations of dissolved constituents of from less than 25,000 to more than 145,000 milligrams per liter (Collins, 1970). The associated brines are characterized by the predominance of Cl among the anions, and Na and Ca among the cations. Those brines not associated with salt domes contain less total dissolved solids, but considerably more Ca is present. This greater abundance of Ca is probably due to most of these oil fields being located in the northern portion of Louisiana, where limestone in the subsurface is more abundant than in the southern part.

Abnormal reservoir pressures are encountered in the area surrounding salt domes. Jones (1968) states that the entrapment of water in geopressed reservoirs of the northern Gulf Basin would be geologically short lived except for osmotic confinement. He believes that water expelled from the reservoir through clay beds is diluted by hyperfiltration and dissolved solids in remaining water are concentrated until osmotic pressure opposing the flow equals the head differential due to the overburden.

The distribution of salinity with depth is extremely variable above depths ranging locally from 8,000 to 12,000 feet in geopressed areas, but below this depth range there is a general progressive freshening (Jones, 1968). Figure 22 illustrates conditions which exist in the geopressed area surrounding Jeanerette Dome, Louisiana. A sharp decrease in salinity, accompanied by a fairly abrupt increase in geopressing can be noted at a depth of approximately 12,000 feet, or about 4,000 feet below the shallowest salt penetration.

Movement of the interstitial water occurs in response to potential fields. The potential fields may originate by differential pressure due to the overburden, differences in elevation, osmotic pressures, differences in temperature, movement of the salt dome or by a chemical potential gradient.

Figures 23 and 24 illustrate that the flow of water moves upward adjacent to and above the salt dome. Fresh water reaches a greater depth toward the flanks of the dome than in the surrounding area, and it is usually absent

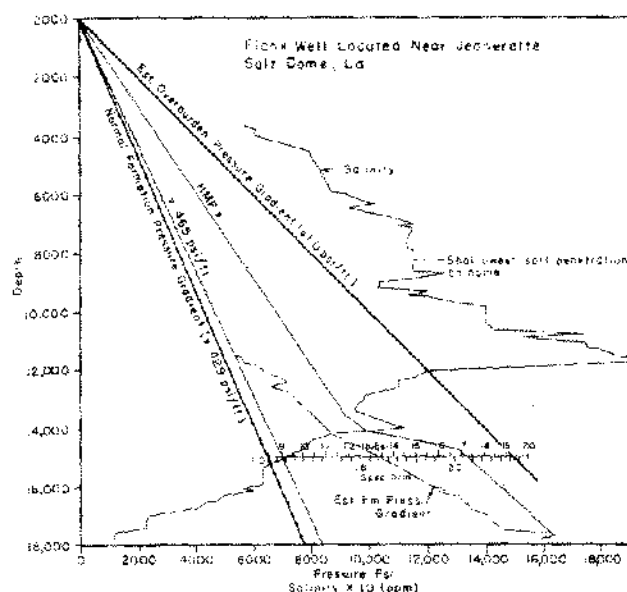


Figure 22. Pressure vs. Depth Plot (source of data classified by contributor's request).

altogether over the apex of the dome (Rollo, 1960). Taylor (1938) notes that the areas in which the more shallow salt domes occur are characterized by saline and "sour" water springs.

#### Geochemistry of caprock interstitial waters

Interstitial waters in caprock are of moderate salinities and are characterized by an abundance of calcium, sulphate and bicarbonate ions in solution. Also associated with these waters is a fairly high concentration of dissolved  $H_2S$ . The equilibrium distribution of sulphur species under standard P-T conditions indicates that

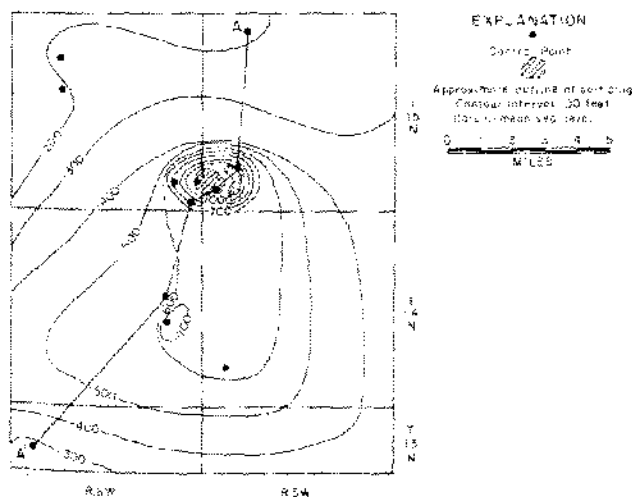


Figure 23. Map showing by contours the altitude of the base of fresh ground water in the vicinity of Rayburns salt dome, Bienville Parish, (after Rollo, 1960)

nonequilibrium conditions probably exist in the caprock environment due to the expected low Eh and fairly high pH values in the environment with the association of  $SO_4^{=}$  and  $H_2S$ . Higher P-T values only slightly effect the equilibrium boundaries, and the ionic species are independent of the total dissolved sulphur since the boundaries are only where the ratios of sulphur species are unity.  $H_2S$  is the stable species under acid reducing conditions, but  $SO_4^{=}$  is the stable sulphur species under basic reducing conditions which are more likely in the caprock.

The iron minerals present in caprock are also an indication of reducing conditions. Pyrite is the major iron mineral and only rarely has hematite been reported. The mineral is stable under a wide pH range but is restricted to negative Eh values above a pH of 6.

The widespread occurrence of the sulphate-reducing bacteria *Desulfovibrio* in the caprock brines is another indication that the environment is a basic reducing one. The organisms survive best between a pH of 6 to 10 and Eh values of +0.2 to -0.4 (Becking, 1960). Feely and Kulp (1957) state that acid conditions depress their growth rate greatly, and a high pH increases the growth rate but the stationary population is reduced.

#### Anhydrite-brine equilibria

The anhydrite-brine equilibrium relationship may be a most important factor in the development of anhydrite caprock. The solubility of anhydrite can be satisfactorily predicted by a model which takes into account ionic strength, temperature and the amount and type of complexes in the solution (Marshall and Slusher, 1968; Lerman, 1970). The following is a discussion of the model applied to those brines in and around caprock:

The molar quotient  $Ca^{++}/(SO_4^{=} + HCO_3^-)$  was first calculated for each brine analysis. These values were then plotted against total dissolved solids, and are shown in Figure 25. The molar quotient is considered an indicator of whether a brine can become depleted in sulphate (and carbonates) by precipitation of  $CaSO_4$  (and  $CaCO_3$ ) min-

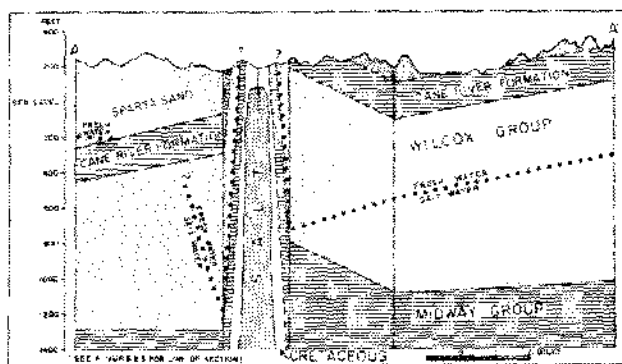


Figure 24. Geologic section of Rayburns salt dome, Bienville Parish, (after Rollo, 1960)

eral phases (Lerman, 1970). Precipitation of anhydrite or gypsum would not deplete the brine of its sulphate if the quotient is smaller than one, but would deplete it if the value is of greater than one.

In order to determine the anhydrite-brine equilibria curve of Figure 25 the composition of the brines was averaged within successive intervals of 25 g/l total dissolved solids, and the concentrations of  $\text{Ca}^{++}$  and  $\text{SO}_4^{--}$  were calculated for each of the "mean" brines at equilibrium with anhydrite at 75°C. New values of the molar quotient  $\text{Ca}^{++}/(\text{SO}_4^{--} + \text{HCO}_3^-)$  were computed and the smooth equilibria curve was drawn between the calculated values. The method and the calculations to obtain this curve were taken from reports by Lerman (1970), Marshall (1967) and Marshall and Slusher (1968).

The curve was calculated at 75°C because this is regarded as reasonable for the depths of caprock formation. The brines supersaturated with respect to anhydrite are the points below the curve (Fig. 25) and those brines undersaturated fall above the curve. An increase in temperature would only slightly move the curve upward, whereas a decrease in temperature to around 30°C would move the curve considerably downward.

It can be seen in Figure 25 that the caprock brines are either close to equilibrium or are supersaturated with respect to anhydrite at 75°C. Most of the sediment brines are fairly well undersaturated with respect to anhydrite, and those supersaturated may indeed be brines located directly on the flanks of the dome. If  $\text{Ca}^{++}$  and  $\text{SO}_4^{--}$  were added in equivalent amounts to the undersaturated sediment brines, the values of the  $\text{Ca}^{++}/(\text{SO}_4^{--} + \text{HCO}_3^-)$  quotient would decrease and fall closer to the equilibria

curve. Thus, brines migrating toward the salt would be undersaturated with respect to anhydrite. Upon contact with the dome and moving upward along the flanks the brines would increase in  $\text{Ca}^{++}$  and  $\text{SO}_4^{--}$  by dissolving the anhydrite which would result in a decrease of the molar quotient.

At some point the brines could become supersaturated with respect to anhydrite, and anhydrite would possibly be precipitated. The addition of  $\text{HCO}_3^-$  by the bacterial sulphate reduction process to the supersaturated brines would increase the molar quotient, and  $\text{CaCO}_3$  could be precipitated.

## ORIGIN OF CAPROCK

The previous discussions were primarily concerned with the features of caprock and its surrounding environment. Table VII summarizes these important caprock and associated features. The features listed in this table will now be examined to ascertain if any of the theories of caprock origin can satisfactorily account for the character of caprock and its relationship to the circumjacent environment. Only two previous theories will be considered; (1) precipitation in place and (2) residual accumulation and secondary alteration. Other theories, such as a block of sedimentary material upthrust by the salt, or the alteration of limestone to form caprock, will not be discussed because these theories have already been disposed of and are seldom seriously considered in the present literature (Taylor, 1938; Murray, 1966; et. al.).

### Precipitation in place theory

Stuart (1931) proposed that precipitation of anhydrite or gypsum would result when meteoric waters containing dissolved calcium carbonate mixed with salt dome waters containing soluble sulphates. Paul Weaver in a written communication with Ralph Taylor during 1937 (in Taylor, 1938) states: "There is also the possibility that the  $\text{CaSO}_4$  may be precipitated from circulating waters originally connate in offside sediments; as these waters, already containing some  $\text{CaSO}_4$  lie along the edge of the salt dome, they dissolve salt and anhydrite from the salt dome until saturated by the latter, and then as upward circulation brings them to the top of the salt dome, they precipitate the  $\text{CaSO}_4$ ."

### Residual accumulation and secondary alteration theory

The theory of the origin of caprock most widely accepted today was first definitely outlined by Hanna (1930) and Goldman (1929; 1933), and later refined by Taylor (1937; 1938). The basic idea of this theory is that the formation of anhydrite caprock results from the accumulation of the less soluble constituents, chiefly anhydrite crystals, of the salt domes. The other minerals found in the caprock result from secondary alteration of the anhydrite.

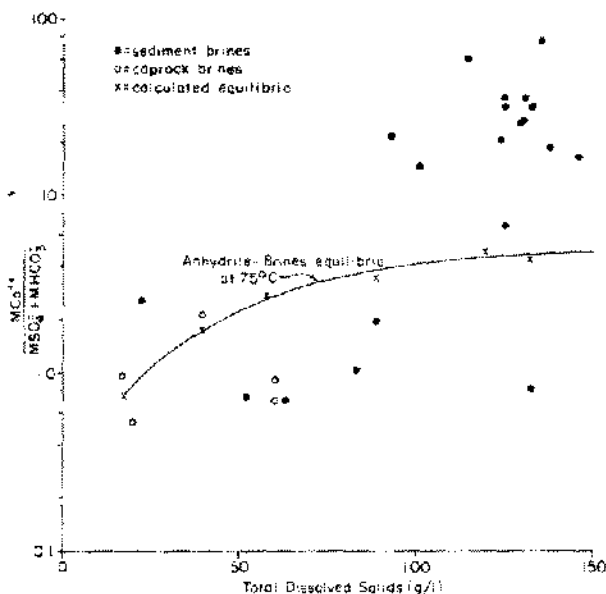


Figure 25. Molar quotient  $\text{Ca}^{++}/(\text{SO}_4^{--} + \text{HCO}_3^-)$  in salt dome associated sub-surface brines.

**TABLE VII**  
Summary of Important Caprock and Associated Features

- |   |   |
|---|---|
| <p>I. Physical Features:</p> <ol style="list-style-type: none"> <li>1. Caprock shape is highly variable.</li> <li>2. Caprock may rest directly on the salt with no intervening anhydrite sand.</li> <li>3. The upper surface of the salt can be very variable.</li> <li>4. The upper portions of caprock are more highly deformed than portions near the salt.</li> <li>5. Sediments adjacent to salt domes are generally brecciated.</li> <li>6. The shale sheath around the salt could behave as a semipermeable membrane and permit selective movement of water toward the salt and the development of osmotic pressures.</li> <li>7. Caprock is present on the Sigsbee Knolls in the Gulf of Mexico.</li> </ol> <p>II. Lithological Features:</p> <ol style="list-style-type: none"> <li>1. The lithological sequence in caprock is variable.</li> <li>2. Caprock lithology is variable from dome to dome.</li> <li>3. Caprock lithology on a single dome can be very variable.</li> <li>4. The interface between celestite and anhydrite is gradational.</li> <li>5. The interface between calcite and anhydrite caprock is somewhat sharp.</li> <li>6. Anhydrite can be found anywhere in the caprock and may alternate with other lithologies.</li> <li>7. The volume of anhydrite caprock can be more easily explained in terms of dissolution and later reprecipitation of the mineral than by accumulation alone.</li> <li>8. Sediments are common in the caprock; as dispersed inclusions or in beds separating any lithology types.</li> </ol> <p>III. Mineralogical Features:</p> <ol style="list-style-type: none"> <li>1. The top of the salt is commonly undergoing dissolution and the less soluble minerals accumulate in this interface.</li> <li>2. At least 30 different minerals have been identified in caprock.</li> <li>3. Only approximately 20 different minerals have been identified in the salt.</li> </ol> | <ol style="list-style-type: none"> <li>4. Dolomite or celestite may be a major mineral in the caprock over a few domes.</li> <li>5. Anhydrite is the most abundant caprock mineral, but not every caprock contains the mineral.</li> <li>6. Crystals in the massive anhydrite caprock form an interlocking mosaic.</li> <li>7. Crystals of the massive anhydrite caprock differ from those in the salt in morphology.</li> <li>8. Dolomite and quartz crystals, characteristic of the salt residue, are found in the caprock.</li> <li>9. False caprock contains the same authigenic minerals as the true caprock, and false caprock grades into true caprock.</li> </ol> <p>IV. Geochemical Features:</p> <ol style="list-style-type: none"> <li>1. Trace element content of residue anhydrite varies but slightly from dome to dome.</li> <li>2. Halite solubility is markedly influenced by other electrolytes in solution.</li> <li>3. Anhydrite solubility is a function of ionic strength, temperature, and the amount and type of complexes in solution.</li> <li>4. Trace element concentrations in the massive anhydrite caprock ranges considerably, but do show interrelationships with each other.</li> <li>5. Caprock banding is largely due to diffusion or an episodic influx of minor elements, or both.</li> <li>6. Trace element concentrations differ significantly between caprock anhydrite and the salt residue anhydrite.</li> <li>7. Waters move upward along the flanks of the domes and only locally affect the quality of the groundwater.</li> <li>8. The caprock geochemical environment may consist of basic and/or reducing conditions.</li> <li>9. Most brines are undersaturated with respect to anhydrite in the surrounding sediments but are at near equilibrium or supersaturated in the caprock environment.</li> </ol> |
|---|---|

A brief summary of the processes thought to be involved in this theory of caprock formation is presented:

When a salt dome rises through the basin sediments, it eventually comes into contact with zones of ground water which dissolve away the upper portion of the salt, leaving the insoluble crystals of anhydrite as a residue. These anhydrite crystals are then compacted and recrystallized

to form the massive anhydrite caprock. This anhydrite caprock may be locally hydrated to form gypsum.

The calcite and sulphur commonly present in caprock are thought to be alteration products from the reduction of anhydrite. The reducing agent in the alteration process may be hydrocarbons or dead organic matter.

Murray (1966) summarizes the sequence of events

which he believes probably take place during caprock formation.

1. Intrusion of the salt plug into a zone of active water circulation.
2. Gradual truncation of the top of the salt plug by solution, decapitation of the fold in the salt and formation of a solution table, and accumulation of residual anhydrite sand.
3. Compaction of the caprock accompanied by precipitation of anhydrite from solution and intergrowth of anhydrite grains.
4. Continued solution of the salt, with growth of the salt plug compensating for removal of salt by solution. Consolidation of the anhydrite and subsequent shearing of it by stresses created by upthrust and collapse.
5. Entrance of altering solutions and development of a transition zone in which anhydrite alters to gypsum and both, in turn, alter to calcite and sulphur; a relic anhydrite structure is commonly preserved.
6. Transgression of the transition zone downward, escape of hydrogen sulfide, or its oxidation to sulphur in place or within the overlying caprock, and deposition of calcite. Secondary calcite, sulphur, pyrite, other sulfides, barite and celestite may develop in the upper part of the calcite zone, or they may replace sulphur in the transition zone. Influx of hydrocarbons may result in the reduction of sulphur, its redeposition in another part of the caprock, or its escape.

#### Analysis of previous theories

A comparison between fact and theory will now be presented. A fact which agrees favorably with one theory may unfavorably agree with the other theory. Table VIII lists arguments for and against the "Precipitation in Place" theory. Arguments for and against the "Residual Accumulation" theory are presented in Table IX.

#### Features compatible with either theory

A number of the features do not give strong preferential arguments, either for or against, one or the other caprock theories. Other less direct features may support the "precipitation in place" theory, but the features are not incompatible with the other theory. A discussion of these features is forthcoming: Many of the features attributed to recrystallization and pressure solutions may be features of precipitation. The "saccharoidal" structure of massive anhydrite caprock which was thought to have resulted from compaction and recrystallization of residue anhydrite could also be due to precipitation in place forming the interlocking mosaic. The deformation at the tops of anhydrite and calcite zones has been attributed to "downbuilding" with an increase in age from the salt-anhydrite contact upward, but the feature can also be explained by the caprock forming at depth, with subsequent movement upward resulting in deformation. The fact that anhydrite is the most abundant caprock mineral can support either theory since the ultimate source for the mineral must be the residue anhydrite. The morphological differences be-

TABLE VIII

Arguments For and Against "Precipitation in Place" Theory

#### Compatible Features

1. Variability of caprock lithology in single domes and from one dome to another.
2. Most of the calcite is definitely precipitated in place.
3. Dolomite may be a major caprock mineral.
4. Large volumes of celestite in some caprock.
5. Trace element concentrations in anhydrite caprock vary considerably.
6. Trace element concentrations differ significantly between caprock anhydrite and the salt residue anhydrite.
7. The volume of anhydrite caprock requires dissolution of much less salt from the top of the dome than the "residual accumulation" theory.
8. Sediments are common to caprock.
9. Waters move upward along the flanks of the domes.
10. Most brines are undersaturated with respect to anhydrite in the surrounding sediments but are at equilibrium or supersaturated in the caprock.
11. False caprock contains authigenic minerals the same as the true caprock, and false caprock grades into true caprock.
12. Caprock is present on the Sigsbee Knolls.

#### Incompatible Feature

Dolomite and quartz crystals, characteristic of the salt residue, are found in the caprock.



TABLE IX

Arguments For and Against "Residual Accumulation" Theory

**Compatible Features**

1. The top of the salt is commonly undergoing dissolution and the less soluble minerals accumulate in this interface.
2. Dolomite and quartz crystals, characteristic of the salt residue, are found in the caprock.
3. The upper portions of caprock are more highly deformed than portions near the salt.
4. Anhydrite is the most abundant caprock mineral.

**Incompatible Features**

1. Most of the calcite is definitely precipitated in place.
2. Dolomite may be a major caprock mineral.
3. Large volumes of celestite in some caprock.
4. Large amount of salt dissolution required from top of dome.
5. Variability of caprock lithology.
6. Trace element difference in caprock and salt residue anhydrite.
7. Presence of false caprock and its gradational boundary with true caprock.
8. Presence of caprock on the Sigsbee Knolls.

tween caprock anhydrite and salt residue anhydrite would indicate either that the crystals were reprecipitated from dissolved residue anhydrite or that the crystals precipitated from  $\text{CaSO}_4$  rich solutions migrating in from external sources. The interface between calcite and anhydrite caprock is fairly sharp, which may result from an alteration "front" in which anhydrite alters to calcite in a progressive, but vertically limited, space or the feature may be attributed to changes in the geochemical environment during precipitation.

The fact that caprock may rest directly on the salt with no intervening anhydrite sand indicates that dissolution is not now occurring at this interface. The brecciated nature of the sediments adjacent to salt domes would increase porosity and permeability allowing greater fluid movement. The shale sheath adjacent to the salt could serve as a semipermeable membrane and permit selective escape of water toward the salt, resulting in osmotic pressures and a more or less enclosed channel (bounded by the salt on one side and shale on the other) in which upward moving water could flow. The fact that partially dissolved anhydrite crystals are found in the shale-salt interface. The interface between celestite and anhydrite is gradational, indicating that strontium was incorporated in the anhydrite during its formation. Direct precipitation is supported by the fact that anhydrite can be found anywhere in the caprock and may alternate with other lithologies or even sediments.

The arguments presented in Tables VIII and IX, and the discussion on the less direct features seem to indicate that the caprock is largely formed from direct precipitation. The main feature that the precipitation theory can-

not account for is the presence of dolomite and quartz crystals, characteristic of the salt residue, dispersed throughout the caprock. Because of this fact, it is proposed that the origin of caprock can be satisfactorily explained by a "modified precipitation in place" theory.

**Modified precipitation in place theory**

The paragenesis of the caprock minerals is postulated as follows: anhydrite and salt would be dissolved from the flanks of the dome by upward moving waters, and anhydrite would later be reprecipitated, as the caprock, from these solutions when the geochemical conditions were favorable to this process. A smaller amount of anhydrite could be incorporated in the caprock by dissolution of the upper salt surface releasing the less soluble residue. The degree of dissolution at this surface, as well as the amount of included impurities in the salt, would determine what percentage the residue anhydrite contributes to the total bulk. The characteristic dolomite and quartz salt-residue minerals would be included in the caprock in an amount dependent upon the above process. Petrographic recognition of the residue anhydrite in caprock would be most difficult, if not impossible, because of such processes as recrystallization and overgrowth. Gypsum can form by either the hydration and alteration of anhydrite or by direct precipitation. Sulphur is an alteration product from the reduction of anhydrite. Calcite is precipitated from solutions containing  $\text{Ca}^{++}$  from the upward moving waters and  $\text{HCO}_3^-$  from the anhydrite reduction process. Celestite is precipitated when sediment interstitial waters containing fairly large amounts of strontium come in contact with the caprock associated waters. Much of the dolo-

mite could be formed by a similar process as the celestite but the sediments waters would contain  $Mg^{++}$ . The less common caprock minerals would largely be formed by the interaction of sediment interstitial waters with those waters in the caprock. The remaining less common minerals have come from the less-soluble fraction in the salt and by alteration from other minerals.

### DEVELOPMENTAL SEQUENCE OF CAPROCK

The following is the sequence of events which may have taken place during the development of caprock.

1. The salt dome is intruded into the overlying sediments, its movement upward is episodic.
2. Dissolution of the salt along the flanks and the top of the dome will occur when the dome encounters waters which are undersaturated with respect to halite. Since salinity can greatly decrease with depth below 8,000 to 12,000 feet in geopressured areas, the depths at which dissolution first takes place can be very great.
3. Substantial movement of water probably occurs at depths as deep as 15,000 feet, moving in response to potential fields resulting from physical or chemical differentials. The brines migrating toward the dome would be undersaturated with respect to both halite and anhydrite. The waters move upward along the flanks dissolving halite and anhydrite. Some of the overhangs of salt have been attributed to these circulating waters, such as at Belle Isle and Anse la Butte Dome, Louisiana (Judson and Stamey, 1933).
4. At depths of 4,000 to 10,000 feet, the flow rate of the hydrologic system would be sufficient enough, as shown by the presence of caprock at this depth, to transport the dissolved solids toward the apex of the dome. During periods of quiescence of the episodic growth, the  $Ca^{++}$  and  $SO_4^{--}$  incorporated in the waters would become supersaturated near the upper surface of the salt. Since the waters would only be supersaturated with respect to anhydrite and not to halite, anhydrite would be precipitated and the salt would continue to dissolve. Because of the two simultaneous processes, the newly formed anhydrite would contain the less soluble residue minerals such as quartz and dolomite.
5. The variations in the trace element concentrations would then reflect the concentrations of these elements in the brines from which anhydrite is precipitating. As the dome moves up episodically, it encounters different quality brines and therefore the anhydrite changes in compositions.
6. The anhydrite grows both upward and downward in direction, with the amount of growth depending on the rate of anhydrite precipitation and the rate of halite dissolution off the apex of the dome.

7. Anhydrite continues to precipitate until the environment changes from acid reducing to basic reducing. This change occurs at a depth where organic material (hydrocarbons), along with other favorable conditions, exist for the growth of the sulphate reducing bacteria. In this environment the pH would increase because of the sulphate reduction process. The bicarbonate ion is a reduction product, therefore due to differences of solubility between calcite and anhydrite, the calcite would precipitate, also increasing the pH or at least buffering above pH 7.

8. If the supply of organic matter was temporarily diminished, bacterial growth would cease, pH would probably lower due to the ionization of  $H_2S$ , and anhydrite (or gypsum) would again precipitate. This could possibly result in the alternation of anhydrite and calcite.

9. If the supply of organic matter was deficient in only parts of the caprock, different minerals would be precipitated in different areas.

10. If other elements were present in fairly large quantities in the associated brines, they could become incorporated in the caprock. This is the case in some of Mississippi caprock where large amounts of strontium were incorporated.

11. The upper deformed surface of anhydrite and calcite zones simply result from the caprock forming at greater depths, followed by later movement upward and resulting in the upper surfaces being deformed.

12. All of the anhydrite dissolved does not necessarily form in the caprock, but some escapes into the surrounding sediments to form the false caprock.

13. The room necessary for caprock growth develops primarily from the dissolution of the top of salt (in other words only 1000 feet of salt would have to be dissolved off the top of the salt in order to accommodate a 1000 foot caprock). Other ways of developing room would be the dissolution of the unstable clastics (common to the false caprock environment) or simply by the force of crystallization (Weyl, 1959).

14. The variability of caprock between domes and on any one individual dome would result from local controls and conditions. Structure would control fluid movement, along with permeability and osmotically derived pressures in the surrounding sediments. The composition of the associated brines would limit the types of minerals precipitated, and the geochemical environment would dictate the type of minerals which precipitate from these brines.

### REFERENCES

- Barnes, V. E., 1933. Metallic minerals in caprock, Winnfield salt dome, Louisiana: *Am. Mineralogist*, 18:335-340.
- Baas Becking, L. G. M., Kaplan, L. R., and Moore, D., 1960. Limits of the natural environment in terms of pH and oxidation-reduction potentials, *Jour. Geol.*, 68:243-284.

- Berner, R. A., 1969. Migration of iron and sulphur with anaerobic sediments during early diagenesis: *Am. Jour. Sci.*, 267:19-42.
- , 1971, *Principles of chemical sedimentology*. McGraw-Hill Co., N.Y., 240 p.
- Braitsch, O., 1971. *Salt deposits, their origin and composition*. Springer-Verlag Co., Berlin and N.Y., 297 p.
- Brown, L. S., 1931. Cap-rock petrography: *Am. Assoc. Petroleum Geologists Bull.*, 15:509-529.
- Collins, A. G., 1970. Geochemistry of some petroleum-associated waters from Louisiana: *U.S. Bur. Mines Rept. Inv.* 7326, 31 p.
- Dickinson, G., 1953. Geological aspects of abnormal reservoir pressures in Gulf Coast Louisiana: *Am. Assoc. Petroleum Geologists Bull.*, 37:420-432.
- Downey, M. W., 1969. Rock description, core 5, Challenger Knoll Gulf of Mexico, in *Initial reports of the Deep Sea Drilling Project*, v. 1; U.S. Govt. Print. Off., p. 427.
- Feely, H. W., and J. L. Kuip, 1957. Origin of Gulf Coast salt dome sulfur deposits: *Am. Assoc. Petroleum Geologists Bull.*, 41:1802-1853.
- Goldman, M. I., 1929. Features of gypsum-anhydrite salt-dome cap rock (abs.): *Geol. Soc. America Bull.*, 40:99-100.
- , 1931. Bearing of cap rock on subsidence on Clay Creek salt dome, Washington County, Texas, and Chestnut dome, Natchitoches Parish, Louisiana: *Am. Assoc. Petroleum Geologists Bull.*, 15:1105-1113.
- , 1933. Origin of the anhydrite cap rock of American salt domes: *U.S. Geol. Survey Prof. Paper* 175:83-114.
- , 1952. Deformation metamorphism, and mineralization in gypsum-anhydrite caprock, Sulphur salt dome, Louisiana: *Geol. Soc. America Memoir* 50, 169 p.
- Hanna, M. A., and Wolf, A. G., 1934. Texas and Louisiana salt-dome caprock minerals: *Am. Assoc. Petroleum Geologists Bull.*, 18:212-225.
- , 1941. Gold, Silver, and other elements in salt-dome cap rocks. *Am. Assoc. Petroleum Geologists Bull.*, 25:750-752.
- , 1953. Fracture porosity in Gulf Coast: *Am. Assoc. Petroleum Geologists Bull.*, 37:266-281.
- Hawkins, M. E., and Jirik, C. J., 1966. Salt domes in Texas, Louisiana, Mississippi, Alabama and offshore tidelands; a survey: *U.S. Bur. Mines Inf. Circ.* 8313, 78 p.
- Jones, P. H., 1968. Hydrodynamics of geopressure in the northern Gulf of Mexico Basin: *Soc. Petroleum Engineers Preprint* 2207, 12 p.
- Judson, S. A., and Stamey, R. A., 1933. Overhanging salt on domes of Texas and Louisiana: *Am. Assoc. Petroleum Geologists Bull.*, 17:1492-1520.
- Kerr, P. F., and Kopp, O. C., 1958. Salt-dome breccia: *Am. Assoc. Petroleum Geologists Bull.*, 42:548-560.
- Kinsman, D. J. J., 1969. Interpretation of  $Sr^{++}$  concentrations in carbonate minerals and rocks: *Jour. Sed. Petrology*, 39:486-508.
- Lerman, A., 1970. Chemical equilibria and evolution of chloride brines: *Mineral Soc. Amer. Spec. Pap.* 3:291-306.
- MacDonald, G. J. F., 1953. Anhydrite-gypsum equilibrium relations: *Am. Jour. Sci.*, 251:884-898.
- Marshall, W. L., 1967. Aqueous systems at high temperature. XX. The dissociation constant and thermodynamic functions for magnesium sulfate to 200°C: *Jour. Phys. Chem.*, 71:3584-3588.
- , and Slesher, R., 1968. Aqueous systems at high temperature. XIX. Solubility to 200° of calcium sulphate and its hydrates in sea water and saline water concentrates and temperature-concentration limits: *Jour. Chem. Eng. Data*, 13:83-93.
- McLeod, R. R., 1960. A theory for the formation of limestone caprock of salt domes: *Gulf Coast Assoc. Geol. Soc. Trans.*, 10:151-153.
- Murray, G. E., 1966. Salt structures of Gulf of Mexico Basin—a review: *Am. Assoc. Petroleum Geologists Bull.*, 50:439-478.
- Rollo, J. R., 1960. Ground water in Louisiana: *Louisiana Dept. Conserv., Geol. Survey* and Dept. Public Works in coop. with the U.S. Geol. Survey, *Water Resources Bull.*, no. 1, 84 p.
- Stuart, M., 1931. A Contribution to "Salt Dome" geochemistry: *Inst. Petrol. Tech. Jour.*, 17:338-345.
- Taylor, R. E., 1937. Water-insoluble residues in rock salt of Louisiana salt plugs: *Am. Assoc. Petroleum Geologists Bull.*, 21:1268-1310.
- , 1938. Origin of the caprock of Louisiana salt domes: *Louisiana Geol. Survey Bull.* 11, 191 p.
- Teas, L. P., 1931. Hockley salt shaft, Harris County, Texas: *Am. Assoc. Petroleum Geologists Bull.*, 15:465-469.
- Walker, C. W., 1968. *False caprock overlying Gulf Coast salt domes—Analyses and origin*: Unpublished M.S. Thesis, Univ. of Mississippi, Oxford, 240 p.
- Weyl, P. K., 1959. Pressure solution and the force of crystallization—a phenomenological theory: *Jour. Geophys. Research*, 64:2001-2025.
- White, D. E., 1965. Saline waters of sedimentary rocks, in *Fluids in subsurface environments*: *Am. Assoc. Petroleum Geologists Mem.* 4:342-366.