1938

Origin of the Cap Rock of Louisiana Salt Domes.

Ralph Emerson Taylor

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ORIGIN OF THE CAP ROCK
OF
LOUISIANA SALT DOMES

A DISSERTATION
SUBMITTED TO THE GRADUATE FACULTY
OF THE
LOUISIANA STATE UNIVERSITY
AND
AGRICULTURAL AND MECHANICAL COLLEGE
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
THE DEPARTMENT OF GEOLOGY

by

Ralph Emerson Taylor
A. B., University of Michigan, 1927
M. S., University of Michigan, 1928
1938
"Slab" anhydrite inclusion in salt, from winnfield salt dome. X 1.56.
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A salt dome is an approximately dome shaped anticline with a central plug of rock salt that in most cases has been vertically intruded from bedded salt deposits at great depth. Cap rock is a body of rock composed essentially of anhydrite, with lesser amounts of calcite, gypsum, and in a few cases sulphur, that overlies the salt plugs of many salt domes. Such cap rock is found in the salt domes of Louisiana, Mississippi, Texas, Mexico, Germany, and other salt dome regions.

The occurrence of cap rock has been the subject of many discussions and a number of theories have been advanced for its explanation. Among these, two theories have been given more consideration than the others. By one, anhydrite cap rock is explained as part of an original bed of primary sedimentary anhydrite that was broken from the original bed and carried upward at the time of salt intrusion. The calcite, gypsum, and sulphur are accounted for either as alteration products of the anhydrite, or as parts of the original sedimentary series. According to the other theory, anhydrite cap rock is an accumulation of water-insoluble residue, chiefly anhydrite grains, dissolved out of the salt, and the calcite, gypsum, and sulphur are alteration products of the anhydrite.

In recent years much information about cap rock has accumulated as a result of the exploration of salt domes for
petroleum, sulphur, salt, and "limestone." The present study was undertaken in order to determine what significance this additional information might have with respect to the origin of cap rock. Because of the dominating position of cap-rock deposits in the world production of sulphur, the origin of sulphur has received special emphasis.

The problem has been attacked by first reviewing the extensive literature on salt domes. A bibliography is appended which includes most of the titles pertaining to salt-dome cap rock, and in addition, those that deal with the origin of "sedimentary" deposits of sulphur. Then, because of the definite association of the cap rock and the salt, the petrography of both the cap rock and the salt was studied in considerable detail. A number of residue samples and salt thin-sections, in addition to over 300 cap-rock thin-sections, were studied with the aid of the petrographic microscope. In appendix B summarized descriptions of 3 suites of well cores are given. All other information on the geology of salt domes that might have a bearing on the problem has also been included. The economic geology of cap rock is treated briefly in appendix A.

Of the 68 salt domes that have been proved by drilling to exist in Louisiana, 53 are known to have cap rock. The salt domes are situated in two areas, one in north Louisiana and the other, including 53 salt domes, in south Louisiana. The depth to the "mother bed" of salt from which intrusion
has taken place is not known, as salt has never been encoun-
tered off structure in the salt-dome areas. Elevation of the
body of salt or salt plug in the structures ranges from a few
feet above sea level to more than 8,800 feet below sea level.
Geophysical surveys indicate that there are salt domes in
south Louisiana in which salt occurs at depths of over 10,000
feet. Estimates based on drilling and geophysical data place
the depth to the "mother bed" at 12,000 to 15,000 feet in
north Louisiana and in excess of 15,000 feet in south Louisi-
ana. The age of the salt is not definitely known, but from
comparison with salt deposits encountered at Rodeessa, La.,
and El Dorado, Ark., it appears to be Permian.

Examination of salt from 19 salt domes shows that the
salt contains from less than one to almost ninety percent,
by weight, of water-insoluble residue, with five to ten per-
cent on the average. This residue consists chiefly of anhy-
drite grains of sand size that are concentrated in the iso-
clinally folded bands typical of the rock salt of salt domes.
In addition to anhydrite, the residues always contain the fol-
lowing minerals: dolomite, as rhombic crystals of sand size
that are often zoned or contain distinctive nuclei; quartz
rosettes with distinctive nuclei; individual quartz crys-
tals; pyrite crystals; and rhombs and scalenohedrons of
calcite. Other minerals that have been found in certain of
the residues are: limonite, hematite, sulphur, celestite,
Barite, marcasite, hauerite, kaolinite, gypsum (?), magnesite, hilgardite, danburite, and boracite. The last four have been found at only one locality, and the hilgardite is a new mineral - a hydrous calcium borate with chlorine. Inclusions of detrital sand, sandstone, clay, black shale, petroleum, natural gas, hydrogen sulphide gas, carbon dioxide gas, nitrogen gas, and "mother liquor" have been found in the salt. Salt from ten of the salt domes gave a positive test for potash.

The salt is similar in composition to that of sedimentary salt deposits in other parts of North America, as well as to that in German salt domes, and is definitely of sedimentary origin. The minerals of the residues were undoubtedly precipitated at the time of salt deposition and the bands in which they are concentrated are "annual rings." Anhydrite and dolomite grains in the residues are larger than those in primary bedded deposits of these minerals. The larger size of the grains included in the salt can be explained by the fact that they were precipitated when their point of maximum concentration had been passed and growth of crystals took place slowly, while bedded deposits were deposited at a time of maximum crystallization and growth of crystals was rapid.

Where a cap rock of appreciable thickness is present it usually lies upon a relatively flat salt surface, known as the salt table, that truncates the isoclinal folds of the salt.
Sand composed of the same minerals as the salt residues is found at the salt-anhydrite contact, associated with brine and "mushy" salt. The brine is not always saturated for salt (sodium chloride). Waters associated with salt domes in many cases have artesian pressure, particularly at the salt-anhydrite contact. The geothermal gradient at salt domes is higher than the regional average. In some cases temperatures approaching the boiling point of water are encountered at depths of only a few thousand feet. Hydrogen sulphide gas and hydrocarbons are in nearly every case associated with cap rock.

Cap rock has its best development at shallow salt domes, although there are a few very shallow ones at which little or none is present. A thickness of 200 to 300 feet is common, and a few salt domes have 1,000 feet of cap rock. At salt domes in which the salt is at 4,000 feet or more below the surface cap rock is thin or wanting. Cap rock is characterized by irregularity in development, although in many cases it is thickest over the center of the salt plug. A thin mantle of cap rock has been found extending down the sides of some salt plugs for distances of 5,000 feet. In places the sediments adjacent to the flanks of the salt plug contain minerals of the salt residues. The age of cap rock is indeterminant as it is unfossiliferous and it appears to be unconformable with the surrounding sediments.
Cap rock is very complex structurally because of intensive brecciation and shearing, particularly in the upper part. Examination of complete suites of cores shows a definite increase in the amount of deformation from the salt-anhydrite contact upward. In all cases where identity could be established, breccia fragments have come from higher in the cap rock. Evidence of sedimentary bedding is confined to very small breccia fragments of sandstone and of what appears to be bedded sedimentary anhydrite. The extensive horizontal banding that is present is caused by secondary minerals that are deposited in shear zones. Cap rock is also characterized by numerous cavities that in many cases connect to form extensive channels.

Anhydrite is the chief constituent of cap rock, and at a few of the salt domes in which salt is 4,000 feet or more below the surface it is the only mineral of importance present. At salt domes that have a considerable thickness of cap rock, however, calcite, gypsum, and in a few cases sulphur, are also important minerals. These minerals occur in fairly well defined zones designated the anhydrite, transition, and calcite zones, occurring in this order upward from the salt-anhydrite contact.

The anhydrite at its contact with the salt is composed of anhydrite grains of the same size and shape as those of
the salt residues, in places loosely compacted and with interstitial salt. Upward it becomes more compacted and shows horizontal shearing with dark bands developed along the shear zones where secondary pyrite and calcite occur. The main body of the anhydrite is the distinctive coarse grained "saccharoidal" type with "pile of brick" structure, many of the grains showing the effects of intergrowth and recrystallization. Scattered through the anhydrite are other typical minerals of the salt residues, including large dolomite rhombs with nuclei and zonal structure, quartz rosettes with nuclei, celestite, barite, and pyrite crystals, and sulphur grains, all of the same age as the anhydrite grains. These minerals occur in about the same proportions as in the salt residues.

Secondary calcite and sulphur appear in the upper part of the anhydrite zone, in places forming pseudomorphs after the anhydrite. The amount of calcite and sulphur increases up to the transition zone, the zone of active alteration. Gypsum also replaces the anhydrite in the zone of alteration and is in turn altered to calcite and sulphur. The shear structure, the dolomite rhombs, and other distinctive minerals of the anhydrite zone, can be traced through the transition zone and into the calcite zone.

The contacts of the anhydrite and transition zones and of the transition and calcite zones are gradational. Isolated bodies of anhydrite occur in the transition and in the calc-
cite zones. Both the calcite and transition zones are very cavernous and both are intensively brecciated. In addition to replacing the anhydrite and gypsum directly, the calcite and sulphur occur as veins of several generations. Secondary pyrite, barite, celestite and a few other minerals also occur in the transition and calcite zones.

The false cap rock, a zone of sediments cemented by calcite, pyrite, or in a few cases, other minerals, overlies the cap rock in many salt domes. Breccia fragments of false cap rock are included in the upper part of the calcite zone. At some salt domes, particularly where the cap rock is in a broken condition, sediments have filtered into the calcite and transition zones.

Analysis of the data presented indicates definitely that anhydrite cap rock has formed by the accumulation of water-insoluble residue in the salt. The theory that it is a block of primary sedimentary anhydrite brought up by the salt is rejected because of (1) petrographic evidence that cap-rock anhydrite differs strikingly from primary, sedimentary anhydrite and (2) the physical difficulties involved in bringing a block of anhydrite up through a great thickness of sediments. The following evidence indicates the residual origin of the anhydrite: (1) the great similarity in composition of the salt residues and the anhydrite cap rock;
(2) the presence of salt residue at the salt-anhydrite contact - proving that solution occurs; (3) the increase in relative age of the cap rock upward from the salt-anhydrite contact; (4) the flat salt table that truncates the isoclinal folds; and (5) the irregularities in the development of cap rock. There is sufficient residue in salt and enough salt available to account for known thicknesses of cap rock. The absence of cap rock at a few shallow salt domes can be explained by erosion and by "shedding" due to recent upthrust of the salt. Lack of cap rock below 4,000 feet probably is due to the salt being below the zone of active ground water circulation.

The manner in which cap rock is formed can be outlined in some detail on the basis of the residual theory. Following elevation of a salt plug into the zone of active ground water circulation, a false cap rock would be formed which eventually would prevent contamination of the residue by the surrounding sediments. As soon as an appreciable thickness of residue had accumulated it would respond to upthrust and collapse by compacting and shearing.

The calcite and sulphur are definitely alteration products of the anhydrite and the gypsum. Alteration has proceeded from the upper part of the cap rock downward. The gypsum has formed by hydration of the anhydrite. The manner in which the calcite and sulphur have been formed cannot be
definitely stated, however. The association of hydrocarbons with cap rock has led to the suggestion that the chemical processes involved are the reduction of the calcium sulphate, of which the anhydrite and gypsum are composed, and oxidation of the resultant sulphides. These reactions can be carried out in the laboratory, but the reduction calls for an amount of heat far in excess of that which could be expected in nature. There is a possibility, however, that the reduction would take place slowly at much lower temperatures, particularly in the case where so great an amount of time as that involved in the formation of mineral deposits is available. Oxidation of the sulphide to sulphur has been explained as occurring in an oxidizing zone removed from the reducing zone, or as resulting from the work of the oxygen released at the time of reduction of the sulphate radicle. This last method could be expected only with nice adjustment of conditions.

Where the relationship has been studied for contemporaneous calcite and sulphur, the ratio of calcite to sulphur is approximately that which would be expected on the basis of their molecular ratios in calcium sulphate.

Experiments have shown that hydrogen sulphide reacts with calcium sulphate at relatively low temperatures to form sulphur. This suggests that hydrogen sulphide from an outside source, possibly associated with hydrocarbons, may have initiated reduction in which the hydrocarbons themselves
later became active. The presence of pseudomorphs of sulphur after anhydrite is evidence that at least in places the alteration was complete, and that the order of reduction at one point followed by oxidation at another was not followed. Such pseudomorphs can be explained by the reaction of hydrogen sulphide on calcium sulphate with the direct formation of sulphur.

Deposits of sulphur associated with sulphates that occur in Sicily, Russia, and a few other places have been attributed to the action of sulphate-reducing bacteria. These bacteria are known to occur in oil-field waters of North America and Europe, and although they have not been found in salt-dome waters, they have been suggested as the active agent in the reduction of the anhydrite and gypsum. While the environment of cap rock and the mode of occurrence of the sulphur are unfavorable to this method of formation, it cannot be dismissed merely on the basis of negative evidence.

Secondary pyrite, barite, celestite, hauerite, and galena that occur in the transition and calcite zones can have been derived from the salt. Concentration of the barite and celestite may have been effected with the aid of warm waters. Although appreciable amounts of galena are difficult to assign to a source in the salt, there is no direct evidence of a possible outside source.

Further work on the cap-rock problem should take the form
of detailed studies of the petrography and structural geology of salt domes for which considerable information is available. Solution of the problem of the origin of sulphur calls for careful laboratory experiments covering all possible reactions, and the careful analysis of salt-dome waters for sulphate-reducing bacteria.
Foreword
The interesting geologic structures in the Gulf Coast region of North America that are known as salt domes offer many intriguing problems to the student of earth science. From the day in 1862 when John Marsh Avery discovered salt at Petite Anse (Avery Island), La., to the present, their anomalous presence has demanded an explanation. It is of interest to note that although Avery's discovery of rock salt was one of the first made on the North American continent, the salt has come from such great depth that its actual source is still unknown. Geologists, in general, agree that the salt plugs of these salt domes must have been intruded from beds of sedimentary salt lying many thousands of feet below the present surface of the Gulf Coast, but the actual depth and age of this "mother" salt bed has not been definitely determined.

The present study is concerned with another problem, but it is one that is closely related to the origin of the salt. This is the origin of the cap rock that overlies many of the Gulf Coast salt plugs, and the paragenesis of the minerals that are found in it. Cap rock is quite as unusual a body of rock as the salt plug, and its definite association with the salt suggests that there is a direct relationship between the two. In order to determine the nature of this relationship the present study has included both cap rock and salt. The method of attack followed has
been the collection of all available data concerning the occurrence of both types of rock bodies, combined with petrographic studies of the cap rock and the salt. The petrographic method of study was selected because it often permits the deciphering of the sequence of events followed during the formation or rocks that are unfossiliferous. During the course of this study, many well cores and other specimens have been examined megascopically, and some 300 thin sections cut from these specimens have been studied in detail with the petrographic microscope. Data thus obtained, supplemented by the evidence from other branches of geology, have been assembled, and an interpretation of the whole has been advanced. It is hoped that the results are presented in enough detail and with sufficient clarity that the reader can distinguish between fact and interpretation.
Acknowledgements
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Introduction
There are 138 proved salt domes in that part of the Gulf Coast region of North America extending as a broad belt from the Rio Grande River on the west to a little beyond the Pearl River on the east. To date, 68 of them have been discovered in Louisiana, 53 in the southern part of the State and 15 in the northern part (map, pl. XXVII, in pocket). These salt domes are very like those which occur in Mexico, Germany, Russia, Roumania, Persia, Northern Africa, and other parts of the world. They are localized domal anticlines, formed by the intrusion from sedimentary beds at great depth of roughly cylindrical plugs of rock salt. The salt plugs usually have a diameter of a little less than a mile and occur at depths ranging from a relatively few feet, as at Avery Island, La., to nearly 9,000 feet, the depth to salt at Henderson, La. The existence of still deeper ones is indicated by geophysical data.

Many of the salt plugs, particularly the shallower ones, are immediately overlain by bodies of rock, most of which is quite well indurated, known as salt-dome cap rock. Although this cap rock, in most cases, lies beneath a covering of unconsolidated sediments, it appears at the surface at Winnfield and Pine Prairie, La., and at Gyp Hill, Tex., and is associated with indurated sediments in north Louisiana and in east Texas. It is quite irregularly distributed over the upper portion of the salt, and its thickness varies from a
relatively few feet at Vermillion Bay, La., to over 1,000 feet at Sulphur, La. The composition of cap rock also shows considerable variation, although its chief constituent in most cases is a coarsely crystalline anhydrite of quite distinctive appearance. In many of the salt domes this anhydrite, that lies immediately above the salt, is overlain by cavernous, rather coarsely crystalline, calcite. Where the depth is not too great, gypsum may be associated with, or may occur between, the anhydrite and calcite. Commercial deposits of native sulphur have been found within the lower part of the calcite cap rock at a few of the salt domes. Several additional minerals, chiefly sulphates, sulphides, and carbonates, are commonly present. The cap rock is unfossiliferous, so far as is known, although fossils occur in the false cap rock, a zone of calcite cementation in the sediments adjacent to the cap rock.

At the present time, salt-dome cap rock supplies the greater part of the world's sulphur and is also a source of oil and "limestone." It has received considerable attention not only because of its economic importance, but also because of the interesting geologic problems associated with its occurrence. The presence of these bodies of hard rock in regions of otherwise unconsolidated rocks, their definite association with the salt, their varied mineral content, and
other characteristics, have been subjects of much interest to geologists.

Although several attempts have been made to explain the origin of cap rock, the problem has not as yet been definitely solved. The presence of the anhydrite is usually accounted for in one of two ways: (1) it is a detached block of sedimentary anhydrite brought up on top of the salt; and (2) it is residual material which accumulated as a result of solution of the salt, in the same way that the "gypsum hat" of the German salt domes has been formed. The minerals other than the anhydrite have been explained as being either a part of the original sedimentary sequence, or as alteration products of the anhydrite.

This study of the cap rock of Louisiana salt domes has been made with the hope of obtaining further data on the geology and origin of these interesting and important bodies. It has included the petrographic examination of both the salt and the cap rock in order to determine their relationship, and particular attention has been given to sulphur-bearing cap rock. For purposes of comparison, salt and anhydrite of known age have also been studied. The evidence obtained from this study indicates that the anhydrite has collected as a residue from solution of the salt and that the calcite, gypsum, and sulphur have replaced the anhydrite, probably altering from it. The detailed discussion of the conclusions
will be deferred, however, until more attention has been given to the results of previous workers, and the data from the present study have been presented.
The Literature
The rock which later came to be known as salt-dome cap rock figures in some of the early accounts and theories of the geology of Louisiana. Hopkins (1870) and Hilgard (1872) speak of outcropping Cretaceous limestone at Winnfield and Bayou Chicot (Pine Prairie), considering these outcrops, along with other elevations which it has since been learned are due to the intrusion of salt, as erosion remnants of a Cretaceous ridge or "backbone" that extended southward from Arkansas toward the Gulf of Mexico, including the Five Islands of Louisiana. A Cretaceous age was assigned to the ridge on the basis of fossils that were found at some of the north Louisiana "peaks," and because of the similarity of the "limestone" to known Cretaceous limestone. The salt discovered in 1862 at one of the Five Islands, Petite Anse (Avery Island), was thought to be Cretaceous in age, as was the sulphur-bearing zone discovered while drilling for oil in 1869 at Sulphur, La.

The "peaks" were explained by Lockett (1871) as remnants of a great natural levee, but little consideration was given this theory. The idea of the Cretaceous ridge,

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It is well to note that the term "cap rock" has been used for other types of rock than that for which it is employed in salt-dome terminology. Cap rock can also mean the impervious layer directly above an oil- water- or gas-producing horizon, and also the relatively impervious stratum, usually dolomite or shale, overlying a bedded salt deposit.
however, was enlarged upon by Lerch (1892; 1893), who de-
picted Cretaceous mountain chains stretching across Louisiana
from Arkansas to the Gulf of Mexico. Clendenin (1896) drew
attention to the recent uplift that has taken place at the
Five Islands, discounting somewhat the possibility that they
were part of the Cretaceous "backbone." The observations
of Harris and Veatch (1899) resulted in abandonment of the
Cretaceous "backbone" theory, although the cap rock and salt
were still referred to the Cretaceous.

It is of especial interest to note that as far back as
the time of Hilgard and Hopkins a definite relationship was
thought to exist between the cap rock and salt, although the
structures in which they occur were not called salt domes
until the beginning of the present century. The establish-
ment of this relationship and the rapid increase in our know-
ledge of the occurrence of salt domes can be attributed to
the interest following discovery of oil in the cap rock at
Spindletop, Tex., in 1901, and the successful development
of the sulphur deposit at Sulphur, La., at about the same
time. The term cap rock first came into use for the Spindle-
top occurrence, where it was used for the upper part of the
cap rock and the false cap rock, which were thought to
function as capping for the cavernous oil-bearing strata.
Rapid exploration followed these events, particularly in
the search for oil. Within a relatively few years the known
salt domes had been explored for cap-rock oil, and the attention of the industry was diverted to production from the sides or flanks of the salt domes. Since this time cap rock has been of interest chiefly as a source of commercial deposits of sulphur.

As the search for oil has increased our knowledge of salt domes, various theories regarding their origin have been proposed. The present concept of the intrusive origin of salt domes, and the abandonment of the volcanic, gas uplift, and crystallization theories, has resulted from the work of Hahn (1912), Rogers (1918), Grabau (1920), Van der Gracht (1917; 1926), Stille (1925), Barton (1925A), and others, by their interpretation of the Gulf Coast structures in terms of those of the "North German Basin." During the time that the intrusive theory was being formulated, the problem of the origin of cap rock received only passing attention. The cap rock seems to have been explained generally as a sedimentary deposit uplifted by intrusion of the salt. In fact, a definite attempt was made by Fishback (1902) to correlate the calcite cap rock with bedded limestone. Later, Hahn (1912) noted that the Germans explain the anhydrite "hat" occurring

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For a detailed account of the development of salt-dome theory the reader is referred to DeGolyer (1925), Barton (1925; 1925A; 1933), Howe and Morosi (1931), and Bettleton (1934).
on some of the salt plugs of the "North German Basin" as
an accumulation of residual material resulting from solution
of the salt, but his work received little attention. In
discussing cap rock, Rogers (1918) stated that the problem
of its origin should be treated as distinct from that of salt
domes. He outlined four principal theories of origin: (1)
a block of sedimentary rock brought up on top of the salt;
(2) action of waters containing sulphuric acid upon lime-
stone; (3) precipitation as a result of the mingling of
ground waters and of saline waters from the salt plug; and
(4) accumulation of residual material after solution of the
salt. He did not accept any of these as conclusive but fav-
ored the first. DeGolyer (1918), in a discussion of Rogers'
work, outlined in some detail the manner in which anhydrite
could be precipitated in place, presenting solubility tables
for calcium sulphate and calcium carbonate. Further atten-
tion was focused upon the "hat" of the German salt domes by
Van der Gracht (1917; 1926), Barton (1925A), and Stille (1925).
Following these articles, DeGolyer (1925; 1931), Hanna (1930;
1934), and others have come to explain the cap rock of Gulf
Coast salt domes as of residual origin, i.e., due to accumu-
lation of anhydrite at the upper surface of the salt plug
as a result of solution of the salt.

At about the same time that these men were making
their studies, the first detailed petrographic study of cap rock was being undertaken by Goldman (1925). He examined thin sections of a suite of cores obtained from a well at Sulphur, La., as well as a few from other salt domes, and concluded that the anhydrite is a block that was detached from a bed of sedimentary anhydrite and carried upward when the salt was intruded. This conclusion was based upon the similarity of banded breccia fragments in the anhydrite to sedimentary anhydrite from the Permian of Texas. He failed to consider the possibility that breccia fragments might have been included in the salt, and did not account for the presence of the much more common coarse-grained and indistinctly banded type of anhydrite cap rock. In later papers, Goldman (1929; 1931; 1933) discarded his previous theory in favor of that of residual accumulation, stating that his original conclusions had been arrived at without knowledge of the German literature and of the composition of the salt.

Goldman (1933) believes that the strongest geologic fact in favor of the residual theory is the "salt table," the relatively flat upper surface of the salt, found on many of the salt plugs of both the "North German basin" and of the Gulf Coast. He cites as additional geologic evidence the presence of brine and anhydrite sand at the anhydrite-salt contact, the great variations in the thickness of cap
rock, the apparent absence of cap rock on the flanks of salt plugs, and the fact that a bed of sedimentary anhydrite overlying the sedimentary bed of salt at depth would be broken up and included in the salt at the time of intrusion, rather than being brought up as a block. The most important petrographic evidence, according to Goldman, is the "katatectic" banding, a type of banding found in the coarse-grained anhydrite and formed as a result of periodicity in accumulation of the anhydrite grains that dissolved out of the salt. Goldman gives very little data concerning the rock salt, although he notes the similarity of the anhydrite grains of the cap rock and the salt and the presence of dolomite rhombs and quartz rosettes in both salt and cap rock. He suggests that solution may have been effected by waters from a water sand intercepted by the intruded salt, thus explaining the existence of the salt table. Goldman does not account for the great thickness of the cap rock at some salt domes and its absence at others, although he suggests that these conditions may be explained by differences in the composition of the salt, variations in the depth of the salt below the surface, and differences in the time of intrusion. The paragenesis of the gypsum, calcite, and sulphur was not determined, although he infers that these minerals result from alteration of the anhydrite; the gypsum (\(\text{CaSO}_4 \cdot 2\text{H}_2\text{O}\)) forming by hydration of the anhydrite (\(\text{CaSO}_4\)) and the sulphur and cal-
cite resulting from reduction of either the gypsum or anhydrite.

A detailed petrographic study of cap rock has also been made by Brown (1931), based upon material from 12 salt domes, with Hoskins Mound, Tex., the best represented. Brown concluded that the anhydrite was brought up on top of the salt at the time of intrusion and that the anhydrite at all of the salt domes is of the same age, - Glen Rose of the Lower Cretaceous. This correlation of the anhydrite was based chiefly on the presence in the cap rock of sulphur and celestite of the same age as the anhydrite, and the presence of the same minerals in known Glen Rose anhydrite of west Texas. It appears that Brown was not aware that celestite occurs as disseminated crystals in the salt of Gulf Coast salt plugs (Taylor, 1937), including two of those from which he examined anhydrite cap rock. He knew of the presence in the salt of disseminated anhydrite, dolomite, quartz, and sulphur, however. It is interesting to note that he based his conclusion that the gypsum and calcite are secondary after anhydrite partly on the presence and relationships of the unique dolomite rhombs and quartz rosettes in them, but made no effort to extend this relationship to the salt, although he was aware that the same minerals occur in the salt. He explained the sulphur as at least in part of primary origin, the gypsum as hydrated anhydrite, and in his earlier paper, accounted
for the calcite as an alteration product of the gypsum and anhydrite. In a later paper, Brown (1934) outlined suitable conditions for the formation of sedimentary limestone, sulphur, and anhydrite deposits that are in accord with his theory of cap rock formation. He altered his previous views somewhat, stating that the cap rock and salt are of different ages in different parts of the Gulf Coast, and that the calcite cap rock is a part of the uplifted sedimentary series. Still later, Brown (1935) suggested that the anhydrite had been reduced by connate hydrogen sulphide, with sulphur resulting directly from the reaction. He carried out several experiments to check this reaction and obtained sulphur in one of them.

Considerable attention has also been given cap rock by Barton, who has favored the theory that cap rock is part of a sedimentary bed of anhydrite (1934). He suggests that if one accepts his theory of downbuilding, i.e., formation of salt plugs by downward movement of the source beds of sedimentary rock salt, accompanying regional subsidence, while the crest of the salt plug remains approximately stationary, the explanation of anhydrite cap rock as a primary sedimentary bed is rendered plausible. However, he considers that intrusions of as much as several thousand feet have been due to actual upthrust of the salt, hence his theory of cap-rock formation raises similar difficulties to those encountered by theories ascribing the salt plug entirely to intrusion.
A very complete survey of the problems connected with the origin of cap rock has been presented by Hanna (1934; also see Hanna, 1930). In a review of the various theories he outlines the objections to each. He considers that there is a lack of field evidence to support the theory of up-thrust of a block of sedimentary anhydrite from depth. The chief objections to the theory of residual accumulation, according to Hanna, are the supposed lack of residual material in the salt, and the lack of water conditions favorable to solution of the salt. In spite of these objections, Hanna favors the theory of residual accumulation, placing the amount of residue in the salt at from 5 to 10 percent, and noting the similarity in mineral composition of the salt residues and of the cap rock. Data on the occurrences of anhydrite sand at the salt-anhydrite contact are assembled in Hanna's paper, as well as data on water circulation at salt domes. Hanna explains the calcite, gypsum, and sulphur as due to alteration of the anhydrite, but does not discuss the manner in which the alteration took place.

On the basis of observations made in India, Stuart (1931) concluded that the calcium sulphate of salt-dome cap rock is secondary, resulting from the action of sulphuric acid or of sulphate waters on carbonate of lime. The calcite cap rock has been attributed by Gwan (1931) to calcium carbonate associated with the original anhydrite, the anhydrite
also containing the sulphur. According to Owen, the calcium carbonate was released, along with the sulphur, as a result of solution of the anhydrite, and redeposited. He accounts for the anhydrite as a primary bed, brought up by the salt. Shepard (1937) has noted the presence of algal limestone on submarine domes off the coast of Louisiana. He refers to these submarine domes as "salt" domes, and suggests that some of the calcite cap rock of known salt domes may have formed as an algal limestone.

In addition to these articles in which the origin of cap rock is considered, studies have been made of several of the salt domes at which sulphur has been produced from the cap rock. These salt domes are: Big Hill (Wolf, 1925); Sulphur (Kelley, 1925; Rauerenschmidt, 1930); Bryan Heights (Kennedy, 1925); Boling (Wolf, 1933); Jefferson Island (O'Donnell, 1935); Hoskins Mound (Marx, 1936); and Lake Washington or Grande Ecaille (Howe and McGuirt, 1936A). While these works are not primarily concerned with theories of origin, they contain much data concerning the mode of occurrence and character of cap rock and reference will be made to them in later parts of this paper; the literature on sulphur will be reviewed in the discussion of the origin of sulphur and calcite.

The extensive German literature on salt domes and salt-dome theory has been reviewed by Lahn (1912), Van der Gracht (1917; 1926), Barton (1925; 1925A; 1926), Escher and Kuenen
(1929), Berliner (1930), and Lilley (1932). The presence of salt domes in the "North German Basin" has long been assigned to the intrusion of salt. The forces which caused the intrusion have been explained in several ways, chief of which are: (1) tangential stress set up during mountain-forming movements that caused flowage of the relatively plastic rock salt (advocated by Stille), and (2) isostatic pressures resulting from the lesser specific gravity of the salt in comparison to that of the enclosing rocks, and the burial of the sedimentary salt bed under a great thickness of younger sediments (the theory developed by Lachmann, Arrhenius and Harbort). These two theories are combined by some, who attribute the inception of movement to tectonic forces and its continuation to isostatic forces.

The "gypsum hat" or cap rock of the salt domes of the "North German Basin" is believed to have been formed as a result of the solution of the more soluble salts and the accumulation of the less soluble materials. The composition of the cap rock seems to be governed directly by the nature of the insoluble material in the salt, and consists variously of gypsum, anhydrite, dolomite, and clay (Lachmann, 1910; Barton, 1925A; Van der Gracht, 1917, 1926). Its thickness varies from a few inches to over 300 feet, depending upon the amount and character of impurities in the salt, as well as the amount of solution that the salt plug has undergone.

The truncation of the intensely folded beds of the salt
plug, occurring where salt lies within the zone of active ground water circulation, with the formation of a relatively flat "salt table," is well shown at Aller-Nordstern (Lachman, 1910), Benthé (Seidl, 1921), Luneberg (Harton, 1925A), Sedgeberg, Langenfeld, and other salt domes (Eby, 1934), and permits no doubt that the upper portion of the salt plug has been dissolved, leaving the less soluble materials to form a cap rock. Further proof of residual origin is afforded by the beds of less soluble materials in the salt that can be traced up into the cap rock.

The cap rock of the German salt domes apparently is much the same in character as that of the salt domes in the Gulf Coast of the United States. The chief differences seem to be a greater diversity of materials, more restricted development, and the relatively small amount of the "saccharoidal anhydrite" typical of the Gulf Coast occurrences. Few petrographic studies of German cap rock appear to have been made, probably owing to the fact that the genesis of cap rock is clearly evident from a study of geologic relationships.

Cap rock also occurs at the salt domes of Mexico, Persia, and Roumania, but little is known about those occurrences other than that they are similar to those of Germany and of the Gulf Coast. Harrison (1930) noted the similarity between limestone debris found on Persian salt domes to calcite cap rock described and illustrated by Goldman (1925).
The possibility that the Persian salt domes may have had cap rocks before they were pushed through to the surface is suggested by Harrison.
The 68 salt domes in Louisiana are usually considered as occurring in two separate areas (map, pl. XXVII), one in the northern part of the State, and one in the southern part. In addition to these salt domes where salt has actually been encountered by the drill, there are about as many salt-dome "prospects," mostly in south Louisiana, that are similar structurally to salt domes, but in which the existence of salt has not been proved. At most of these "prospects," the presence of salt has been indicated by data obtained with geophysical instruments.

The limits of the salt-dome areas of Louisiana cannot be outlined definitely because information about them is obtained largely as a result of the search for oil, sulphur, and salt production, and there remain extensive parts of the areas that are incompletely explored. It is known, however, that the salt domes of north Louisiana, 15 in number, occur on the eastward plunging nose of the Sabine uplift and in a saddle between this nose and the Monroe uplift to the east. This area apparently extends as far north as Smackover, Ark., where salt was encountered at a depth of approximately 6,000 feet, underlying sediments that are thought to be Permian in age (Spooner, 1932; also Bell, 1933). The recent discovery of salt, also referred to the Permian, at Rodessa in northwestern Louisiana, at a depth of 11,370 feet (Oil Weekly, July 12, 1937), is evi-
dence that a connection may exist between the salt-dome areas of north Louisiana and east Texas.

The salt-dome area of south Louisiana is separated from that of the northern part of the State by a strip about 50 miles in width that does not appear to contain salt domes, although it is as yet relatively undrilled. The coastal salt domes occur in the Louisiana portion of the Gulf Coast geosyncline (Barton, 1933; Howe, Russell, McGuirt, 1935; Russell, 1936). It is possible that the two Louisiana salt-dome regions will prove to be connected when the area between them has been thoroughly explored.

The rocks with which the salt domes of north Louisiana are known to be associated are sediments of Upper Cretaceous and Eocene age, and those of the southern area are of Eocene to Recent age. That the salt in the salt plugs is of sedimentary nature, i.e., a deposit resulting from the evaporation of normal sea water, is evident from the presence in the salt of algae (DeGolyer, 1929; Tilden, 1930), "year rings," a type of sedimentary banding caused by periodic changes in concentrations of solutions during salt deposition, and of detrital materials. These bedded salt deposits, from which the salt in the salt plugs was derived, could have been deposited as a result of concentration of sea water in any one of the several ways that have been pro-
posed for the formation of other salt deposits. Perhaps they can be most plausibly explained as having formed in a series of connecting marine basins during a time of arid climate, in view of their great extent and relative uniformity. The large amount of salt involved in the formation of the salt plugs (Lees, 1931; Howe and Moresi, 1931) is evidence that the bedded salt deposits were of considerable thickness.

A Permian age has been suggested for the salt of the "interior" regions of north Louisiana and northeast Texas by Powers (1926). This correlation has been borne out by the previously mentioned discoveries at Smackover, Ark., and Rodessa, La., of salt associated with rocks that are probably of Permian age. The salt can be assigned a Lower Cretaceous age, however, if the bedded anhydrites that occur in the Glen Rose (Lower Cretaceous) at the northern limits of the salt-dome areas of north Louisiana and northeast Texas are interpreted as being the shoreward facies of a basin of salt deposition. These bedded anhydrites appear to be lensing out down the dip, however.

3 Detailed accounts of the various theories of salt deposition are given by Ochsenius (1877); Walther (1900); Harris (1908); Branson (1915); Grabau (1920); Alling (1928); and Baker (1929).
A possible means of correlation of the salt of the two Louisiana areas has been suggested by studies of the water-insoluble residues of rock salt (Taylor, 1937). The residues show that while Gulf Coast rock salt is of the same general character as rock salt of known age in other regions, there are differences between the salt of the Gulf Coast and that of the other regions which are much greater than those between the salt of the two Louisiana areas. This suggests that all of the salt in the Louisiana salt plugs is of the same age, but it should be noted that this line of evidence cannot be considered conclusive. The only other possible evidence bearing on the age of the salt of south Louisiana is the discovery, in salt from Markham salt dome, in coastal Texas, of fossil algae that are the same as fossil algae in the salt of the Kansas Permian.

On the basis of the available evidence, then, the salt of the two Louisiana areas may be of the same age, probably Permian — although the Lower Cretaceous must still be considered as a definite possibility. Final proof of the age of the salt probably must await discovery by the drill of the "mother" bed of salt where it is known definitely to be in an undisturbed condition.

The depth at which this "mother" bed of salt lies can only be estimated, using known thicknesses of overlying sediments and geophysical data as a basis. It is evident from
these considerations that the source bed or beds must lie at great depths, possibly 12,000 to 15,000 feet in the northern part of Louisiana, and from this last figure to as much as 30,000 feet in south Louisiana (Howe, Russell, and McGuirt, 1935). That the salt has been intruded from deeply-lying source beds is definitely indicated by the structure of the salt and of the sediments that surround the salt plugs, as well as by comparison with other salt-dome regions, particularly that of Germany. The structure of the salt is characterized by isoclinal folding of the bands or "year rings," best explained as due to intrusion of the relatively plastic salt from great depths. (See DeGolyer, 1925; Escher and Kuenen, 1929; Barton, 1934; and Nettleton, 1934.)

Knowledge of the shape of the Gulf Coast salt plugs and of the structure of the salt is incomplete. Perhaps the best idea of the shape assumed by the salt plugs at the time of intrusion is afforded by the subsidiary spines of the type at Jefferson Island, where sediments as young as Pleistocene have been displaced. The shape that is suggested, at least for the upper surface of the plug, approximates that of a cone, apparently reflecting the structure within the salt. That is, if the outline of the salt plug were reconstructed on the basis of the folding in the bands or "year rings" of the salt, as exposed in the mines, the resulting structure would be a relatively steep-sided domal
anticline. Some of the salt plugs have one horizontal axis definitely longer than the other, as for example, Boggy Creek, Tex. (McLellan, Wendlandt, and Murchison, 1932), Anse La Butte (Howe and Moresi, 1933), and to a lesser extent, Lake Washington, La. The upper part of the salt plug at Boling, Tex., has a cross-sectional area of over 12 square miles, the largest of any known, and Sulphur, La., has the smallest known, slightly less than one-eighth of a square mile. The average area is about one square mile, with the upper surface of the plug approximately circular in plan.

The flat "salt table" present on many salt plugs decapitates the isoclinal folds in the salt. In addition to this modification, there is "overhang" of the salt, i.e., the upper part of the salt plug protrudes out over the adjacent sediments. This phenomenon has been explained variously as due to bulging of the top of the salt plug and as resulting from solution of the flanks. There is little evidence of lateral intrusion of the salt; on the contrary, the flanks are usually so well defined and steep as to suggest that intrusion was nearly vertical. Variations in the steepness of the flanks on different sides of the salt plug have led to the inference that the salt plugs are slightly tilted, but solution may also be involved here. At many of the salt domes in the southern area the steepest side of the salt plug is the side away from the Gulf of Mexico.
Collapse is evident in the sediments overlying many salt plugs, such as Chestnut, La. (Lahee, 1931), and Clay Creek, Tex. (Lahee, 1931A; Goldman, 1931), and apparently is due either to subsidence, solution of the salt, or both. Faulting has been active in the salt at some plugs, for example at Jefferson Island, where there are very abrupt changes in the depth to the salt over parts of the salt table, and at Boggy Creek (McLellan, Wendlandt, and Murchison, 1932).

The sediments into which the salt has been intruded are very much deformed and displaced, particularly at the shallow salt domes. The zone of sediments affected by intrusion of the salt is very limited, however, and at distances of several hundred feet, or a few thousand feet at most, the regional dip prevails. Adjacent to the flanks, the sediments dip away from the salt plugs at high angles. Displacements of thousands of feet have occurred in some instances, bringing beds far up from their normal stratigraphic position. "Rim synclines" are thought to be present at a few of the salt domes (Ritz, 1936). These structures, synclinal areas in the sediments peripheral to the salt plug, are thought to reflect structure in the source beds of salt, or to have resulted from solution of the flanks (Barton, 1933; Ritz, 1936). Deformation is less intense at the deep-seated salt domes, structures that are similar in conformation to ordin-
ary salt domes but where salt has not been discovered, although its presence is indicated by geophysical and other data. At some of these deep-seated salt domes, sets of radial and peripheral faults, of the type that would be expected to result from upthrust, have been encountered in drilling.

Water circulation at salt domes is of particular interest in a consideration of the origin of cap rock. The areas in which the salt domes occur are characterized by artesian conditions; saline and "sour" water springs occur at many of the more shallow ones. These springs probably form where the intruded salt plug intersects an aquifer bearing fresh water. This fresh water passes up the side of the salt plug, taking salt into solution, and gains the surface by following a fault or a steeply dipping stratum. Upward moving salt-dome waters are responsible for the false cap rock or zone of secondarily cemented sediments immediately overlying the cap rock, or salt, where cap rock is absent. The leached condition of the unconsolidated sediments close to the flanks of the salt plugs is probably due to the upward movement of ground water. The leached condition of these sediments has been called to the writer's attention by Mr. J. B. Garrett, Jr., Paleontologist, Stanolind Oil and Gas Co., Houston, Tex., who also referred to the salt minerals in sediments close to the flank, noted by the writer in samples from Darrow salt dome, Louisiana.
contain water-insoluble residue minerals from the salt. The "sour" waters are associated with the cap rock, and will be discussed under the geology of cap rock.

The geothermal gradient at salt domes is also of interest in connection with cap rock problems. Hawttof (1930) found that temperatures are somewhat greater at all salt domes than they are away from these structures. He found that the increase in temperature is more rapid above the salt plug and at the flanks than it is within the salt plug. This condition is thought to be due in part to ascending waters. The temperature data for a number of salt domes and salt-dome "prospects," are presented in table I. These figures show that at the shallow salt domes a temperature of 212° F. (100° C.) is reached at a depth of about 8,000 feet and indicate that a temperature higher than the melting point of sulphur orthorhombic (235° F. or 112.8° C.) will be encountered at about 10,000 feet. The high temperature at Clay Creek is attributed to waters brought up along a fault and shows the possibilities of relatively high temperatures in the cap-rock zone at shallow salt domes.

The forces which have caused intrusion of the salt in the Gulf Coast, and its behavior during intrusion, must be inferred from the structure of the salt and the associated sediments, from comparison with other occurrences, and from experimental data. The most plausible explanation seems to be that inception of movement was due to tectonic forces and
<table>
<thead>
<tr>
<th>Locality</th>
<th>Well Depth (Ft.)</th>
<th>Reading Temp* (F.)</th>
<th>Extrapolation to 212° F. Min. Depth (Ft.)</th>
<th>Max. Depth (Ft.)</th>
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<tr>
<td>Abbeville, La.</td>
<td>8,000</td>
<td>148°</td>
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<td>Bel, Allen Parish, La.</td>
<td>7,400</td>
<td>156°</td>
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<tr>
<td>Blue Ridge, Tex.</td>
<td>2,900</td>
<td>123°</td>
<td>5,300</td>
<td>3,100</td>
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<td>(d)</td>
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<td>Boggy Creek, Tex.</td>
<td>4,900</td>
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<td>6,000</td>
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<td>(e)</td>
<td>2,029</td>
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<td>Clay Creek, Tex.</td>
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<td>Damon Mound, Tex.</td>
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<td>Grand Saline, Tex.</td>
<td>875</td>
<td>83°</td>
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<td>121°</td>
<td>3,200</td>
<td>8,600</td>
</tr>
<tr>
<td>(f)</td>
<td>6,399</td>
<td>146°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intracoastal City, La.</td>
<td>10,577</td>
<td>154°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(g)</td>
<td>12,134</td>
<td>225°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jefferson Island, La.</td>
<td>8,340</td>
<td>180°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(d; e)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Point, Tex.</td>
<td>3,300</td>
<td>129°</td>
<td>3,600</td>
<td>8,000</td>
</tr>
<tr>
<td>(e)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pierce Junction, Tex.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(g)</td>
<td>8,000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tepetate, La.</td>
<td>3,000</td>
<td>146°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(h)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winnfield, La.</td>
<td>811</td>
<td>72°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
TABLE I (con't.)

(a) Continental Oil - Hebert No. 1, data from Max Hornhauser, Lafayette, La.

(b) Humble Oil & Refining Co. - Bel Estate No. 2, data from Olin G. Bell, Houston, Tex., and Dean Metts, Roanoke, La. (Temperatures after cementing; first figure at 45 3/4 hours, and second at 51 1/4 hours.)

(c) Data from Ferguson and Minton (1936).

(d) Data from Spicer (1936).

(e) Data from Hawtof (1930).

(f) Stanolind-Stovall No. 1, data from R. B. Grigsby, Lake Charles, La.

(g) Data from Deussen and Guyod (1937).

(h) Data from J. Runer, Jr., Louisiana Geological Survey (temperature in salt mine).
that continuation of movement was aided by pressures result-
ing from the constantly increasing weight of overlying sediments. Comparison with the occurrences in Germany where there is every gradation of structural conditions from the relatively undisturbed bedded deposits, through anticlinal folds, to the salt domes of the "North German Basin," show the importance of both folding or displacement and load. The influence of folding or displacement is indicated by the anticlinal form of such structures as that at Boggy Creek, Tex., the very close association of some of the salt domes, as for example Old Hackberry and East Hackberry, and such alignment and similarity in structure as at the Five Islands.

The geologic history of the intrusion of the salt plugs is difficult to piece together because of the great thickness of the sediments in which these bodies occur. It is not known when movement of the salt started or even if movement started at the same time for all of the salt plugs. The displacement of the salt is known to have affected strata as old as the Navarro of the Upper Cretaceous, and possibly the Glen Rose of the Lower Cretaceous (Barton, 1934B), in the coastal area, and the Lower Cretaceous in the northern area (Spooner, 1926). It is probable that the movement was periodic rather than continuous. There has been movement at some of the salt domes in comparatively recent
times. If the salt is Permian in age, it probably was affected by the world-wide tectonic disturbances that took place toward the close of Paleozoic time. Although there is little evidence of important tectonic disturbances in the Gulf Coast during Tertiary time, it seems probable that stresses of some magnitude must have accompanied formation of the steep-sided and very deep Gulf Coast geosyncline. At any rate, the heavy deposition of sediments throughout Tertiary and Quaternary time, particularly in the southern region, probably was a very important factor in the intrusion of the salt plugs.
The Salt
General Geology

Wherever cap rock is found it is definitely associated with a salt plug. The anhydrite part of the cap rock rests directly upon salt that is "mushy" and cavernous, the cavities being filled with brine and anhydrite sand, or less commonly, on hard and compact salt, the contact in such cases being sharp. This striking relationship between cap rock and salt must be taken into consideration in a study of cap rock. Therefore, the treatment of the geology and petrography of the cap rock will be preceded by a consideration of the mode of occurrence and character of the salt, with particular attention being given to water-insoluble material in the salt that might contribute to the formation of cap rock.

Rock salt obtained from mines and from wells in the salt plugs of the Gulf Coast is all of the same general character (Taylor, 1937). Most of it is very compact, although there are zones of "soft" salt in some of the mines. The salt from some of the well cores, and all of that in the mines, is composed of alternate bands of light- and dark-gray salt. The darker bands, termed "pencil-stripes" by the miners, have an average width of from one to four inches, attaining widths of as much as 18 inches, while the lighter-gray salt is in bands of somewhat greater width. The banding
is a very persistent feature, and in the mines, series of bands can be traced from room to room. They run virtually parallel to each other and have a nearly vertical attitude, although in mine rooms with high ceilings many of them can be traced upward to the apices of isoclinal folds. Overfolding and faulting are also shown by the bands. The salt of the darker bands contains somewhat more anhydrite sand than that of the lighter ones, and there seems little doubt that the bands are "year rings" formed in the original bedded salt. Their present intensely folded condition must have been brought about during intrusion of the salt from great depth. Bands of nearly pure anhydrite sand, such as the "slab" anhydrite at Winnfield (frontispiece), and of detrital sand, occur parallel to the other bands, but are discontinuous, as if pulled apart during intrusion.

Rock cleavage is developed along horizontal planes in the mines, and at angles of 45 degrees or greater in some of the well cores. Macroscopically, the salt is of granular appearance and is composed of interlocking elongate crystals of halite that average 1/4 to 1/2 inch in length. Some larger crystals are present, and many of them have curved faces with a sheared or fibrous appearance. Most of the crystals do not show a definite orientation, although they tend to align themselves parallel to the banding where the "soft" salt is in contact with the compact or "hard" salt.
Chemical Composition

The chief water-soluble mineral is, of course, halite. Potash salts have been identified chemically in salt from a number of salt domes, but only in minute amounts in most cases. A number of other elements have also been identified in chemical analyses of Gulf Coast rock salt.

Although complete chemical analyses have not been attempted during the present study, fairly detailed analyses have been obtained for the two Louisiana salt domes from which brine is being produced for industrial uses. These analyses are based upon composite samples of rock salt from well cores.

<table>
<thead>
<tr>
<th></th>
<th>Old Hackberry Salt Dome</th>
<th>Choctaw Salt Dome</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl</td>
<td>95.720%</td>
<td>97.710%</td>
</tr>
<tr>
<td>CaSO₄</td>
<td>3.950</td>
<td>2.140</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>0.140</td>
<td>none</td>
</tr>
<tr>
<td>CaCO₃</td>
<td>none</td>
<td>----</td>
</tr>
<tr>
<td>Li₂O</td>
<td>0.030</td>
<td>0.064</td>
</tr>
<tr>
<td>MgCl₂</td>
<td>0.008</td>
<td>none</td>
</tr>
<tr>
<td>MgSO₄</td>
<td>----</td>
<td>0.036</td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>----</td>
<td>0.046</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.012</td>
<td>0.005</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>----</td>
<td>0.004</td>
</tr>
</tbody>
</table>
Calcium sulphate is present both as anhydrite and in solution. A trace of barium has been found in salt from Winnfield.

In general, it can be said that the chemical composition of rock salt from the Gulf Coast is much the same as that from other regions, a composition such as would be expected for salt deposited by the evaporation of sea water. (For analyses of salt from other regions and of sea water, refer to Clarke, 1924.)

**Insoluble Residues**

The salt is of interest in the present study particularly in connection with the amount and character of the water-insoluble residue that it might contribute to the formation of cap rock. Analyses of samples from 21 Gulf
Coast salt plugs show that the residue from the salt of the different salt plugs, and from different parts of the same salt plug, varies in amount from less than one percent to nearly 90 percent. The weight percentage of water-insoluble, or slightly soluble, residue was determined for rock salt samples dissolved in a slight excess of distilled water, and the averages for each salt plug studied are present in table II. With respect to light and dark bands, the former contain one to three percent of residue, and the latter 4 to 15 percent. The greatest amount of residue is found in the broad dark bands and in the "slabs" or lenses of anhydrite sand. (frontispiece).

The residues are composed almost entirely of anhydrite grains ranging from submicroscopic size to 14 mm. in maximum dimension, except in the case of residues of quartz sand. Most of the anhydrite grains are of very fine to coarse sand size (16 mm. to 1 mm.). In the mines certain zones or series of bands have been noted that carry anhydrite predominantly of fine sand size while others are characterized by larger anhydrite grains. Quartz sand is a much less common inclusion than the disseminated anhydrite grains, but has been found in all of the mines and in several well cores.

For a more detailed treatment of this subject, see Taylor (1937).
<table>
<thead>
<tr>
<th>Salt Dome</th>
<th>Sample Number</th>
<th>Description of Rock Salt Sample</th>
<th>Weight Percentage of Water-Insoluble Residue in Salt Plugs Studied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anse La Butte</td>
<td>1</td>
<td>Stanolind Oil - Patin No. 1, 4,601-4,603 feet; bluish gray, nearly colorless</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Stanolind Oil - Patin No. 1, 4,641-4,643 feet; gray, loosely compacted</td>
<td>2.8</td>
</tr>
<tr>
<td>Avery Island</td>
<td>1</td>
<td>E. part of mine; light and dark gray banded</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>N.E. part of mine; light and dark gray banded</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>S.E. part of mine; light and dark gray banded, chiefly dark gray</td>
<td>7.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>E. part of mine; light gray band with H²S odor</td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>S.S.E. part of mine; light and dark gray banded</td>
<td>3.5</td>
</tr>
<tr>
<td>Bayou Bleu</td>
<td>1</td>
<td>Standard Oil - Wilbert's and Son No. 6, 2,307-2,825 feet bluish gray, compact</td>
<td>0.8</td>
</tr>
<tr>
<td>Choctaw</td>
<td>1</td>
<td>Solvay Process - No. 1, 657-1,064 feet; composite sample, powdered</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Solvay Process - No. 1, 1,065-1,448 feet; composite sample, powdered</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Standard Oil - Wilbert's Myrtle Grove No. 1, 2,566-2,575 feet; gray, granular</td>
<td>3.9</td>
</tr>
<tr>
<td>Darrow</td>
<td>1</td>
<td>Humble O. &amp; R. - Community No. 5, 5,448-5,456 feet; gray, granular</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Humble O. &amp; R. - Community No. 9, 5,633-5,638 feet; bluish gray, granular</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Humble O. &amp; R. - Community No. 9, 5,674-5,684 feet; bluish gray, granular</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Humble O. &amp; R. - Community No. 13, 5,672-5,682 feet; bluish gray, granular</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Rio Bravo Oil - Gumbel No. 1, 6,035-6,041 feet; gray, granular, compact</td>
<td>7.0</td>
</tr>
<tr>
<td>E. Hackberry</td>
<td>1</td>
<td>Stanolind Oil - Gulf Farm No. 21B, 6,946-6,965 feet; small colorless crystals</td>
<td>0.5</td>
</tr>
</tbody>
</table>
### TABLE II (cont.)

**Weight-Percentage of Water-Insoluble Residue in Salt Plugs Studied**

<table>
<thead>
<tr>
<th>Salt Dome</th>
<th>Sample Number</th>
<th>Description of Rock Salt Sample</th>
<th>Weight Per Cent Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. Hackberry</td>
<td>2</td>
<td>Gulf Production - Erwin &quot;A&quot; No. 22, 6,201-6,206 feet; light gray, granular</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Gulf Production - Erwin &quot;A&quot; No. 23, 5,500-5,505 feet; gray, granular (methane gas)</td>
<td>6.4</td>
</tr>
<tr>
<td>Garden Id. Bay</td>
<td>1</td>
<td>Texas Co. - State No. 7, 2,107-2,117 feet; small colorless crystals</td>
<td>1.6</td>
</tr>
<tr>
<td>Jefferson Id.</td>
<td>1</td>
<td>S.W. part of mine; yellow, oil-stained, flecked with gray</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>N.W. part of mine; bluish gray, nearly transparent, coarsely crystalline</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>E. part of mine; bluish gray, compact</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>S.E. part of mine; brown, granular, loosely compact</td>
<td>1.8</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>N.E. part of mine; gray, flecked with dark gray</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Jefferson L. Oil - State No. 151; bluish gray, granular, well compacted</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Jefferson L. Oil - State No. 230, 888-893 feet; dark gray</td>
<td>12.6</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Jefferson L. Oil - State No. 238, 867-874 feet; dark gray</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Jefferson L. Oil - State No. 264, 903-913 feet; dark gray with narrow bands</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Jefferson L. Oil - State No. 272, 820-824 feet; dark gray, banded</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Jefferson L. Oil - State No. 296, 884-890 feet; dark gray</td>
<td>12.5</td>
</tr>
<tr>
<td>Jennings L. Hermitage</td>
<td>1</td>
<td>Humble O. &amp; R. - State No. 1, 4,013 feet; light gray, granular, compact.</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Humble O. &amp; R. - State No. 1, 4,013-4,276 feet; gray, with knots of anhydrite sand</td>
<td>3.4</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Humble O. &amp; R. - State No. 1, 4,276-4,283 feet; gray, with stringers of anhydrite</td>
<td>4.0</td>
</tr>
</tbody>
</table>
### TABLE II (cont.)

Weight-Percentage of Water-Insoluble Residue in Salt Plugs Studied

<table>
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<tr>
<th>Salt Dome</th>
<th>Sample Number</th>
<th>Description of Rock Salt Sample</th>
<th>Weight Per Cent Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>L. Washingtion</td>
<td>1</td>
<td>Freeport Sulphur - Cockrell &amp; Moran No. 7, 1,588-1,589 feet; light gray, granular</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Freeport Sulphur - Cockrell &amp; Moran No. 59, 1,580-1,711 feet; light gray, granular</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Freeport Sulphur - Cockrell &amp; Moran No. 61, 1,630-1,680 feet; gray, granular, compact</td>
<td>4.1</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Freeport Sulphur - State No. 1,035, 1,650 feet; bands of anhydrite sand</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Freeport Sulphur - Misc.; gray, with patches of anhydrite sand</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Humble O &amp; R. - State No. 2, 1,807-1,850 feet; light gray, granular, loosely compacted</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Humble O. &amp; R. - Cockrell &amp; Moran No. 23, 4,780-4,783 feet; light gray, granular</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Humble O. &amp; R. - Cockrell &amp; Moran No. 23, 4,789-4,809 feet; gray, granular</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Humble O. &amp; R. - Cockrell &amp; Moran No. 23, 4,809-4,834 feet; gray anhydrite sand incl.</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>Humble O. &amp; R. - Cockrell &amp; Moran No. 23, 4,860-4,867 feet; gray, granular compact</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>Humble O. &amp; R. - Cockrell &amp; Moran No. 23, 4,933-4,938 feet; gray, with anhydrite sand</td>
<td>11.9</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>Humble O. &amp; R. - Cockrell &amp; Moran No. 23, 4,933-4,938 feet; light gray, granular</td>
<td>3.9</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>Humble O. &amp; R. - Cockrell &amp; Moran No. 23, 5,048-5,053 feet; light gray, granular</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Humble O. &amp; R. - Cockrell &amp; Moran No. 23, 5,213-5,252 feet; bluish gray, granular</td>
<td>1.8</td>
</tr>
<tr>
<td>Sikes</td>
<td>1</td>
<td>Ohio Oil - Rollin No. 1, 4,145 feet; gray, with vertical bands of anhydrite sand</td>
<td>7.2</td>
</tr>
</tbody>
</table>
TABLE II (cont.)

Weight-Percentage of Water-Insoluble Residue in Salt Plugs Studied

<table>
<thead>
<tr>
<th>Salt Dome</th>
<th>Sample Number</th>
<th>Description of Rock Salt Sample</th>
<th>Weight Per Cent Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur</td>
<td>1</td>
<td>Union Sulphur - miscellaneous, light gray, compact, flecked with dark gray</td>
<td>4.0</td>
</tr>
<tr>
<td>Venice</td>
<td>1</td>
<td>Tidewater Oil - Manhattan Fruit No. 1, yellow, oil-stained</td>
<td>4.0</td>
</tr>
<tr>
<td>Weeks Island</td>
<td>1</td>
<td>N.E. part of mine; granular, bluish gray, flecked with gray impurity</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>N.E. corner of mine; nearly colorless, with gray flecks</td>
<td>2.6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Tailings; gray, &quot;soft salt&quot; banded with anhydrite sand</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>N.W. part of mine; dark, brownish gray &quot;hard salt&quot; (methane gas)</td>
<td>24.0</td>
</tr>
<tr>
<td>White Castle</td>
<td>1</td>
<td>Shell Oil - Shingle No. 1, 5,041-5,056 feet; nearly colorless, granular</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Shell Oil - Shingle No. 2, 5,211-5,215 feet; gray, granular, fairly well-compacted</td>
<td>2.5</td>
</tr>
<tr>
<td>Winnfield</td>
<td>1</td>
<td>Mine sample; banded light and dark gray, granular and compact</td>
<td>8.7</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>From near shaft; gray &quot;soft salt,&quot; gray, with bands of coarse anhydrite sand</td>
<td>29.3</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Mine sample; bluish gray, coarsely crystalline &quot;hard salt&quot;</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Mine sample; dark gray, banded, &quot;hard salt&quot;</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>&quot;Slab&quot; anhydrite from lens in &quot;hard salt&quot;</td>
<td>31.8</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Series of 25 samples of salt as mined, ranging from 0.3 to 8.0 per cent, average</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Series of 25 samples of salt as mined, ranging from 0.1 to 8.0 per cent, average</td>
<td>1.7</td>
</tr>
<tr>
<td>Hoskins, Tex.</td>
<td>1</td>
<td>Freeport Sulphur - Hoskins Mound No. 365, 2,060 feet, bluish gray, granular, compact</td>
<td>4.2</td>
</tr>
<tr>
<td>Lamar, Miss.</td>
<td>1</td>
<td>Sun Oil - Scanlan &amp; Semmes No. 1, 2,524-2,543 feet; gray, vertical bands of anhydrite sand</td>
<td>19.5</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Sun Oil - Scanlan &amp; Semmes No. 1, 2,524-2,543 feet; light gray to bluish gray</td>
<td>3.2</td>
</tr>
</tbody>
</table>
TABLE II (cont.)

Weight-Percentage of Water-Insoluble Residue in Salt Plugs
Studied

<table>
<thead>
<tr>
<th>Salt Dome</th>
<th>Sample Number</th>
<th>Description of Rock Salt Sample</th>
<th>Weight Per Cent Residue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamar, Miss.</td>
<td>3</td>
<td>Sun Oil - Scanlan &amp; Semmes No. 1, 2,564-2,583 feet; gray, with bands of anhydrite sand</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Sun Oil - Scanlan &amp; Semmes No. 1, 2,564-2,583 feet; bluish gray, faintly banded</td>
<td>0.5</td>
</tr>
</tbody>
</table>
It occurs in lenses of considerable extent that parallel the bands, as angular fragments, one to two or three inches in diameter, scattered through the salt, and as disseminated grains. Gas, seeps of brine and petroleum, pebbles of argillaceous and of siliceous sandstone, gray shale, and black, oil-soaked shale, also are known to occur in the salt. In the mines, the gas and brine move upward along the bands, particularly the bands containing a large amount of anhydrite sand, and locally are under enough pressure to cause "blowouts." The oil, and in some instances the gas and brine, occur in small pockets. An analysis of gas from salt of the Lake Hermitage salt plug is as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>2.8%</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>0.0%</td>
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<tr>
<td>Helium</td>
<td>0.0%</td>
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<tr>
<td>Nitrogen (by difference)</td>
<td>97.2</td>
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<tr>
<td></td>
<td>100.0%</td>
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</table>

(This analysis was made at the U. S. Bureau of Mines Cryogenic Laboratories, Amarillo, Tex., and is published by permission of the Director of the Bureau of Mines.)

Methane and hydrogen sulphide gases have also been encountered in the salt, in very small quantities.

Small inclusions of gas and liquid have been found within individual halite crystals from the salt plugs, although they are apparently less common than in salt from some
of the bedded deposits. Microscopic capillary tubes, typical of rock salt, are illustrated in plate III, fig. 2. From their character, and the manner in which they occur, the liquid and gas inclusions appear to be connate, i.e., sealed in the salt at the time of its deposition from sea water.

The average amount of residue in an individual salt plug, or in salt plugs in general, is difficult to estimate because of the lack of uniformity in residue content. Such data as are available, however, indicate that the amount suggested by Hanna (1934), 5 to 10 percent, is reasonably accurate for the Gulf Coast in general, but that considerable portions of some salt plugs contain at least twice this amount. This is about the same as has been given for the salt plugs of the "North German Basin" by Lachmann (1910) and others.

The Minerals

The water-insoluble residues, which represent the less soluble constituents that crystallized from solution at the time of salt deposition, contain a number of other minerals in addition to the chief constituent, anhydrite. These minerals, together with the anhydrite, will be described briefly, in the order of their abundance. Table III is a check list of the more common of these minerals.
### TABLE III

Check List of Minerals in the Water-insoluble Residues of the Salt Plugs Studied

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<tbody>
<tr>
<td>Anhydrite</td>
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<td>Dolomite</td>
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<td>Pyrite</td>
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<td>Quartz</td>
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<td>Wacanite</td>
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<td>Kaolinite</td>
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<td>Other Inclusions</td>
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<tr>
<td>Potash Salts</td>
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<td>Oil</td>
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<tr>
<td>Gas</td>
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<tr>
<td>Quartz Sand</td>
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</tbody>
</table>
Anhydrite (CaSO₄). This mineral, which constitutes 99 percent of most of the residues, occurs as tabular grains, that are either subhedral crystals or cleavage fragments, ranging in size from submicroscopic to unusual ones as much as 14 mm. in maximum dimension, the greater part being of fine to coarse sand size. "Stem shaped" subhedral to euhedral crystals are also present, and fairly common in some residues. Inclusions in the anhydrite consist of smaller anhydrite grains, quartz, pyrite, dolomite, sulphur, gas, liquid, and carbonaceous matter. In some cases, anhydrite grains containing inclusions of black carbonaceous matter occur in sufficient abundance to make the salt a very dark gray. The anhydrite grains in the more impure salt are smaller than those in the salt containing a small amount of residue, and many are etched and worn as if having been subjected to solution. Traces of barium and strontium are present in some of the anhydrite. Typical anhydrite grains are illustrated in plate I, fig. 1 and 2 and plate XXVI, fig. 1.

In order to determine the manner in which the anhydrite and other residue minerals occur in the salt, a number of thin sections of the salt were examined. It was found that the anhydrite grains occur within the individual salt crystals, apparently in the same way that they were originally precipitated. The anhydrite and the other less soluble minerals are scattered throughout all of the rock salt, with a
greater concentration along the dark bands (pl. IV, fig. 1). They show a tendency to orient themselves parallel to the banding in the areas where they are more concentrated, and some of the grains appear to have been crushed, with the resulting cleavage fragments forming trains that parallel the bands (pl. IV, fig. 1). Along the irregular discontinuous shear zones in the salt, the included anhydrite grains have been displaced along with the salt (pl. III, fig. 2).

**Dolomite** (Ca, Mg\([\text{CO}_3]\)). All of the residues contain this mineral, and some of those from Choctaw, Jefferson Island, Weeks Island, and Lake Washington contain as much as several percent, chiefly as well developed rhombonedral crystals with a characteristic nucleus of opaque substance, white by reflected light. Intergrown aggregates of crystals are common, and some of the crystals are intergrown with anhydrite, pyrite, quartz, and also, at Choctaw, with danburite crystals. In some crystals the positive rhombohedron is modified by the base and the negative rhombohedron, resulting in a hexagonal outline in extreme cases. The crystals vary from colorless to deep orange or pale brown; they range in size from 0.1 mm. to 1.0 mm. Plate I, fig. 4, and Plate II, fig. 5 are photomicrographs of several crystal forms.

**Calcite** (Ca\(\text{CO}_3\)). This carbonate is much less common than dolomite, but is also found in all of the residues.
It is present in the form of rhombohedrons, scalenohedrons, and irregular grains, of about the same size as the dolomite. Most of the grains are colorless, although yellow- or brown-tinted crystals are common in certain of the residues. Plate II, fig. 6A includes photomicrographs of the scalenohedral form.

Pyrite (and Marcasite) FeS₂. Crystals of this mineral, in a variety of forms, occur sparingly in all of the residues. Some grains are irregular and some occur as encrustations on other minerals. Grains vary from 0.05 mm. to 2.5 mm. in diameter.

Cock's-comb aggregates of marcasite, microscopic in size, occur in residues from two localities.

Quartz (SiO₂). Well developed individual crystals and rosettes of this mineral are found in all of the residues of appreciable size. The rosettes are very distinctive in appearance, containing a nucleus of finely divided white substance, very like that in the rhombs of dolomite. Inclusions of anhydrite are common in both the rosettes and the crystals; black, carbonaceous matter likewise occurs as an inclusion. The quartz crystals and rosettes are of the same size as the dolomite crystals. Typical ones are illustrated by photomicrographs in plate I, fig. 3.

Limonite (Fe₂O₃·nH₂O). Minute grayish-brown to brownish-black submetallic crystals, apparently pseudomorphs
after pyrite, have been identified as limonite on the basis of microchemical tests. They occur sparingly in many of the residues. One of them is shown in plate II, fig. 6 B.

**Hematite (Fe₂O₃).** Minute reddish-brown hexagonal and irregular flakes of this mineral occur in several of the residues.

**Hauerite (MnS₂).** The identification of hauerite has also been made with the aid of microchemical tests. It is present in several residues as flat pseudo-hexagonal or octahedral reddish-brown to brownish-black submetallic crystals, and as a cementing material between aggregates of anhydrite grains. The grains range in maximum dimension from 0.05 mm. to 1.0 mm. A typical form is shown in plate II, fig. 6 B.

**Sulphur.** Irregular, and some subhedral, grains of sulphur are fairly common in a few of the residues. The grains are all quite small, 0.3 mm. or less in diameter, and vary from yellow to greenish yellow in color. Their distribution is very irregular, as they may be comparatively abundant in salt from one part of a salt plug, and absent or rare in salt from other parts.

**Celestite (SrSO₄).** This sulphate has been found in salt from Hoskins Mound, Tex., and Weeks Island, Lake Washington, and Sulphur, La. At the first three localities it occurs in divergent subparallel groups of tabular crystals,
and at Sulphur it is present in highly modified forms of subspherical shape. These last crystals are filled with inclusions of sulphur and anhydrite. The crystals vary from 0.2 mm. to 3.0 mm. in maximum dimension. Identification was made on the basis of optical properties and checked by the flame test for strontium. The two forms of the crystals are shown in plate II, fig. 1 and 2.

**Barite (BaSO₄).** Tabular, thin, nearly square crystals of this mineral, as much as 2.0 mm. on a side, are fairly common in residues of Winnfield salt, particularly the "soft" salt, and also have been found in residues of Jefferson Island salt. The crystals are colorless, transparent to translucent, and have inclusions of anhydrite grains. Plate I includes a photomicrograph of several crystals.

**Kaolinite (H₄Al₂Si₂O₇).** Minute, very thin hexagonal plates of a colorless mineral have been identified as this hydrous aluminum silicate on the basis of optical and physical properties.

**Gypsum (CaSO₄·2H₂O).** A few crystals of the selenite variety of gypsum occur in a Choctaw residue, and some were also found in one Winnfield residue. These are the only residues in which the hydrous form of CaSO₄ has been found, and there is a decided possibility that it was formed secondarily in these two cases. It probably did not occur in either of the original samples, as the Choctaw residue was
subjected to weathering for several months, and the Winnfield residue was from "slab" anhydrite that had been allowed to remain in distilled water for several weeks because its compactness made it difficult to break down.

**Magnesite (MgCO$_3$).** Residues from two Choctaw wells contain well-developed elongate hexagonal prisms, which have been identified as magnesite on the basis of their refractive indices and their complete insolubility in 1:1 HCl. The crystals are colorless and vary in length from 0.1 mm. to 3.0 mm. The presence of these rare crystals is one of the distinctive features of the Choctaw residue. They are illustrated in plate II, fig. 4.

**Danburite [Ca$_5$2(SiO$_4$)$_2$].** The occurrence of this unusual mineral in residues from two Choctaw wells is another striking feature of the salt from this locality. The crystals are slender colorless prisms, having lengths of as much as 3.0 mm.; many occur in divergent subparallel groups. Plate III, fig. 1, is a photomicrograph of some of them.

**Kilgardite [Ca$_9$(BeO)$_3$Cl$_4$.4H$_2$O].** This new mineral species forms about one percent of the residue from a Choctaw well. It occurs as good crystals, tabular and hem-

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Data for this mineral and a description of the residue in which it occurs are given in "Kilgardite, a New Mineral Species from Choctaw Salt Dome, Louisiana," by R. E. Taylor, in the Am. Mineralogists, vol. 10, pp. 1052-1057 (1937).
Imorphite, which belong to the monoclinic system, with a maximum dimension ranging from 0.5 mm. to 15.0 mm. A crystal of this mineral is illustrated in plate II, fig. 3.

Boracite (Mg7Cl2B16O30). A fourth mineral found only at Choctaw is boracite. It occurs as small pseudocubic crystals with internal radial structure, two of which are illustrated in plate II, fig. 6 C.

Sand Inclusions

The inclusions of quartz sand are also of interest in connection with the origin of cap rock, as lenses of detrital sand have been reported in the anhydrite cap rock (Goldman, 1926, 1933; Teas, 1931). Petrographic analyses of thin sections and of washed and treated samples have been made of the red sand inclusions from the mines at Avery Island and Jefferson Island. The sands from these two localities are strikingly similar. They are essentially poorly sorted feldspar-free quartz sands, containing somewhat less than one percent by weight of heavy minerals (pl. IV, fig. 2 and 3, and pl. V, fig. 1 and 2). The cementing material is halite, associated with appreciable amounts of clay. Small dolomite-cemented areas are also present (pl. V, fig. 1). The red color is due to a coating of iron oxide on the grains and to small flakes of hematite in the halite cement. Brine resulting from solution of the cement gave a strong potash
reaction when tested chemically. The quartz grains are characterized by inclusions of rutile and tourmaline, and the larger ones are well rounded. The heavy separates are dominated by an assemblage of the more resistant minerals, chiefly leucoxene and ilmenite, zircon, tourmaline, and rutile. Varying amounts of magnetite, hematite and limonite are also present. Anhydrite grains are found in the heavy separates, but they are not common.

An inclusion of red sand from the salt plug at New Iberia salt dome differs from these sands in that it contains several percent of feldspar, volcanic glass, and a less varied tourmaline assemblage. Gray sand from within the salt at Jefferson Lake Oil Co. well No. 245, Jefferson Island salt dome, is quite like the sand of the inclusions from the salt mines, differing only in color, slightly higher clay content, and the presence of more anhydrite sand. The gray sandstone pebbles from Choctaw have an argillaceous matrix and in a few cases are cemented by silica, but mineralogically they closely resemble the other inclusions.

Geochemistry of Salt Deposition

The data which have been presented bear out the similarity in chemical composition between Gulf Coast rock salt (including both water-insoluble and soluble constituents) and the soluble salts in normal sea water. As a result of experimental work on the evaporation of sea water (see
Grabau, 1920; Clarke, 1924; and Twenhofel, 1932), and the study of salt deposits, particularly those of Germany (Vant Hoff, 1909), the character of the salts and the conditions under which they were deposited are fairly well known. An interpretation of the Gulf Coast rock salt in the light of this knowledge is of value in the present study because of the bearing it has on the development of the salt minerals.

Normal sea water has been the subject of many detailed studies because most of the extensive deposits of rock salt have been explained as forming through its evaporation. About 3.5 percent, by weight, of normal sea water is composed of soluble salts, consisting chiefly of the elements chlorine and sodium, with some oxygen, magnesium, sulphur, calcium, potassium, carbon and bromine also present. In addition, traces of the following elements have been found: iodine, fluorine, nitrogen, phosphorus, arsenic, silicon, boron, lithium, rubidium, cesium, barium and strontium, aluminum and iron, manganese, nickel and cobalt, copper, zinc, lead, silver, gold, and radium (Clarke, 1924; Twenhofel, 1932).

The evaporation of normal sea water, or of solutions of similar composition, results in the precipitation of iron oxide, calcium and magnesium carbonates, calcium sulphate, sodium chloride, and a number of simple and complex
compounds of magnesium and potassium. These compounds are listed in the order of their deposition, which is the reverse of the order of their solubilities. During evaporation, sea water behaves as a polyphase system, and the times of crystallization for the different phases overlap. Thus, when the concentration for the maximum crystallization of NaCl is reached, CaSO₄ continues to crystallize slowly, after its maximum crystallization point has been passed.

Temperature is an important factor in the crystallization of some compounds, and the crystallization of certain salts is aided by the presence of other salts. CaSO₄ is precipitated as the mineral anhydrite when the solution is near saturation for sodium chloride and the temperature is above 25°C (77°F; some place this temperature at 30°C or 86°F; see Grabau, 1920), while gypsum is deposited at lower temperatures and at lower concentrations of NaCl.

The order of crystallization has been modified in the case of most salt deposits by periodic changes in concentration and temperature. The dark bands or "year rings" of the Gulf Coast salt, in which anhydrite grains are concentrated, are due to changes in these conditions, probably reflecting seasonal changes in temperature, accompanied at the time of increased anhydrite crystallization by influx of fresh water.

During the stage at which anhydrite is the principal mineral being precipitated, it is deposited as minute cry-
stals. However, when the maximum stage of crystallization has passed and sodium chloride is the chief precipitate, growth of crystals takes place more slowly, and the crystals grow larger. The results are evident in the final product. Where anhydrite occurs as disseminated grains in the salt, it is in the form of relatively large crystals, in somewhat smaller crystals where it is concentrated in "slabs" or lenses in the salt, and in very small crystals in thick-bedded deposits of primary anhydrite.

Dolomite also crystallizes from evaporating sea water, but the conditions necessary for this are not well known (Twenhofel, 1932). It is known, however, that the point of maximum crystallization for dolomite is reached before that of either CaSO₄ or NaCl. Apparently, from the manner in which it occurs in the salt, dolomite is also being precipitated when the solution is concentrated for NaCl, and its crystallization is aided by the presence of substances that can act as nuclei. Further, precipitation of the double carbonate, dolomite, seems to be favored over that of the separate carbonates of magnesium and calcium when sea water is concentrated for NaCl, for dolomite is by far the most common carbonate in the salt residues. That the dolomite crystals formed slowly is borne out by the fact that many of them are zoned.

Most of the other minerals in the residues likewise
appear to have formed contemporaneously with the salt. The sulphates of strontium and barium crystallize during the same stage of evaporation as the anhydrite (Noll, 1934), although they are present only in very small quantities. Quartz also is a precipitate, and its presence in the crystalline form probably is accounted for by the fact that $\text{SiO}_3$ can exist in sea water in an ionized state, rather than in the colloidal state (Schwartz, 1934). When sea water becomes concentrated enough for precipitation of NaCl, a maximum concentration for $\text{SiO}_2$ seems to be reached, despite its presence in very small quantities. The boron minerals, from the manner in which they occur in the German deposits, are thought to appear during stages of evaporation somewhat later than that required for maximum NaCl precipitation.

The metallic sulphides and oxides, however, (excepting some of the iron oxide) do not owe their presence to precipitation from the evaporation of normal sea water. The occurrence of the sulphides of iron and manganese indicates that reducing conditions must have been present throughout all but the final stages of evaporation, although the preponderance of sulphates over sulphides shows that conditions of oxidation must have been dominant in all except very localized areas, probably the deeper waters. The presence of the iron oxides, and particularly of limonite as pseudomorphs after pyrite, is evidence that reducing conditions were not
persistent, even locally, but were followed by conditions of oxidation that have continued to exist in the salt since the time of deposition.

These minerals of the salt residues appear, therefore, to have been precipitated from sea water at the time of salt deposition. The precipitation of the anhydrite and dolomite as unusually large crystals can be explained as the result of their formation after the point of maximum crystallization for these minerals had been passed, hence they crystallized at a slower rate.

Summary

Rock salt in the salt plugs of Louisiana salt domes is of sedimentary origin and is similar in composition to that of other rock-salt deposits. The structure of the salt is similar to that of other salt-dome regions. Light- and dark-gray bands in the salt are arranged in isoclinal folds that were formed at the time of intrusion of the salt. Where cap rock is present, these folds are usually abruptly decapitated by the relatively flat "salt table." The salt is composed of interlocking grains of halite, 1/4 to 1/2 inch in diameter, that frequently show considerable shearing and recrystallization. The light- and dark-gray layers or "bands" apparently are "year rings" resulting from periodic changes
in conditions during salt deposition. This is indicated by the difference in their composition; the darker bands contain appreciably more grains of disseminated anhydrite. These anhydrite grains, as well as a number of much less abundant minerals, are contemporaneous in age with the salt, having been formed by precipitation from solution at the time that the salt was being deposited. These minerals are only very slightly soluble in water and hence constitute the water-insoluble residue of the salt. Anhydrite, as crystals and cleavage fragments ranging in size from fine to coarse, sand, comprises nearly 99 percent of these residues, associated with the following minerals, listed in order of abundance; dolomite, as rhombic crystals with distinctive nuclei, many of which are zoned; calcite; pyrite; quartz, as crystals and as rosettes with nuclei; limonite; hauerite; hematite; celestite; sulphur; barite; marcasite; kaolinite; magnesite; danburite; hilgardite; boracite; and possibly gypsum. The amount of these residues is quite variable, but probably averages from 5 to 10 percent for Gulf Coast salt in general, and is higher at a few of the salt domes. In different part of the same salt plug, the amount of residue may vary from less than one percent in the light bands, to nearly 90 percent in certain lenses ("slab" anhydrite). The salt also contains lenses and pockets of detrital sand, fragments of sandstone and shale, dissemin-
ated grains of detrital minerals, connate liquid (brine), petroleum, and gases (nitrogen, carbon dioxide, methane, and hydrogen sulphide).

The minerals of the water-insoluble residues are distinctive, and differ strikingly from those of other modes of occurrence. The grains in the residues are unusually large, particularly in the case of the anhydrite and dolomite. The unusual size of the grains or crystals of these minerals is not surprising, however, when it is considered that they crystallized from sea water at a stage in the evaporation when their rate of precipitation had passed the maximum point, hence they crystallized more slowly and grew to a larger size. Other distinctive features of the minerals in the residues are the nuclear and zoned rhombs of dolomite, the quartz rosettes with nuclei, and the perfection in crystal development of most of the minerals.

The detrital materials also appear to be distinctive, i.e., different from the sediments surrounding the salt plugs. Many of the sand and sandstone inclusions are red, and are composed of minerals resistant to weathering, chiefly quartz, with subordinate amounts of the iron oxides, of ilmenite and leucoxene, and of tourmaline, zircon, and rutile.

A condition of oxidation seems to have been dominant during and after salt deposition, although reducing conditions must have been locally present during the time of evaporation.
The Cap Rock
A study of cap rock must be based largely upon cores and data obtained in drilling wells, because in most cases the cap rock is rather deeply buried. The only surface outcrops known in the Gulf Coast are those at Winnfield and Pine Prairie, La., and at Gyp Hill, Tex., where only the upper parts are exposed. At a few salt domes, however, a large number of wells have been drilled in the cap rock in connection with the production of sulphur by the Frasch process. Use of this process involves the drilling of many 3- or 10-inch drill holes in order that superheated water can be pumped into the cap rock to melt the sulphur. The drill holes must be closely spaced because of the utter lack of uniformity of cap rock, and frequent coring is necessary. The cores taken are usually of sufficient size and closely enough spaced in depth to afford a good idea of the character of the cap rock encountered.

In the course of the present study, cores of this type were examined for some 100 wells at Lake Washington salt dome, and about the same number for the Jefferson Island salt dome. In addition, some cores were available from the following salt domes: Bayou Bouillon, Choctaw, Darrow, East Hackberry, Garden Island Bay, Lake Barre, Pine Prairie, Sorrento, Sulphur, White Castle, and Winnfield, La.; Big Hill (Matagorda County), Grand Saline, Hockley, and Hoskins Mound, Tex.; and Midway (Lamar County), Miss. Quarry samples
were obtained from Pine Prairie and Winnfield. All of the material was subjected to megascopic study and some 300 thin sections were examined with the aid of the petrographic microscope.

One hundred and seventy-five of the thin sections represent three wells, two at Lake Washington and one at Jefferson Island, for which fairly complete suites of core-samples are on file in the museum of the School of Geology, Louisiana State University. The remaining thin sections are of other material from these salt domes, and of material from the other salt domes listed.

The greater part of the thin sections are of cap rock from the anhydrite and the transition zones, but the calcite zone was also studied in some detail. Sulphur-bearing cap rock was given particular attention. A résumé of the petrographic analyses for the three more completely sampled wells is presented in appendix B, and photomicrographs of typical features in the thin sections from these three suites of cores, as well as of some of the other material thin-sectioned, are shown in plates III to XXVI.

Additional data concerning the cap rock have been obtained from the observation of drilling operations at Lake Washington and Jefferson Island, and from the study of drillers' logs. Samples of bedded anhydrite from central Florida, north Louisiana, and southeastern New Mexico, were
studied for purposes of comparison.

General Geology

Cap rock forms a mantle of rock, most of which is well indurated, and of variable thickness, that is found directly overlying the salt plug at many Gulf Coast salt domes. Its existence has been proved at more than 100 of the 138 known salt domes of this region, and at nearly all of the Louisiana salt domes. (See map, pl. XXVII.) Cap rock has not been found at all of the salt domes of north Louisiana, and has not been reported at several of the shallow salt domes and certain of those of intermediate depth in the southern part of the State, but further drilling probably will disclose its presence over at least a part of all except the deeper salt plugs. The most extensive and thickest development of the cap rock occurs at salt domes where salt is relatively near the surface, as for example at Drakes, Winnfield, Pine Prairie, Lake Washington, Black Bayou, and Sulphur, La., and Barbers Hill, Boling, Bryan Mound, Hockley, Hoskins Mound, Long Point, and Spindletop, Tex. Thick cap rock has been reported at considerable depth at East Hackberry and Caillou Island, but little is known about these occurrences. According to Sawtelle (1936), cap rock occurs at Hankamer, Tex., where top of salt is at a depth of 7,666 feet; at Esperson, Tex., top of salt 7,323 feet; at East
Bay Junop, top of salt 6,488 feet; and Gueydan, top of salt 5,751 feet. This deep cap rock is known only from well records.

The most important feature in the occurrence of salt-dome cap rock is its very definite relationship to the salt plug. Where it is well developed it shows virtually no relationship to the enclosing strata, other than the presence of the intervening false cap or calcite- or pyrite-cemented sediments, as at Lake Washington (fig. 1), East Hackberry, and other salt domes. Its geologic age is indeterminate because it is unfossiliferous and is associated with rocks that range in age from Lower Cretaceous to Recent. The associated rocks are in every case sedimentary, and are the products of a wide variety of environments, including those of continental, deltaic, brackish, and marine waters.

Considerable thicknesses of gumbo, or sticky, impervious clay, occur above the cap rock at Lake Washington and Jefferson Island. In the case of the latter dome, the gumbo, along with sands and silts, has filtered into the very much faulted and broken cap rock. Here there is evidence that the overlying sediments and the cap rock have suffered an appreciable amount of both collapse and upthrust. At Chestnut salt dome, some 2,500 feet of collapse has occurred, according to Moody (Lahee, 1931); Clay Creek salt dome has also been the scene of a considerable collapse, accord-
ing to Lahee (1931; also see Goldman, 1931). The tendency for cap rock to collapse is borne out by the manner in which an appreciable amount of subsidence has occurred at Sulphur, La., and Big Hill, Tex., following removal of sulphur. Doming of some 900 feet has apparently taken place in the sediments overlying the cap rock at Lake Washington (Howe and McGuirt, 1936 A), in sediments that carry a deep water Pliocene or Pleistocene fauna. The structure of the sediments at the sides of the cap rock is quite variable. In some instances they have about the same dip as those at the flanks of the salt plug, in others they show considerably more faulting, while in a few they are much less disturbed.

The area of the cap rock is limited by that of the salt plug with which it is associated. Typically, it covers the entire upper surface and extends down the flanks for considerable distances, as at Lake Washington (fig. 2), Calcasieu Lake, Old Hackberry, and other salt domes. In some instances, however, it is developed over only a part of the upper portion of the salt plug, as at Jefferson Island (fig. 3), Belle Isle, Côte Blanche, New Iberia, and White Castle. In most cases the thickest portion of the cap rock overlies the central part of the salt plug, although this is not the case at some salt domes, including Choctaw, Darrow, Vinton, and Gueydan, La., and Sugarland (McCarter and O'Bannon, 1933),
and Brenham (Burford, 1935), Tex. Where cap rock extends
down the flanks of the salt plug it is a relatively few feet
in thickness and in places is in a broken condition. 
Although almost everywhere limited to the area of the salt
plug, the cap rock may also "overhang," i.e., extend out bey-
ong the edge of the salt plug a short distance, as at Vint-
ton salt dome, La., and Allen salt dome, Tex. (Judson and
Stamey, 1933).

Where it is well developed, the main body of the cap
rock rests upon a comparatively flat salt surface, the "salt
table." However, at White Castle, East Hackberry and Cal-
casieu Lake, La. (Howe and McGuirt, 1935 A), Hoskins Mound
(Marx, 1936), and Brenham, tex. (Burford, 1935), and a few
other salt domes, the salt surface upon which the cap rock
lies is rounded or irregular. At most places where the con-
tact between salt and cap rock is known from drilling, there
are minor irregularities that are due to cavities in the
salt. Brine with associated anhydrite sand was encountered
at or near the contact during shaft sinking at Hockley, Tex.,
Winnfield, La. (Goldman, 1933), and Grand Saline, Tex.
(Hanna, 1934). When the contact is encountered in drilling
with rotary equipment at Jefferson Island and Lake Washi-
ngton, a cavity of from a few inches to several feet is found,
and "returns are lost," indicating that extensive cavities
or channels are present. Ordinarily, the first salt recov-
ered in coring is "mushy," and full of anhydrite sand. An-
hydrite sand has also been encountered next to the salt at
Belle Isle, Choctaw, Darrow, White Castle, Sorrento, Guey-
dan, and Calcasieu Lake, La., and according to Hanna (1934),
at Hockley, Lost Lake, and Hawkinsville, Tex. In a few wells
at some of these salt domes, and also in the shaft at Hockley,
Tex. (Teas, 1931), however, the cap rock has been found in
direct contact with solid salt. The presence at the salt-
anhydrite contact of cavities, and also of salt and anhy-
drite in direct contact, has led O'Donnell (1935) to suggest
that cap rock rests upon pinnacles or ridges of relatively
solid salt that are separated by channels through which the
water that effects solution circulates.

Teas (1931) has reported the presence of a small lens of
pure salt (this salt did not leave a residue on solution) in
the anhydrite at Hockley, 37.9 feet above the salt-anhydrite
contact. Goldman (1933) has noted that anhydrite from near
the salt-anhydrite contact at Hockley contains microscopic
cavities filled with salt. Specimens of anhydrite from near
the contact at Jefferson Island, Lake Washington, Lake Barre,
Bayou Bouillon, and Sorrento, contain sufficient salt to
made them hygroscopic when exposed to moist air.

Cavities are also common within the cap rock; their
occurrence has been discussed in some detail by Judson and
Stamey (1933) and Hanna (1934). These cavities are often
extensive, and series of them form channels through which water circulate. Water pumped into the Freeport Sulphur Co. No. 5 well, Lake Washington, at the time when sulphur mining was started was returned almost immediately through No. 7 well, over a quarter of a mile distant. The same company's No. 36 well had in excess of 2,000,000 cubic yards of mud pumped into it in an attempt to close off cavities, an amount far in excess of any that could be explained by removal of sulphur. The cavity encountered at the salt-anhydrite contact during sinking of the shaft at Winnfield, proved to have an outlet near the surface, for some of the grout forced into the cavity at the shaft appeared in a small seepage hole in the cap-rock quarry a quarter of a mile away. Ferguson and Minton (1936) report that the cap rock at Clay Creek salt dome, Tex., is very cavernous, and that analyses of salt water from two cap rock wells about a mile apart are so closely similar that there must be a connecting channel between the wells. Nearly all of the calcite cap rock which has been examined during the present study was found to be quite porous, and much of it distinctly cavernous. Hanna (1934) states that cavities comprise 50 percent of some cap

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7 Personal communication from J. Huner, Jr., who is preparing a report on the Geology of Winn and Caldwell parishes for the Louisiana Geological Survey.
rock, and Barton and Paxon (1925 B) consider that the cap rock at Spindletop has a porosity in excess of 33 percent, on the basis of the amount of oil produced.

Some of the saline springs occurring at the surface of the salt domes probably have found their way to the surface through cap-rock channels. The "sour" or hydrogen sulphide springs associated with salt domes have undoubtedly come from the cap rock. In fact, heavy flows of water accompanied by hydrogen sulphide gas have been encountered in the cap rock at Spindletop, Tex. (Barton and Paxon, 1925 B), Vacherie (Spooner, 1926), Jefferson Island, Lake Washington, and other salt domes. This gas was present in sufficient quantity to make drilling hazardous at both Jefferson Island and Lake Washington, during the time that the first wells were drilled, as well as after sulphur production had begun. Cap-rock waters, which the sulphur miner refers to as "formation water," usually contain hydrogen sulphide. The "bleed water" that is drawn from the cap rock while sulphur is being mined contains both sulphates and sulphides, and also sodium chloride.

Methane gas and petroleum are present in the cap rock of many salt domes, but they have been found in commercial quantities at very few of them. It is quite likely that the gas and petroleum have been flushed from the cap rock as the result of the very active water circulation. This probably
explains the absence of commercial quantities of oil in the main body of the cap rock at Lake Washington, where oil is produced from the upper part of the calcite cap rock and from sands overlying the cap rock, and where the remaining, very cavernous calcite cap rock, as well as the dense anhydrite portion, contains at least traces of petroleum.

The structure, taking the cap rock as a whole, is that of a broad dome with gentle dips. This simplicity disappears, however, when the structural conditions are examined more closely. It becomes evident that cap rock is a very heterogeneous mass, particularly in its upper portion, that has been subjected to intensive faulting and brecciation. High-angle shearing, with breccia fragments from the surrounding sediments and from overlying parts of the cap rock, characterizes the calcite cap rock in particular. These smaller structural features will be treated in some detail under the discussion of the petrography of the cap rock.
Petrography

General Considerations

Cap rock differs strikingly from other bodies of rock in the Gulf Coast because of its complex structure and its highly varied mineral composition. In addition, its common consolidated state sets it apart from the normal unconsolidated sediments in which it occurs. It is fully as anomalous a rock body as the salt plug that is essential to its presence. Aside from its unusual mode of occurrence, cap rock of the Gulf Coast salt domes is characterized by a distinctive assemblage of minerals, chiefly anhydrite, gypsum, and calcite - with sulphur, certain sulphides, and additional sulphates and carbonates locally present. The succession most often encountered is that of anhydrite of varying degrees of consolidation forming a somewhat irregular zone immediately above the salt, with gypsum and calcite overlying the anhydrite. Where it is present, calcite usually forms a zone in the upper part of the cap rock, with calcite-cemented sediments, the false cap rock, overlying this calcite zone (fig. 1). The contact between the anhydrite and calcite is a zone of varying thickness, sometimes designated the transition zone, in which the anhydrite and calcite grade into each other, and the gypsum, sulphur, and some of the less common minerals occur in greatest abundance.
Although the amount and the position in the cap-rock sequence of each of these minerals vary greatly in different parts of the cap rock of the same salt dome, as well as at different salt domes, cap rock of the Gulf Coast is often depicted as a relatively uniform and simple body of rock in salt-dome literature. This is due largely to lack of information, because very few wells have been drilled through, or even into, the cap rock at many salt domes. Usually, the data from a few widely spaced wells are interpreted conventionally as indicating a regular succession, from the salt upward, of relatively uniform, horizontal beds of anhydrite, gypsum, and "limestone," in much the same manner as primary sedimentary deposits. Wherever the cap rock has been extensively explored, however, as at the salt domes where sulphur has been produced, the relationships found do not show this simplicity (figs. 1, 2, 3, and 4). Kelley (1925) has noted the lack of uniformity at Sulphur, stating that the upper part of the cap rock in particular shows "no uniformity or continuity, even as between two closely adjacent wells" (p. 459). Striking irregularity also characterizes the cap rock at Bryan Mound or Bryan Heights (Kennedy, 1925), Big Hill (Wolf, 1925), Jefferson Island (O'Donnell, 1935), Hoskins Mound (Marx, 1936), and Lake Washington (Howe and McGuirt, 1936 A), all salt domes at which sulphur has been produced and for which considerable detail-
ed cap-rock data are available. At Jefferson Island, and also at Lake Washington, the variation in section from well to well is so great, that only the most generalized correlation of "zones" can be made. The one definite "marker" for cap-rock wells is the top of the salt, and even it is somewhat variable at Jefferson Island, perhaps in part owing to faulting in the salt and in part to differential solution of the salt. "Top of cap rock" often must be estimated because of the false cap rock which grades into it, and because of its "broken" or brecciated condition.

Intensive brecciation has affected much of the cap rock; it is most pronounced in the upper part at Jefferson Island and Lake Washington. In cores from the cap rock of these salt domes there is a definite increase in the amount of brecciation upward from the salt-anhydrite contact. The dense, saccharoidal anhydrite that usually comprises the lower part of the cap rock is relatively massive, although it has numerous well-developed horizontal joints with associated slickensides (Teas, 1931). The only breccia fragments present in the main body appear to be ones derived from the salt, as the sandstone from Lockley, Tex. (Teas, 1931), Midway, Miss., Winnfield, Lake Washington and Jefferson Island, La., and the "chalcedonic" anhydrite

The term "chalcedonic," as used here, does not refer to the presence of chalcedony or any other form of silica in the anhydrite, but to the similarity in appearance of this type of anhydrite to chalcedony or chalcedonic chert.
from Garden Island Bay, La. (Barton, 1934 b). Where the anhydrite is of considerable thickness, it becomes sheared and fibrous farther above the salt, and breaks into thin horizontal plates, or slickenside plates with a dip of about 45 degrees. The brecciation is usually very complex in the transition zone, and there are many fragments from the shallower parts of the cap rock. From this position up to the top, the cap rock is highly brecciated, although many of the breccia fragments near the top are partially or entirely replaced by younger calcite. The anhydrite cap rock from the flanks is thin and much of it is rather poorly consolidated, containing considerable salt. Most of it is composed of breccia fragments of cap-rock anhydrite and of material from the adjacent sediments. A specimen from the flanks at Lake Barre salt dome contains small breccia fragments of hard buff-colored limestone.

Some cap rock is quite distinctly banded. This banding is of several kinds and is not confined to any particular part. The considerable thickness of dense anhydrite exposed in digging the shaft at Rockley (Teas, 1931), and similar anhydrite at Sulphur (Goldman, 1926, 1933), Winnfield (Barnes, 1933), Lake Washington, parts of Jefferson Island, and other salt domes, has nearly horizontal dark bands of about 1 mm. width that are irregularly spaced and discontinuous. Some of the sheared, fibrous anhydrite has similar appearing
bands that are more closely and regularly spaced. Banding is strikingly developed in the calcite at Winnfield (Harris and Veatch, 1899; Harris, 1908; Spooner, 1926), and Pine Prairie (Barton, 1925 C). The bands are blue- and light-gray, or dark- and light-gray, with the darker bands from a millimeter to a centimeter in width, irregularly spaced, and sometimes continuous over distances of several feet. This banding can be observed in the faces of the quarry at Winnfield and to a lesser extent at Pine Prairie. The darker bands show many complexities; they can be traced only a short distance before they die out, broaden, curve to merge with others, or are broken by faults or cavities. Some of the lighter colored calcite occurs as large crystals of dogtooth spar that appear to have grown between the fine-grained darker bands. Banding due to alternating layers or veins of gypsum and anhydrite, of calcite and sulphur, or of calcite, sulphur and barite, is present at Lake Washington, especially in the transition zone. Banding in the cap rock is thought to be of especial significance by Goldman (1926, 1933) and several other students of cap rock, and for this reason the subject will be treated further under discussion of the cap-rock zones.

The Minerals

The complexity in the character of cap rock is illus-
trated by the detailed logs of cores from sulphur wells presented in appendix B. The very heterogeneous make-up of cap rock is evident from the fact that it is composed of 25 different minerals (Hanna and Wolf, 1934; Rolshausen, 1934), exclusive of a number of detrital minerals, petroleum, several gases — including methane, hydrogen sulphide, and carbon dioxide — and carbonaceous and argillaceous matter. A brief summary of the characteristics and mode of occurrence of each of the cap-rock minerals identified in the course of the present study, and a list of the additional minerals that have been reported by other workers, are given below.

**Anhydrite (CaSO₄).** The physical properties are essentially the same as those given for the pure mineral by Winchell (1933) and Larsen and Berman (1934), i.e., hardness of 3, or slightly more, specific gravity of 2.93, good cleavages in three planes, decomposition by HCl difficult. The color varies from nearly white to dark bluish or brownish gray, with blue-gray predominant; in thin sections, the anhydrite is colorless unless discoloring inclusions are present. The optical properties are also those assigned to the pure mineral, and are as follows: positive, 2V of 42°, distinct dispersion of χ ν, and refractive indices of 1.614, 1.576, and 1.570, for ρ, χ, and κ, respectively. Brown (1931) has reported that strontium and barium were detected spectroscopically in all anhydrite cap rock tested for these elements.
Anhydrite occurs both as tabular and "stem-shaped" subhedral crystals and as cleavage fragments, ranging in size of grain from submicroscopic to 2.0 mm. in length. These grains, in general, have the same appearance as the anhydrite grains in the water-insoluble residues of the salt. Compacted, and in places partly recrystallized and intergrown, masses of them form the typical "saccharoidal" anhydrite of cap rock (pl. XXVI, fig. 2), referred to as "pile-of-brick" structure by Brown (1931). The grains tend to form interlocking mosaics, but not so completely as do the other cap-rock minerals, and without the formation of larger crystals at the expense of smaller ones. Elongate fibrous-appearing crystals occur in the "schistose" type of anhydrite cap rock. In this type recrystallization has resulted in the formation of larger crystals. Anhydrite does not replace any of the other cap-rock minerals, but is replaced by all of the other minerals except quartz, and possibly barite, celestite, and aragonite. Inclusions within the anhydrite grains consist of smaller anhydrite grains, dolomite rhombs, and crystals of quartz (pl. XXI, fig. 1), celestite, and barite. Gypsum, calcite, and sulphur contain remnant grains of anhydrite, indicating replacement of anhydrite by these minerals. Breccia fragments of fine-grained "chalcedonic" anhydrite occur in the cap rock at Garden Island Bay (pl. XXV, fig. 2); other similar occurrences have
been reported by Goldman (1933).

**Calcite (CaCO₃).** At all of the salt domes where thick cap rock is developed there are extensive bodies of nearly pure calcite; it is second in abundance to the anhydrite. Cap-rock calcite ranges from nearly colorless to very dark gray or brownish gray. Size of grain varies from 0.05 to 0.10 mm. in the very fine grained, dark-gray type, to very coarsely crystalline types with grains up to 1.0 cm. in maximum dimension.

Calcite replaces all of the other cap-rock minerals except the sulphides and possible halite. Typically, the calcite contains inclusions of a finely divided dark-gray opaque substance, which appears to be carbonaceous matter. A finely divided white opaque substance that is probably argillaceous matter is present in some of the calcite.

**Gypsum (CaSO₄·2H₂O).** Gypsum is much less common in cap rock of the Gulf Coast than a survey of the literature would lead one to believe. Gypsum, chiefly as scattered selenite crystals, is widely distributed in Gulf Coast sediments in general, whereas outside of cap rock, anhydrite is only en-

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9 The term limestone should not be used for these occurrences as it ordinarily implies a primary, sedimentary deposit, and the evidence presented in this paper indicates that the calcite cap rock is of secondary origin. (See also Goldman, 1923; Brown, 1931; and o'Donnell, 1933, p. 1627.)
countered in the bedded deposits of the northern part of
the region. Further, rock gypsum and anhydrite are quite
similar in general appearance. As a result, anhydrite, and
mixed anhydrite and gypsum, are often logged as gypsum by
drillers. However, the two can be readily distinguished on
the basis of hardness, as gypsum, having a hardness of 2, can
be scratched with the finger nail, whereas anhydrite cannot
be. Gypsum has a specific gravity of only 2.32 and has but
one good cleavage, the (010). Under the petrographic micro-
scope, gypsum differs from anhydrite in having larger 2V,
rather strong dispersion, lower refractive indices, and less
birefringence.

The amount of gypsum in cap rock is comparatively small,
rarely being as much as 23 percent. Only a very few cores
of the cap rock at Lake Washington show more than a few per-
cent of gypsum. It is more abundant, however, at Jefferson
Island, where it makes up as much as 20 percent of the cap
rock in a few wells. All four of the common varieties of
gypsum occur in cap rock. The gray or bluish-gray fairly
massive rock type that resembles anhydrite, usually associ-
ated with varying amounts of admixed anhydrite grains, is
most common. The selenite, or crystalline variety, is
rather common in veins, while satirine, the fibrous silky
variety, and alabaster, the very fine grained chalky variety,
are present, but rare. Gypsum replaces anhydrite, and to a
small extent, calcite, sulphur, dolomite, celestite, and
barite. It is replaced by all of the cap-rock minerals ex-
cept anhydrite, quartz, and halite.

Sulphur. Native sulphur is an important mineral in
the cap rock of several salt domes and is present at all
salt domes that have an appreciable thickness of cap rock.
Its occurrence is restricted to local areas, and there are
considerable areas of barren cap rock, even at salt domes
that have commercial deposits of sulphur. The total amount
of sulphur present in cap rock may be as much as several
percent, with the sulphur-bearing part averaging about 20
percent. Cores a few feet in length consisting of nearly
pure sulphur have been reported from Sulphur and Lake Wash-
ington.

Sulphur occurs in orthorhombic crystals that vary in
size from microcrystalline to as much as 3 cm. in length.
The greater part consists of interlocking crystals that are
transparent to translucent and yellow or greenish yellow,
though some is brown or brownish gray. It has poor cleavage,
a hardness of 1.5-2.5, a specific gravity of 2.05-2.09, a
melting point of 235° F. (112.8° C.), is readily soluble in
CS₂ and CCl₄, and is not attacked by acids. Optically pos-
itive, sulphur has a 2V of 69°, weak dispersion of n < v
and extremely high refractive indices and birefringence.
A considerable amount of the sulphur at Jefferson Island and a small amount of that at Lake Washington is in the form of a pale-yellow powder that appears opaque except under high magnification and is composed of micro- to cryptocrystalline grains (pl. XI, fig. 1 and 2). This type of sulphur has also been reported from other salt domes, variously designated as opaque or "amorphous" sulphur.

Discoloration of cap-rock sulphur is due to the presence of small amounts of carbonaceous matter, in most cases in the form of hydrocarbons, in combination with the sulphur or intimately admixed with it. Chemical analysis of a gram-size grain of greenish-brown sulphur from the Freeport Sulphur Co. No. 2 well, Lake Washington, 1,389-1,392 feet, showed 0.062 percent of carbonaceous matter (as CH₂). The presence of a trace of carbonaceous matter in even the bright-yellow sulphur is one of the characteristics of cap-rock sulphur. Some of the bright-yellow sulphur contains almost as much of this carbonaceous matter as the discolored sulphur. Native sulphur from cap rock also differs from sulphur of other modes of occurrence, particularly volcanic sulphur, in the virtual absence of arsenic and selenium.

An analysis made by the Freeport Sulphur Co. in their laboratories at Lake Washington (Grande Ecaille), La.
The sulphates and calcite are replaced by sulphur, and it is replaced by calcite and the sulphide minerals, as well as by all of the sulphate minerals except anhydrite.

Pyrite (FeS₂). Finely divided aggregates and occasional euhedral crystals of this brass-yellow metallic iron sulphide occur throughout the cap rock in close association with all of the other minerals present. The other iron sulphide, marcasite, is also present locally. Although pyrite is very common in cap rock, it seldom constitutes more than one percent. The grains vary in size from submicroscopic to those of two mm. in diameter. A few crystals that are of the same age as the anhydrite occur in the anhydrite cap rock. The largest percentage of the pyrite is secondary; it occurs in veins following shear zones, and lends to the banded appearance of the cap rock. Crystals form in cavities and coat surfaces. Sulphur, particularly that which occurs disseminated, is replaced by pyrite. Zoned dolomite rhombs that have been replaced by calcite also contain pyrite. Locally pyrite is found in considerable abundance in the false cap rock.

Barite (BaSO₄). White finely divided powdery barite is a common mineral in the cap rock at Lake Washington, and is present at many other salt domes. It also occurs as well-developed crystals. The properties were found to be those of the pure mineral (Winchell, 1933; Larsen and Berman, 1934)
wherever they were checked. The powdery type is made up of radiating fibers that frequently show a spherulitic structure, replacing sulphur or in close association with it. This type appears to be younger than the sulphur and calcite matrix wherever the relationship could be determined. Obs- litic and pisolitic barite have been reported from the cap rock at several salt domes (Hanna and Wolf, 1934). Tabular crystals in the anhydrite are of the same age as the anhydrite, dolomite, quartz and celestite. Similar crystals, much embayed by calcite, and in some cases entirely replaced, occur in the fine-grained calcite and sulphur areas in the same relationship as the dolomite rhombs (pl. VI, fig. 2). Some of these crystals contain inclusions of anhydrite and sulphur grains. Radiating crested groups of tabular crystals line cavities. They are both younger and older than the associated vein sulphur and calcite. Calcite replaces bar- ite of all generations, and one instance was found where sulphur appeared to be replacing it also.

Celestite \((\text{SrSO}_4)\). The sulphate of strontium is much less common than that of barium, both at Jefferson Island and Lake Washington, but it is the more important mineral at Hoskins Mound and possibly at Sulphur. The anhydrite cap rock contains radiating groups of elongate crystals that are of the same age as the anhydrite grains.
tabular crystals line cavities in the calcite in the same manner as the barite. A microcrystalline variety occurs at Koskins Mound (Marx, 1936). In general, celestite has the same mode of occurrence and relationship to other minerals as the barite, i.e., it occurs as both a primary mineral, contemporaneous with the anhydrite, and as a secondary mineral, younger than the anhydrite.

**Dolomite (Ca,Mg\([CO_3]\)2).** Simple and modified rhombohedrons of 0.2 to 0.5 mm. diameter, that vary from colorless to brown, constitute the only development of dolomite in the cap rock. This mineral has been identified on the basis of its insolubility in dilute HCl and its indices of refraction. The nucleus in the grains is a white or pale-yellow substance that appears faintly anisotropic at high magnification. This substance has not been definitely identified, but it appears to be in part cryptocrystalline sulfur (Brown, 1931), and in part argillaceous matter, possibly a magnesian clay. The zonal structure is probably due to the presence of iron in varying amounts.

Chemical analyses of calcite cap rock show only a trace of magnesium, rarely as much as one percent. Aside from that in the dolomite rhombs which have not been replaced, this magnesium may be in combination with the calcium carbonate, or may be present in the finely divided argillaceous matter included within some of the calcite crystals.
Dolomite is replaced by calcite, pyrite and gypsum; it does not replace any of the other cap-rock minerals.

Quartz (SiO₂). Cubed quartz crystals of microscopic size, and rosettes of quartz crystals, are found throughout the cap rock. Brown (1931) has described and illustrated the rosettes that occur around a nucleus of cryptocrystalline sulphur, pyrite, or finely divided material like that in the dolomite rhombs. Some of the crystals, both as individuals and in the rosettes, contain inclusions of black carbonaceous matter and of anhydrite grains (pl. XXI, fig. 1) of the same type as those in the salt residues. Quartz crystals are a definite characteristic of all cap rock studied, although they are not sufficiently abundant to occur in all of the thin sections (pl. VI, fig. 1, pl. IX, fig. 1, 2 and 3, and pl. XXIII, fig. 1). They are of the same age as the anhydrite grains and dolomite rhombs. Detrital grains of quartz sand occur throughout the cap rock, but they are not common except in the upper portion of the calcite zone. Quartz does not replace any of the other cap-rock minerals, and is not replaced by them.

Aragonite (CaCO₃). This mineral fills small cavities in the calcite, and is also replaced by calcite. In thin sections, it is rather difficult to differentiate from calcite, and also from strontianite, but has been identified on the basis of optical properties (Winchell, 1935; Larsen and
Berman, 1934). Well-developed pseudo-hexagonal crystals, a centimeter in diameter and several centimeters in length, with internal radial structure, have been reported by Hanna and Wolf (1934), Hanna and Wolf (1938).

**Strontianite** (SrCO₃). Acicular crystals that are associated with dog-tooth spar (calcite) from Winnfield have been identified as strontianite on the basis of flame tests. Wolf (1926) and Hanna and Wolf (1934) also report strontianite from calcite cap rock.

**Galena** (PbS). Aggregates of small shiny black metallic grains of this mineral have been identified in a few thin sections of calcite cap rock. It has been identified from the cap rock and from adjacent sediments at several salt domes, locally occurring in appreciable amounts.

**Hauerite** (MnS₂). A few reddish-brown to brownish-black grains of this mineral have been found in both the anhydrite and calcite. Well-developed tetragonal crystals as much as a centimeter in maximum dimension have been reported from Big Hill, Matagorda County, Tex., by Wolf (1925) and Hanna and Wolf (1934). Some of the grains in the anhydrite may be contemporaneous with the anhydrite, otherwise it is secondary.

**Halite** (NaCl). Most of the cap rock from near the salt-anhydrite contact contains a small amount of halite, interstitial to the rather loosely compacted anhydrite grains.
Locally there is sufficient to make this cap rock quite deliquescent. The occurrence of a lens of salt 37.9 feet above the salt-anhydrite contact at Hockley has been reported by Teas (1931).

**Rare minerals.** Alabandite (MnS) and sphalerite (ZnS) have been reported from the cap rock at Big Hill, Matagorda County, Tex. (Wolf, 1926 A; Hanna and Wolf, 1934). Chalcolite (Cu$_2$S), chalcopyrite, (CuFeS$_2$), realgar (As$_2$S$_3$) and enargite (Cu$_3$AsS$_4$), associated with native arsenic, have been identified from the anhydrite at Winnfield, where they occur along shear planes, replacing anhydrite grains (Barnes, 1933). Smithsonite (ZnCO$_3$) occurs in the calcite cap rock at Palangana, Tex. (Hanna and Wolf, 1934). Rolshausen (1934) has reported siderite (FeCO$_3$) from the cap rock at Carlos salt dome, Tex. Hematite (Fe$_2$O$_3$) has been reported by Hanna and Wolf (1934). A green copper mineral occurs secondarily within the anhydrite at Hockley (Teas, 1931; Hanna and Wolf, 1934). A green copper mineral has also been reported from Winnfield (Barnes, 1933).

**Detrital minerals.** Sand grains, chiefly quartz, occur as lenses and in small sandstone fragments in the anhydrite at several salt domes. These occurrences are rare in the anhydrite zone, but are locally abundant in the upper part of the cap rock. At Lake Washington, sand and shale of the same type as in the surrounding sediments occurs in the upper
part of the calcite cap rock, but there is very little in the lower part, and none whatever was found in the anhydrite cores examined. In most instances, too, there was very good core recovery, eliminating the possibility that soft detrital material may have been passed up in coring. Samples of the sand inclusions from the anhydrite have not been examined in thin section, but in polished section they bear a striking resemblance to sand inclusions encountered in the salt. Sand inclusions from the lower part of the calcite cap rock at Lake Washington and Winnfield resemble sand inclusions in the salt both mineralogically and in outward appearance. At Jefferson Island the cap rock of the sulphur-bearing area is badly broken and contains gumbo, sands and shale, evidently from the surrounding sediments. Calcite-cemented sands in the lower part of the cap rock at Jefferson Island are chiefly quartz, with some feldspar, magnetite and ilmenite, leucoxene, zircon, and tourmaline, and assemblage which also suggests sands derived from the salt by solution. Breccia fragments of sandy limestone and limy sandstone from the false cap rock are found in the upper part of the cap rock at Jefferson Island, Lake Washington, and other salt domes.

**Petroleum and gas.** As has been noted, much cap rock contains appreciable amounts of petroleum and natural gas. Cap-rock petroleum is characterized by high sulphur content [2.31 percent at Spindletop, according to Barton (1935)],
low A.P.I. gravity, and its association with wet gas containing a large amount of hydrogen sulphide, as at Spindletop (Barton and Paxon, 1926), Sulphur (Kelley, 1926), Bryan Mound (Kennedy, 1926), Big Hill (Wolf, 1926), Hoskins Mound (Marx, 1936), Jefferson Island, Lake Washington, and other salt domes.

The Zones

Cap rock cannot be divided into a satisfactory series of continuous beds or layers because of its great complexity and irregularity. There are, however, three fairly well defined zones that can be distinguished where cap rock is well developed. The most important of these is the zone in which anhydrite predominates; in most cases it is the most consistently developed, and in some domes is the only zone present. A calcite zone is found above the anhydrite zone in the thicker and better developed cap rocks. It is separated from the anhydrite zone by a transition zone containing, in addition to calcite and anhydrite, the greater part of the sulphur, gypsum, and less important cap-rock minerals. The occurrence and association of the minerals will be treated by zones.

Anhydrite zone. Occurring immediately above the salt, the anhydrite forms a zone that mantles the entire upper part of the salt plug in many cases, and extends down the flanks
for distances of as much as 5,000 feet. In most cases it constitutes the greater part of the cap rock, and at a few salt domes, that have relatively deeply buried cap rock, makes up the entire thickness.

The anhydrite in contact with the salt occurs as a loose sand like that derived from solution of the salt, as a rock of varying degrees of consolidation formed of these sand grains, and as a rock composed of breccia fragments of consolidated anhydrite sand. Typically, the anhydrite of the lower part of the cap rock is of the fairly massive, relatively undeformed "saccharoidal" type (pl. XXVI, fig. 2). There is a gradation in the anhydrite upward from this relatively undisturbed type showing "pile-of-brick" structure (Brown, 1931), in the lower part, to the intensely sheared, fibrous, or "schistose" type in the upper part. This increase in deformation in the anhydrite, upward from the salt-anhydrite contact, has also been noted by Goldman (1925) and Brown (1931), particularly the former, who made the observation on a very complete suite of diamond-drill cores from Sulphur salt dome. The increase is not uniform, but in a general way it is a persistent characteristic of the anhydrite zone.

The anhydrite grains in cap rock have undergone some recrystallization, particularly in the "schistose" type. The grains do not tend to form an interlocking mosaic so
completely as do the gypsum and calcite grains; they have more the appearance of a closely packed poorly sorted sand, with some suggestion of horizontal orientation of the elongate grains. There appears to be little tendency for larger crystals to develop at the expense of the smaller grains, as is the case with gypsum and sulphur. Some anhydrite appears to have been precipitated from solution during and after the formation of cap rock, but this factor has been less important than the compaction and intergrowth that accompanied shearing, judging from the rarity of cementing materials. Further, anhydrite does not replace any of the other cap-rock minerals. When exposed to weathering, anhydrite cap rock, and particularly that from near the salt contact, breaks down rapidly forming an anhydrite sand.

There are two types of banding in the anhydrite. One consists of irregular, usually horizontal, dark bands, about a millimeter in width, separating thicker bands of lighter color. The other type is distinguished by rather indistinct horizontal zones of fine-grained anhydrite of a centimeter, or a little less, in width, alternating with thicker zones of the common coarse-grained type. The first type appears to be due to secondary pyrite and carbonaceous matter deposited along horizontal joint planes and in narrow shear zones. The other type may be what Goldman (1933) calls katatectic banding, that
is banding due to periodicity during the formation of cap rock as a result of solution of the salt and compaction of the residue. Some of the intensely sheared anhydrite has bands formed by veins of gypsum, calcite, and sulphur. This type of anhydrite also has microscopic very irregular bands, along which dolomite rhombs and quartz crystals are concentrated.

Aside from the fact that it is composed of compacted, poorly sorted, but relatively coarse, anhydrite sand, anhydrite cap rock is characterized by large dolomite rhombs with nuclear or zonal structure and by the quartz crystals and rosettes that are scattered at random through it. These minerals occur in about the same relative abundance in the anhydrite cap rock that they do in the salt residues. Deformational stresses that have affected the anhydrite grains have also affected the dolomite rhombs (pl. XIV, pl. XV, fig. 1, pl. XVI, and pl. XVII, fig. 1) and the quartz crystals and rosettes. Rarer crystals of celestite, barite (pl. VI, fig. 2), pyrite, and calcite, and grains of sulphur and possibly of hauerite, also occur in the same relationship. Small amounts of calcite and sulphur also occur as replacements of the anhydrite throughout this zone, particularly in the upper part where the shearing is more intensively developed. Typically there is a gradual increase in the
amount of calcite and sulphur from the point where they first appear, upward to the transition zone. The anhydrite also contains lenses of quartz sand and fragments of sandstone; these, however, are not of common occurrence. As previously noted, these sand inclusions resemble those that occur in the salt more closely than they do material from the surrounding sediments.

Cap-rock anhydrite can be distinguished from that of other modes of occurrence on the basis of large grain size and by the character of the dolomite rhombs. This conclusion has been reached after a review of the literature on other occurrences and the examination of thin sections of anhydrite from other deposits. Strikingly banded fine-grained sedimentary anhydrite of Permian age, from west Texas, contains rhombs, but they are very minute and are confined chiefly to the bands. Udden (1924) presented photomicrographs of this anhydrite, one of which was reproduced by Goldman (1925). This banding has been attributed by Udden to seasonal changes in concentration of the solution from which precipitation occurred, like "year rings" in the salt. Anhydrite associated with the deposits of potash salts in the Texas-New Mexico Permian has been studied in detail by Schaller and Henderson (1932). They described it as typically very fine grained, composed of rectangular crystals that
average 0.01-0.10 mm. in diameter, and noted the presence of horizontal bands that are due to the concentration of very small magnesite crystals and some clay. Thin sections of this material examined in the course of the present study show that recrystallization has developed larger rectangular crystals, fan-shaped groups of crystals, and "pegmatite-like" veins. Schaller and Henderson (1932) refer to fine-grained gray anhydrite containing white breccia fragments, but it is given only passing attention. Alling (1928) remarks of the recrystallized condition of the anhydrite associated with salt deposits of Silurian age in New York. Anhydrite collected from dump piles at two Kansas salt mines and described by Rogers (1910) resembles cap-rock anhydrite more closely than any that the writer has seen. (See Roger's figure.) It is relatively coarse grained, although considerably altered to gypsum, and contains irregularly distributed crystals of dolomite, celestite, quartz, and pyrite. It is thought to have come from lenses in the shales associated with the salt. If it occurs in this manner, it may represent a secondary accumulation of the less soluble minerals after solution of the more soluble ones, in the manner outlined by Lang (1900) for certain of the German deposits. The fact that it came from a dump pile suggests to the writer that it may be from a lens in the salt, like the "slab" an-
The typical bedded deposits of Zechstein age in Germany have been described by Hammerschmidt (1883) as being finely granular or fibrous, with the granular type containing dust-like rhombohedrons of calcium and magnesium carbonate.

The "chalcedonic" anhydrite of Glen Rose age from north Louisiana differs strikingly, both in thin section and in hand specimen, from cap-rock anhydrite. It is very fine grained and fibrous, with narrow, irregular veins or bands of calcareous and argillaceous material that contain grains of calcite or dolomite of less than 0.01 mm. in diameter (pl. XXII, fig. 2). Anhydrite of supposed Eocene age from central Florida is very similar to that from north Louisiana. It contains recrystallized areas that are coarser grained, and the argillaceous material in the veins is finer grained and is not calcitic. Minute grains of a carbonate, either dolomite or magnesite, occur with the argillaceous matter, or border some of the larger, secondarily developed anhydrite grains.

On the basis of these comparisons, then, it appears that the anhydrite of cap rock, because of its coarser-granular character, and the presence in it of the distinctive large rhombs of dolomite and crystals and rosettes of quartz, can readily be distinguished from the anhydrite of primary bedded deposits.
Transition zone. 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. This zone is rather irregular in its development, although as a rule it is thicker near the flanks than in the central portion of the cap rock. There are isolated blocks of anhydrite within the calcite zone at Big Fill (Wolf, 1925), Hoskins Mound (Marx, 1936), Boling, Jefferson Island, and Lake Washington. The blocks at Jefferson Island and Lake Washington are of typical cap-rock anhydrite and at their boundaries are altering to gypsum, calcite and sulphur. The transition zone is the part of the cap rock in which active alteration of the anhydrite to calcite, sulphur, and gypsum is occurring, as shown in thin sections. Where a thick anhydrite zone is present, the alteration of anhydrite to calcite and sulphur begins on a small scale well down within the anhydrite zone, increasing in amount up into the transition zone, while the alteration of anhydrite to gypsum is confined to the transition zone. In the transition zone, however, the alteration of anhydrite to gypsum appears to take place more rapidly than that of anhydrite to calcite and sulphur.

The manner in which gypsum has replaced the anhydrite in cap rock has been discussed in considerable detail by Goldman (1925) and Brown (1931). The waters which effect
hydration gain entry along shear planes and fracture lines and from these work around the individual anhydrite grains and along the cleavages. Some expansion occurs during the change, causing distortion of the anhydrite remnants and of the inclusions inherited from the anhydrite. Immediately after the completion of hydration, the gypsum consists of many small interlocking crystals that retain the outlines of the replaced anhydrite grains, as illustrated in plates XII, XIII, and XXV, fig. 1. These small crystals gradually coalesce to form large irregularly interlocking crystals, with relatively large areas of the same optical orientation where shear planes are closely adjacent.

Where the alteration to sulphur and calcite has preceded gypsification, it usually continues after the anhydrite has been altered to gypsum, although in a few cases the alteration to sulphur and calcite seems to have been retarded or halted upon the inception of gypsification. The crystals of dolomite, quartz, calcite, barite, and celestite are carried over from the anhydrite into the transition and calcite zones. Many of them remain unaltered. Primary gypsum, i.e., gypsum of the same age as the anhydrite, was not found. Much of the gypsum that occurs in veins actually is a direct replacement which has occurred at a shear zone or along a fracture. Only a relatively small amount appears to have been carried in mineralizing waters and deposited in another place. The
depth at which gypsum is found is quite variable. At Gyp Hill and Winnfield it occurs at or near the surface, but it is found at a little over 2,000 feet below the surface at Garden Island Bay and Calcasieu Lake. However, it appears to be more abundant where cap rock lies at depths of less than 1,000 feet.

Much of the calcite and sulphur replace the anhydrite and the gypsum directly, although important amounts occur in veins. Replacement of sulphates takes place in all parts of the anhydrite and transition zones, being least common in the compact little disturbed anhydrite just above the salt, and most common in the transition zone. Calcite replaces anhydrite directly, in the complete absence of gypsum, and in this occurrence it is often associated with sulphur that also directly replaces the anhydrite.

Replacement of the anhydrite by calcite and sulphur begins along shear zones and around the dolomite rhombs, working around individual grains from these, and then penetrating along cleavage planes. The manner in which the anhydrite is gradually replaced by networks of small calcite scalenohedrons has been well illustrated by Brown (1931); this relationship is here illustrated in plate XIII. In many places the replacement is carried out with great faithfulness and the details of the anhydrite structure are well
preserved. The sulphur is particularly faithful in its replacement of the anhydrite and in many cases occurs as pseudomorphs that retain even the cleavage structures of individual anhydrite grains (pl. XIX, pl. XX, fig. 2).

If the anhydrite has been replaced by gypsum, the alteration to calcite and sulphur often is controlled by the granular structure and the shear planes inherited from the anhydrite, especially if the change to sulphur and calcite had started before gypsification (pl. XIII, pl. XX). Anhydrite, however, seems to alter more readily to calcite and sulphur than does gypsum, probably because its more granular structure and greater number of cleavage planes allow much easier entry to the altering solutions. In the alteration of gypsum, however, the good cleavage is followed in many cases. The dolomite rhombs, quartz rosettes and crystals, and celestite and barite crystals, can be traced from the anhydrite into the calcite and sulphur areas, although all of the minerals but the quartz may be replaced by calcite, and occasionally by sulphur.

Most of the sulphur and calcite are closely associated and appear to be contemporaneous in age. The manner in which finely crystalline calcite occurs within sulphur areas, with grains of sulphur within the calcite, and the intergrowth of the calcite with the intricately ramifying veins
of sulphur that branch off the larger sulphur veins and areas in the shear zones, are evidence of the contemporaneous development of the two minerals (pl. VII, fig. 2, and pl. XX, fig. 1).

The sulphur in the transition zone is the "disseminated sulphur" of the sulphur miner. It forms an important part of the sulphur deposits and is most abundant in the cap rock of the transition zone, or directly above it. Vein calcite and sulphur, younger than the disseminated sulphur, and of several different generations, are associated with this disseminated sulphur in nearly every case. Where the veins follow the horizontal shear zones they lend a banded appearance to the cap rock. Well-developed sulphur and calcite crystals occur in cavities and coat the surfaces of shear zones where there are partings.

**Calcite zone.** Where a calcite zone is present it overlies the transition zone and is influenced by the irregularities of that zone. Like the transition zone, it is thicker toward the edges of the salt plug than it is in the center in most cases. It also extends down the flanks, in some instances to depths of several thousand feet. These general similarities in development are not surprising if the transition zone is considered as being a zone of alteration that moves downward through the anhydrite zone, leaving the calcite and sulphur behind. That this is actually the case is
borne out by a comparison of thin sections of cap rock from the three zones. One of the striking features in thin sections of cap rock from both the transition and calcite zones is the presence of the dolomite rhombs and the quartz crystals and rosettes, sometimes accompanied by the "pile-of-brick" structure and shear zones, all of which are characteristic of the anhydrite.

The dolomite, celestite, barite, and other less common minerals of the anhydrite zone, except the quartz and pyrite, are usually replaced by calcite and pyrite in the calcite zone, but their outlines are well preserved (pl. VI, pl. XVI, and pl. XX, fig. 2) except where they have been disrupted by shearing or crushing. The calcite, other than that in veins and vugs, is fine grained and filled with inclusions of finely divided carbonaceous matter and white or cream-colored opaque substance. Brown (1931) identified some of the black opaque substance as iron and silica, rather than carbonaceous matter. The other opaque substance appears to be argillaceous material. The vein calcite is coarse grained, and has partially replaced the fine-grained calcite where recementing breccia fragments of it. Some of the calcite cap rock, particularly the fine-grained type, shows at least a trace of petroleum, and in places it is well saturated.

Calcite occurs in all parts of the cap rock, and with
the possible exception of halite, all of the other cap-rock minerals are directly associated with it. All of the cap-rock minerals, except quartz and the sulphides, are replaced by calcite. Calcite and sulphur are contemporaneous in much of the fine-grained calcite of the sulphur-bearing cap rock of the calcite zone. The two minerals occur in the same manner, replacing anhydrite grains and forming pseudomorphs after them. The relationship between vein sulphur and vein calcite, however, is very complex, and varies throughout the cap rock, as both occur in a number of different generations. The calcite ranges in age from the few grains that are contemporaneous with the anhydrite to that which forms veins cutting across all of the cap rock.

Where sulphur is present in the transition zone in appreciable amount, it is also an important mineral in the calcite zone, particularly in the lower part. In the upper part of the calcite zone, the "barren cap" of the sulphur miner, a small amount of sulphur apparently has been replaced by calcite and pyrite. This is evident from the manner in which younger calcite and pyrite embay older sulphur. Cavities, common in both the transition and calcite zones, are particularly abundant in the "barren cap." Brecciation also occurs throughout the calcite zone, increasing in amount upward from the transition zone.

Calcification extends from the cap rock into the adja-
out sediments. These sediments, chiefly sands, which have been cemented by calcite and sometimes by pyrite, from the false cap rock. The mineral content of these sands is similar to that of sands in the adjacent sediments — quartz, chert, and feldspars, in order of abundance, with heavy minerals rare. Calcite-cemented shales are also fairly common in the false cap rock, particularly at the flanks. At Darrow salt dome, shale from near the flank of the salt plug (Humble Oil and Refining Co., No. 9 Gumbel well, at a depth of nearly 8,000 feet) contains solution-worn anhydrite grains.

Summary

The following general facts have been brought out in the consideration of cap rock:

1. The occurrence of cap rock is confined to salt domes and it has been found at most of the known salt domes of the Gulf Coast. It cannot be considered as definitely missing at any of the salt domes, as in every case where it is not reported exploration has not been complete.

2. Cap rock is highly variable in development and thickness, attaining the greatest thickness at shallow salt domes, yet being unreported at a few of the very shallow ones. It ranges in thickness from a few feet to more than 1,000 feet.

3. The greatest thickness of cap rock overlies the central part of the salt plug in most cases, although exceptions
are common. It extends down the flanks of some salt plugs as much as 5,000 feet. Overhang of cap rock is developed at a few salt domes.

4. A zone of calcite-cemented sediments, the false cap rock, separates the surrounding sediments from the cap rock proper. The sediments adjacent to the cap rock are highly faulted and steeply dipping at many of the shallow salt domes, owing to upthrust of the salt and to collapse of the cap rock. In some cases the sediments that directly overlie the cap rock show a small amount of uplift, and on a few domes they are depressed. These sediments in most cases, however, are not so steeply dipping, and not so far removed from their normal stratigraphic position, as those at the sides.

5. The cap rock is highly brecciated and sheared, with the deformation slight or wanting at the salt-anhydrite contact, and becoming increasingly pronounced upward. Most of the breccia fragments are of cap rock from a portion of the cap rock overlying that in which they are found. Fragments of the false cap rock occur in the upper part of the cap rock.

6. The chief constituents of cap rock are anhydrite, calcite, gypsum and sulphur, in order of abundance, with some 20 rarer minerals often present. Anhydrite is always present, and in some instances is the only mineral present
in any abundance.

7. Cap rock is in no sense a bedded deposit but consists of zones that are usually of very irregular distribution. Three zones - the anhydrite zone, the transition zone, and the calcite zone - are present, with very few exceptions, wherever a considerable thickness of cap rock is developed. The anhydrite zone is the lowest zone; it grades irregularly into the transition zone (the zone of alteration), which is characterized by gypsum, calcite, and sulphur. The calcite zone irregularly overlies the transition zone and may contain variable amount of gypsum and sulphur, as well as remnant grains and isolated blocks of anhydrite. The cap rock of the flanks may contain only the anhydrite zone, or may contain all of the zones of the main body.

8. The salt-anhydrite contact is cavernous in most places and has associated brines which carry anhydrite sand of the same type as that found in the salt. Some anhydrite in direct contact with the salt is saturated with salt, and is composed of loosely packed anhydrite sand, like that in the salt, that has undergone very little cementation and intergrowth or shearing. The fairly massive anhydrite cap rock with "pile-of-brick" structure is also found at the salt-anhydrite contact.

9. Upward from the salt, the anhydrite grades into the typical, fairly massive saccharoidal anhydrite that is dis-
tinctive of cap rock. It is composed of the same minerals as the loosely compacted anhydrite, but the grains have become sheared and intergrown. Banding occurs along the predominant horizontal shear zones where secondary pyrite, carbonaceous matter, calcite, and sulphur have been deposited.

10. Dolomite rhombs and quartz crystals and rosettes occur throughout all three zones. In the anhydrite zone, they have about the same relative abundance that they do in the water-insoluble residues of the salt. Although the dolomite rhombs are sometimes fragmented, and many are replaced by calcite, they are so distinctive that their identity is usually evident. These minerals are identical in appearance and properties with those in the salt, even to the character of the inclusions and zoning. Dolomite rhombs occur in primary, sedimentary anhydrite, but apparently only as minute grains, quite different from those in the cap rock and salt.

11. The anhydrite grains in cap rock are also identical with those occurring in the salt, but differ strikingly from those occurring in beds of primary sedimentary anhydrite.

12. Sulphur and calcite directly and completely replace the anhydrite, and in general are closely associated. The replacement increases in amount upward toward the transition zone, where gypsum appears in considerable amount, al-
tering from the anhydrite. Calcite and sulphur replace both the anhydrite and gypsum in the transition zone, in many cases retaining remnants of the replaced minerals. The quartz rosettes and dolomite rhombs associated with the anhydrite retain their identity during alteration of the anhydrite, and with the "pile-of-brick" and banded structure of the anhydrite that are locally preserved, from distinctive features of the cap rock of the transition and calcite zones.

13. Cap rock of the cavernous transition and calcite zones has undergone intensive brecciation and resolution, with subsequent recementation and secondary deposition. Sulphur has been replaced by calcite, gypsum, pyrite, barite, and celestite. The secondary calcite and sulphur represent a number of generations.

14. Appreciable amounts of petroleum, natural gas, and hydrogen sulphide occur in cap rock. These appear to be more abundant where calcite and sulphur are present, but sulphur does not always occur in appreciable quantities wherever these substances are found.
Origin of Cap Rock
The manner in which the cap rock of salt domes has been formed must be determined by the interpretation of the data, relative to its mode of occurrence and character, summarized in the preceding section. In order to be acceptable, a theory of origin must take into consideration all of these factors, explaining them within the limits of present knowledge. The several theories that have been advanced have already been discussed briefly. These theories will now be examined in more detail in order to determine whether or not any of them can account satisfactorily for all cap-rock phenomena.

Theories of Origin

A Block of Sedimentary Material Upthrust by the Salt

The early concept of salt domes as rather gently dipping quaquaaversal structures quite naturally led to the conclusion that the somewhat dome-shaped bodies of cap rock were sedimentary beds resting upon the salt in their normal stratigraphic position. This belief led to attempts such as that by Fishback (1902) to correlate the cap rock with sedimentary formations of known stratigraphic position. As more became known about salt domes, and the intrusive theory of their origin became adopted, this concept was modified by some to the idea that cap rock is a segment of a sedimentary bed.
pushed up by the salt. Recently, this modification also has been abandoned by most students of salt domes. At first the theory was objected to largely on the grounds of the physical difficulties involved. With the continued increase in our knowledge of the mode of occurrence of cap rock and the inception of detailed cap-rock studies, a number of other factors have been introduced which render acceptance of this explanation difficult. In fact, those who still adhere to this theory seem to do so largely because of an unwillingness to accept other theories.

Some contend that considerable thicknesses of cap rock, such as are developed at a few salt domes, are best explained by this theory, i.e., as blocks of primary sedimentary anhydrite, and according to a few, of limestone as well, that rode the salt up through the sediments. Known deposits of sedimentary anhydrite of comparable thickness are cited as evidence in favor of this contention. The fundamental difference in character between the anhydrite of cap rock and that of known primary sedimentary deposits, and the existence of numerous intercalated beds of dolomite, limestone, shale and sandstone in primary anhydrite deposits, in contrast to the rarity of even sandstone inclusions in anhydrite cap rock, are factors which must cause the rejection of this correlation. Brown (1931) apparently did not know that the salt also contains celestite crystals when he attempted to
correlate cap-rock anhydrite with bedded anhydrite of the
Glen Rose on the basis of the presence of celestite. This
same worker held (Brown, 1931) that the highly sheared con-
dition of the upper part of the anhydrite cap rock can be
accounted for only by stresses set up during the intrusion
from great depth. There are few quantitative data avail-
able, but it is known that anhydrite, a mineral having un-
usually good cleavage, yields relatively easily to shearing
stresses. Further, a definite increase in the degree of
shearing can be traced from the salt-anhydrite contact up-
ward. Brown (1931) suggested that this phenomenon might be
due to insulation from shearing stresses of the anhydrite
directly in contact with the salt. As pointed out by Gold-
man (1933), not only would intensive shearing stresses be
set up during intrusion, but there would also be a strong
tendency for the more plastic salt to break up and engulf
an overlying anhydrite bed. The manner in which salt shat-
ters and engulfs a hard rock covering through which it is
intruded is well illustrated by the salt domes of Persia
(Harrison, 1930).

Banding in the anhydrite cap rock was considered by
Goldman (1925) and Brown (1931) as proof of primary sedi-
mentary origin. The anomalous preservation of this banding
during intrusion was also explained by Brown (1931) as owing
to the insulating effect of the salt, although banding
occurs well up from the salt contact. After doing further work, Goldman (1933) became convinced that the banding is not proof of primary sedimentary origin, but that it is in part due to periodicity in residual accumulation, and in part to shearing.

The suggestion by Barton (1934) that if salt domes are formed by "downbuilding," a block of the sedimentary material overlying the "mother" bed of salt would quite naturally be retained as cap rock, has already been considered. As he admits of actual upthrust of the salt amounting to a few thousand feet, the same objections would be raised as in the case of an intrusion of several thousand feet.

In addition to the objections to which reference has already been made, there are several others. The great variability in the development of cap rock at different salt domes is difficult, if not impossible, to explain on the basis of its origin as a block of primary sedimentary anhydrite. There should be the best development of cap rock where there has been the least amount of intrusion, i.e., where salt lies 4,000 to 9,000 feet below the surface, whereas cap rock is either thin or wanting at these salt domes. The great irregularity in development in different parts of the same cap rock and at closely adjacent salt domes of the same type also would not be expected if cap rock were of this origin. Howe and Moresi (1931) have noted what appears to be
"shedding" of cap rock at Jefferson Island and New Iberia, where the cap rock has been left at a lower level, and a subsidiary spine without cap rock has been upthrust. As these authors have suggested, a bed of sedimentary anhydrite overlying the "mother" bed of salt probably would be left behind in the same manner. The flat-topped salt table that decapitates the isoclinally folded salt, as it does at Jefferson Island and Lake Washington, is also difficult to explain on the basis of this theory.

The petrographic evidence, which has already been referred to, is particularly unfavorable. Cap rock of the anhydrite zone, and of the transition and calcite zones as well, is distinctive, and differs strikingly from anhydrite and limestone of known primary, sedimentary deposits. Only one specimen of anhydrite cap rock was encountered during the present study that might be of primary sedimentary origin. This is the sample of "chalcedonic" anhydrite from Garden Island Bay, definitely an inclusion in typical cap-rock anhydrite.

Little attention has been given parts of the cap rock other than the anhydrite zone in the foregoing discussion. This same mode of origin, however, has been assigned to the entire cap rock by some workers. The petrographic studies of both Goldman (1925) and Brown (1931) have shown that the
cap rock of the anhydrite zone alters to form that of the other zones. Brown (1931), however, contended that part of the calcite cap rock was of primary sedimentary origin, including that containing sulphur. He appears to have been led to this conclusion as a result of his attempt to correlate cap rock with Glen Rose formations. Later, Brown (1934) considered all of the cap rock to be a primary deposit. In a recent paper, however, he apparently has finally come to accept the calcite and sulphur as products of secondary development (Brown, 1935). The evidence pertaining to the origin of the cap rock of the calcite and transition zones will be considered further under the discussion of the paragenesis of the minerals.

Alteration of Limestone

Certain bedded gypsum and anhydrite deposits have been explained as having formed by the action of waters containing sulphuric acid upon limestone. This mode of formation has been proposed for the gypsum and anhydrite of cap rock. The chief argument in favor of this theory seems to be the fact that the reaction involved is chemically possible. There are, however, physical objections that definitely eliminate it. In the first place, limestones that are suitable to the reaction occur in the vicinity of very few of the salt domes having cap rock. Derivation of the limestone
by its intrusion as a block from depth would entail the same difficulties outlined for the preceding theory. Further, at some of the salt domes only anhydrite cap rock has been found. Petrographic studies show that formation of the anhydrite has taken place from the salt upward, that the gypsum is formed by hydration of the anhydrite, and that the calcite is an alteration product of the anhydrite and gypsum.

Precipitation in Place

The partially intergrown condition of the anhydrite grains in the typical "saccharoidal" anhydrite cap rock, and the presence of soluble sulphates in salt-dome waters, have led to the consideration that cap rock may have been precipitated in place. There are at least two ways in which this could take place. Mixing of meteoric waters containing calcium carbonate in solution with salt-dome waters containing soluble sulphates would result in the precipitation of anhydrite or gypsum, according to Stuart (1931). With regard to the precipitation of anhydrite cap rock, Mr. Paul Weaver of Houston, Tex., has suggested: "There is also the possibility that the CaSO₄ may be precipitated from circulating waters originally connate in offside sediments; as these waters, already containing some CaSO₄ 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 up-
ward circulation brings them to the top of the salt dome, they precipitate the $\text{CaSO}_4$.\textsuperscript{10}

Precipitation of the cap rock in place would eliminate the difficulties encountered in the theory of its origin as a block of sedimentary material thrust ahead of the salt. Either of the methods of precipitation noted calls for a rather nice adjustment of conditions over long periods of time, however. If cap rock were formed by precipitation, it should contain interbedded contemporaneous sediments in considerable amount, a condition existing only where cap rock is broken or poorly developed, or in the upper portion where a thick cap rock is present. The anhydrite cap rock is particularly free of detrital sediments where thick cap rocks occur, and the rare sand inclusions that are present resemble those in the salt strikingly. The petrographic evidence is particularly unfavorable to the origin of cap rock entirely by precipitation. The similarity in composition of the anhydrite cap rock and the salt residues, the increase in the age of the cap rock from the salt upward, the absence of vein anhydrite, and the subordinance of vein gypsum, would not be expected. Precipitation of the anhydrite directly

\textsuperscript{10} Letter of December 1, 1937, in which Mr. Weaver, who is making a study of this mode of origin for cap rock, discussed the possibilities of precipitation of the anhydrite cap rock from solution.
from salt-dome waters in such a way that the size of grain and the relative mineral composition of the salt residues were re-established, seems to call for entirely too great a coincidence.

While formation of the entire cap rock by precipitation, or of even the anhydrite portion of it, is precluded by the evidence assembled in this paper, certain evidence suggests that some precipitation from solution may have taken place. Gypsum that occurs as veins in the cap rock and in a few cases in the false cap rock, is probably a precipitate. Solution and reprecipitation appear to have been involved where partial intergrowth of anhydrite grains occurs in the "saccharoidal" type of anhydrite cap rock.

Residual Accumulation and Secondary Alteration

The theory of the formation of anhydrite cap rock by the accumulation of the less soluble constituents, chiefly anhydrite grains, of the salt plugs has attained the acceptance of many salt dome students since it was first definitely outlined by Hanna and Goldman. A number of reasons for supporting this theory have been presented by Hanna (1930; 1934), Goldman (1929; 1933), DeGolyer (1931), Howe and Moreci (1931), and others. The objections to this theory that have been voiced are few, and they have lessened in number as our knowledge of salt domes has increased.
There are some who contend that the amount of residue in Gulf Coast salt is insufficient to account for thicknesses of cap rock such as those found at Sulphur, Winnfield, and a few other salt domes. Recent studies have shown that rock salt of the Gulf Coast salt plugs contains an average of 5 to 10 percent of water-insoluble residue. This is about the same amount of residue found in salt of the German salt plugs which also have cap rock that appears to be of residual origin. Aside from the average residue content, considerable portions of the layers or "year rings" of some of the salt plugs carry appreciably more residue, up to 90 percent, in fact. It is significant that at Hockley, Tex., and Winnfield, La., salt domes that have unusually thick cap rock, considerable portions of the salt contain more than the average amount of water-insoluble residue. There is a definite possibility, therefore, that where the thicker cap rocks occur, salt of higher residue content has been involved. In this connection Goldman (1933) has considered the possibility that appreciable amounts of bedded anhydrite have been derived from the salt, although the only evidence of their presence has been indirect - the occurrence of bedded anhydrite inclusions in the cap rock.

There is some evidence pertaining to the amount of salt that has been involved in the formation of salt plugs and is available for solution. Harrison (1930) has described Pers-
ian salt plugs as much as several miles in diameter and with elevations up to 7,000 feet above sea level. Salt glaciers extend from some of these salt plugs, in one instance for a distance of nearly four miles. At others there is evidence that at least several thousand feet of salt has been dissolved. The evidence of collapse at Clay Creek, Tex., and Chestnut, La., as well as that afforded by the relation of breccia fragments in cap rock, also indicate solution of the salt. For the intrusion of 15,000 feet or more of salt, the thickness of the "mother" bed necessary is not more than could be expected, as Howe and Moresi (1931) have shown. That intrusion has been continuous over long periods of time, or more probably, has occurred periodically, is indicated by the rejuvenation of some of the Gulf Coast salt plugs, and by the stratigraphic and structural relationships of the salt and the surrounding sediments. There seems, therefore, ample reason to believe that several thousand feet of salt may have been dissolved at some of the salt plugs, and even that salt columns as much as 10,000 to 20,000 feet thick, the maximum required on the basis of salt of the average composition at salt domes having a thousand feet of cap rock, may actually have been removed.

There is abundant positive evidence in favor of the residual theory. The presence at the salt-anhydrite contact of brine associated with sand containing the water-insoluble
minerals of the salt, the existence of a relatively flat-topped solution table that decapitates the salt folds, the similarity in composition of the salt residues and the anhydrite cap rock, and the great irregularity in the development of cap rock, all indicate origin by residual accumulation. In fact, the evidence obtained in the present study points so strongly to the origin of anhydrite cap rock by residual accumulation of the less soluble minerals in the salt, and to formation of the cap rock of the transition and calcite zones by alteration of the anhydrite, that no other explanation seems at all plausible.

The petrographic studies have shown that the water-insoluble minerals of the salt can be traced directly into the cap rock. Strong flows of brine, usually only partly saturated for both CaSO₄ and NaCl, that are encountered at the salt-anhydrite contact, associated with the water-insoluble minerals of the salt, show that the salt is being dissolved, in some cases rapidly, leaving behind a residue of the same composition as anhydrite cap rock. The amount of residue is variable in different parts of the same salt plug, as well as at different salt plugs, and these characteristics are reflected by the great variability in thickness of cap rock. Likewise, the typical "saccharoidal" anhydrite cap rock is of much the same character at all of the salt domes, just as the salt residues are much the same. It seems pro-
bable that when sufficient data on the amount of residue in
the salt for the different salt domes are available, thickness of the cap rock can form the basis for estimates of the
amount of salt dissolved, as has been done for some of the
German salt domes (Lachmann, 1910).

Cap rock shows a general increase in age from the salt-
anhydrite contact upward, as would be expected from its
growth by accumulation of residual material derived from the
salt. Just above this contact the cap rock is in many cases
made up of loosely compacted anhydrite grains and other min-
erals of the salt residues, with salt in the interstices.
More resistant beds in the salt, such as the bed of detrital
sand at Jefferson Island, are known to extend above the
usually flat-topped salt table and into the cap rock. The
greater part of the anhydrite zone consists of the distinc-
tive "saccharoidal" anhydrite cap rock, with the minerals of
the salt residues in characteristic "pile-of-brick" structure.
These minerals are the distinctive large anhydrite grains,
the dolomite rhombs and quartz rosettes with nuclei, and the
quartz, barite, celestite, pyrite, hauerite, and sulphur cry-
stals. It is interesting to note that both Brown (1931)
and Goldman (1925) used the dolomite rhombs and quartz ro-
settes to prove that the calcite and gypsum are derived from
the anhydrite, but did not trace the same relationship from
the anhydrite into the salt. The occasional lenses of de-
trital sand and the sandstone fragments in the anhydrite cap rock are strikingly similar to the sand included in the salt. Rarely, there are also fragments of bedded anhydrite that probably were derived from the salt.

Horizontal joints, sometimes with slickensided surfaces, are well developed in cap rock. In places there are narrow, dark bands that are due to the deposition of secondary pyrite, carbonaceous matter, calcite, and sulphur along the joints or shear planes. Bands of lighter-gray slightly finer grained anhydrite may be due to periodicity during accumulation of the residue, or to the solution of salt containing anhydrite grains that are smaller than the average. The less common minerals of the residues, particularly the dolomite and quartz, are locally concentrated along some of the narrow bands that show the effect of shearing. This concentration may be due to some type of sorting action during solution of the salt. In general, however, it can be said that "katatectic banding" as described by Goldman (1933), or any type of banding resulting from conditions of accumulation, is subordinate to the banding that is due to shearing. The anhydrite becomes more sheared upward from the salt-anhydrite contact, grading into the fibrous-appearing closely-banded anhydrite just below the transition zone. Small patches of finer-grained anhydrite, that give some of the
anhydrite cap rock a mottled appearance, appear to be the same, in most cases, as the "knots" of fine-grained anhydrite that are rather common in the salt, though they may, in some instances, be due to crushing. The bending in the calcite cap rock follows structures inherited from the anhydrite.

The stresses that have sheared the anhydrite, and brecciated the calcite, have come from both collapse and up-thrust. The high-angle, as well as the horizontal, shear planes or zones, could be formed by either force. Wherever the relationship can be established, breccia fragments appear to have been derived from overlying cap rock, suggesting a predominance of collapse. An appreciable amount of upthrust appears to result in shattering of the cap rock, as at White Castle, or in the stranding of part of the cap rock at lower levels, as at Jefferson Island and other salt domes.

Consideration of the data on both the cap rock and the salt, therefore, leads to the conclusion that anhydrite cap rock has been formed by the accumulation of the water-insoluble residue of the salt. Formation of the anhydrite cap rock in this manner accounts in particular for the relatively flat-topped solution table that decapitates the salt folds, for the brine at the salt-anhydrite contact that contains the same minerals as the salt residues and the anhydrite cap rock, for the great irregularity in development of cap rock, in
contrast to its striking similarity in character, at all salt domes where it is well developed, and for the increase in deformation from the salt-anhydrite contact upward. Studies of the salt indicate that it contains sufficient water-insoluble residue to allow for the formation of a thick cap rock by solution of plausible amounts of salt. Petrographic studies of the salt and cap rock afford conclusive evidence that the anhydrite is derived from the salt. Presence in both the salt and the anhydrite cap rock of the same, and in some cases quite distinctive, minerals, in the same proportion and of the same size and character, cannot be explained satisfactorily in any other manner.

Although considerably more data are needed before the manner in which cap rock is formed can be definitely outlined, certain generalities can be drawn from the data that have been presented, based on the interpretation of cap rock as of residual origin.

There is reason to believe that an anhydrite cap rock will be formed wherever the salt plug encounters circulating water that is not saturated for the soluble salts in the salt plug. The maximum depth at which this can occur cannot be inferred from present depths to cap rock, because undoubtedly some of the cap rock is more deeply buried by sediments than it was at the time of formation, while in other cases it is
shallower. Evidence of burial is found in the replacement of gypsum by anhydrite at depths of 2,000 feet, and in the erosional truncation of cap rock now deeply buried. Cap rock that at present is outcropping inevitably was at one time covered by sediments that have since been eroded away, as accumulation of the anhydrite cap rock in any sort of local basin is rather definitely precluded by the scarcity of detrital minerals.

Thick cap rocks probably have formed relatively near the surface where the circulation of ground waters is sufficiently active to dissolve the salt rapidly. Absence of cap rock on shallow salt domes can be due to one or more of several reasons: solution at or near the surface, with immediate removal of residual material; erosion subsequent to formation; and, upthrust of the salt plug after cap-rock formation, with the cap rock left behind, as in the case of the spine at Jefferson Island. Depths at which cap rock can accumulate are dependent largely upon conditions of water circulation. Coninate waters, as well as normal ground waters of the Gulf Coast, are not saturated for sodium chloride, and are capable of dissolving the salt. The most favorable conditions for the accumulation of a thick anhydrite cap rock would be depths far enough below the surface that the anhydrite sand would not be altered or eroded away as rapidly as dissolved out, and yet shallow enough for active circulation
of ground waters. Because of its very low solubility, anhydrite would not be dissolved rapidly, even by very active water circulation. The solubility of anhydrite increases with an increase in content of NaCl up to a certain point, and this would probably result in the solution of some of the anhydrite of the residues, at least locally. Under the conditions of rapid solution that appear to obtain where thick cap rock is present, however, circulation would probably be too rapid to allow a concentration of NaCl that would result in appreciable solution of the anhydrite.

Immediately following intrusion, the salt plug probably has a shape like that of recently upthrust salt spines, a shape approximating that of a cone. The apex of the cone would undergo the most rapid solution, with waters attacking it from above, and laterally, and with some also coming up the flanks. Calcification of the immediately adjacent sediments would be effected as a result of the mingling of saline waters from the salt plug with ground waters, possibly accompanied by reduction of some of the sulphates. Gypsum might also be crystallized from solution at this time. After formation of a false cap rock, solution would be carried on by waters from lateral sands and from deep sands, both of which would, in many instances, be under artesian pressures. Under the false cap rock, water-insoluble residue from the salt would collect, uncontaminated by material
from surrounding sediments, excepting when collapse or up-thrust of considerable magnitude occurred. With the accumulation of an appreciable thickness of anhydrite, the continually recurring collapse and upthrust, although probably not of great magnitude, would have a compacting and shearing effect on the anhydrite, rather than brecciating it. Waters circulating upward from the top of the salt plug would effect some precipitation of calcium sulphate as anhydrite, and of sodium chloride. Recrystallization of the anhydrite would accompany the compaction and shearing. The isoclinal folds of the salt plug would be decapitated by a solution table, with only the more resistant folds extending above it and up into the cap rock.

As solution continues, the upward thrust of the salt may keep pace with the salt removal, it may exceed salt removal, or collapse may predominate. The rapid sedimentation taking place throughout most of the salt-dome region during the time of cap-rock formation must have complicated the sequence of events that governs the growth of cap rock. The rate of sedimentation, the character of the rocks intruded, the local thickness, structure, and character of the source beds of salt, and minor tectonic disturbances, all are reflected in the variations in the development of salt plugs and of their cap rocks.

There is definite petrographic evidence that the cap
rock of the transition and calcite zones has been formed by alteration of the anhydrite. This relationship will be discussed in some detail under the section on the paragenesis of minerals.

Paragenesis of Minerals

Anhydrite

The manner in which the anhydrite was derived from the salt has already been discussed in detail. The anhydrite grains in the salt were precipitated at the time of deposition of the "mother" bed of salt. These anhydrite grains are larger than those in primary sedimentary anhydrite because they were precipitated after concentration for CaSO₄ had been passed, and the rate of precipitation had decreased. Although they occur widely disseminated through the salt, they are concentrated in closely spaced "annual" layers. The degree of concentration in these "annual" layers is highly variable, with the anhydrite constituting from 5 to as much as 90 percent of the bands. The average amount in the bands appears to be from 7 to 15 percent. Because of its low solubility, the anhydrite remains as a residue on solution of the salt in water. A number of other relatively water-insoluble minerals are associated with the anhydrite in the salt, having also been precipitated from the same solution as the "mother" bed of salt. Of these minerals, dolo-
mite, as large rhombs with nuclei, quartz, as single crystals and as rosettes with nuclei, and crystals of pyrite, sulphur, celestite, and barite, occur both in the residues and in the anhydrite cap rock, contemporaneous with the anhydrite. Dolomite is the most abundant of these, but constitutes slightly less than one percent, on the average. Where sulphur is an important cap-rock mineral, it occurs secondarily. Celestite and barite also are found in cap rock as secondary minerals.

Gypsum

This mineral is developed from the anhydrite by hydration that occurs chiefly in the transition zone. The petrographic evidence for this alteration has been noted by Goldman (1925) and Brown (1931). The progress of the alteration can be traced from its inception between grains and along shear planes and cleavages of the anhydrite, to the development of large selenite crystals that retain only the dolomite rhombs and quartz crystals and rosettes as evidence of origin from the anhydrite. Rarely, gypsum replaces dolomite rhombs, and infrequently, sulphur also. Gypsumification seems to progress rapidly once it starts, overtaking the alteration of anhydrite to calcite and sulphur where this has started. Gypsum also alters to calcite and sulphur, but the change apparently takes place less rapidly than when the alteration is directly from the anhydrite.
Calcite and Sulphur

The perfect replacement of anhydrite by these two minerals, and the fact that they usually occur together, constitutes one of the most interesting features of cap rock. With considerable amounts of both of the minerals occurring in secondary veins as well as directly replacing anhydrite, volume relationships are usually obscured. In some cores from near the transition zone, the molecular ratio for anhydrite, i.e., about four parts of calcite to one of sulphur, is maintained. The total amount of calcite, however, is usually in excess of the required amount. Gypsum bears the same relationship to the calcite and the sulphur as the anhydrite, but its presence does not seem important in their occurrence. Anhydrite is replaced where gypsum is not present, but the rapid transformation from anhydrite to calcite and sulphur occurs in the transition zone, also the seat of active gypsification. Further, sulphur is present in only small amounts at many salt domes where there is an appreciable amount of calcite cap rock that is a replacement of the anhydrite.

The presence of hydrocarbons in all cap rock containing calcite and sulphur has led to the inference on the part of many workers that the anhydrite or gypsum is broken down through reduction of the CaSO₄ by hydrocarbons or carbon, either directly or biochemically, with formation of the cal-
cite and sulphur from the resulting compounds through oxidation or other processes. Reducing conditions certainly exist in parts of the cap rock, particularly the transition zone. Large flows of hydrogen sulphide gas have been encountered in drilling into calcite cap rock, where sulphur is of minor importance as well as where it is an important mineral. A trace of carbon or of hydrocarbons, either free or combined, is usually found in Gulf Coast sulphur. It is also known that hydrogen sulphide will react with anhydrite, at temperatures obtainable in cap rock, with the formation of sulphur, calcium hydroxide, and water (Mellor, 1930; Brown, 1935). Oxidation of hydrogen sulphide also produces sulphur; the mingling of carbonate waters with a calcium hydroxide solution results in the precipitation of calcium carbonate. Therefore, if the reduction can be satisfactorily accounted for, the chemical reactions that brought about the transformation from anhydrite and gypsum to calcite and sulphur can be outlined. This explanation, modified in various ways, is the one usually adopted for the calcite and sulphur of cap rock. It is strengthened by the fact that similar deposits of associated sulphates, hydrocarbons, calcite, and sulphur occur in many parts of the world (Stutzer, 1933; Thieler, 1936), and that enough experimental work has been done to show that the necessary reactions will take place.
Although the largest sulphur deposits are those associated with sulphates and hydrocarbons or bituminous matter, there are important volcanic deposits, such as those of Japan, Chile, Mexico, and the western United States (Stutzer, 1935, Thieler, 1936). The volcanic deposits are usually explained as due to the oxidation of solfateric or magmatic hydrogen sulphide. The Sicilian deposits were assigned to a volcanic origin by earlier workers, one explanation being that the hydrogen sulphide had been released by springs into lakes or lagoons, where it was immediately oxidized, being precipitated out in the manner of a sedimentary deposit (Hunt, 1915). However, there is no evidence that there have been solfateric or magmatic influences associated with the Gulf Coast deposits.

Other outside sources have been suggested for the minerals, i.e., oxidation of sulphide ores, petroleum of high sulphur content, or connate hydrogen sulphide gas, for the sulphur, and ground water for the calcium carbonate, but these sources are unsatisfactory.

Sedimentary deposits of sulphur in Sicily, Russia, and other countries have come more and more to be considered as due to reduction resulting from bacterial action. There is considerable indirect evidence in support of this explanation, but so far, direct evidence has not been found. A very complete survey of the earlier literature on so-called sedimentary sulphur deposits was made by Hunt (1915), in a study of
the Sicilian deposits, and another has been made recently by Murzaiev (1937) in connection with his studies of Russian sulphur deposits. Hunt outlined conditions for the formation of the Sicilian deposits by bacterial reduction of sulphates, basing his conclusions upon early qualitative work, the quantitative work of Beyerinck and Van Delden, and the evidence that bacteria are reducing sulphates to sulphides under anaerobic conditions in the Black Sea and similar bodies of water. The sulphur deposits of Sicily are in small, isolated, basin-like areas, and the sulphur occurs in a limestone in the form of nearly pure bands and disseminated. The limestone is overlain by massive gypsum containing a little sulphur, and is underlain by tripoli. Hunt concluded that deposition of sulphur took place in small lagoons with waters of high sulphate content from which bacteria produced hydrogen sulphide. Sulphur and calcium carbonate were precipitated in these lagoons at the same time, the former through oxidation of hydrogen sulphide, the latter from the action of carbon dioxide upon calcium hydroxide. Concentration in bands was explained by Hunt as being due to periodic accumulation and decomposition of calcium polysulphide. The gypsum was deposited from sea water as a result of continued evaporation, and Hunt suggested that it contains little sulphur because bacteria do not thrive in solutions of evaporated sea water that are
of high enough sodium chloride content for the active precipitation of gypsum to occur.

Hunt rejected inorganic reduction by carbon or hydrocarbons because in the known processes, temperatures of 500° to 700° C. (932° to 1292° F.) are required, and there was no evidence that high temperatures were involved in the formation of the Sicilian sulphur. This temperature requirement has caused others to favor bacterial reduction of sulphates.

Since the time of Hunt's work, sulphate reduction in oil-field waters has received much attention. Recently, Ginter (1934) has summarized the work on subsurface waters, including that of Bastin (1926), Bastin and Greer (1930), Cahl and Anderson (1928), and Thiel (1930), which report identification of bacteria. Ginter concludes, in part, as follows: "Neither is it known whether petroleum and its constituents can serve as a source of energy and of nitrogen for these sulphate-reducing anaerobes" (p. 925). He also observes, "It seems indeed unusual that sulphate-reducing organisms (Microspira desulfuricans, Microspira asetuarii, and Vibrio thermo desulfuricans), isolated from shallow sources in Europe, as well as from the bottom waters of the Black Sea, are to be found in some of our deep subsurface waters" (p. 917). The possibility that there is a limiting concentration of hydrogen sulphide beyond which bacteria could not exist, is suggested by Ginter.
He notes further, that sulphate-reducing bacteria do not thrive in waters containing more than six percent sodium chloride, a much lower figure than that for average oil-field waters, and certainly for salt-dome waters. Sulphate-reducing bacteria are not spore producing and this leads Ginter to conclude that their presence in waters cannot date back to the time of deposition. The reduction of sulphates by inanimate organic matter is supported only by field evidence, i.e., "the paucity of sulphates in some waters associated with petroleum, and in the occurrence of bitumens with some of the sulphide ore deposits" (Ginter, 1934, p. 925).

Murzaiev (1937), in discussing the syngenetic or bedded sulphur deposits of the U.S.S.R., favored biochemical reduction of sulphates and oxidation of the sulphides for the origin of these deposits. He considered that they were formed in lagoons that had a lower reducing zone and an upper oxidizing zone. Reduction by carbon and hydrocarbons without the aid of organisms was rejected by Murzaiev, also because of the high temperatures involved. Murzaiev mentions the theory of Uklonsky (1928) and Ahfeld (1934) that sulphur could result from the action of an unsaturated, hydrocarbon-rich petroleum on the calcium sulphate of surface waters, in a relatively arid region. Field evidence is the basis of this theory, and comes from Uklonsky's study of the sulphur
deposits of Schor Su, Turkestan. Since the publication of Murzaiev's paper, Ahlfeld (1937) has stated that he is in accord with Murzaiev's conclusion that bacteria are the agency that effected reduction of the sulphates.

The origin of cap-rock sulphur and calcite has been considered in the light of the reduction theory by Wolf (1925) and others. There is rather general agreement that these minerals have resulted from the reduction of the anhydrite or gypsum. Wolf (1925, p. 731) states: "One almost insurmountable argument in favor of the theory that the sulphur was formed in place from the reduction of calcium sulphate, with the resulting formation of calcium carbonate and native sulphur, is the relative proportion between the calcium carbonate and the calcium sulphate and the sulphur, as shown by a series of analyses of the sulphur body at Gulf [Big Hill salt dome, Matagorda County, Tex.] from various depths. The carbonate increases and the sulphate decreases with an increase in the amount of sulphur present." He concludes that Hunt's theory of reduction by bacteria in lagoons is difficult to apply to the origin of cap-rock deposits of sulphur and calcite, and suggests that temperatures sufficiently high to effect reduction without bacteria may have resulted from the stresses set up during salt intrusion.

The figures usually presented as necessary for reduction of sulphates by hydrocarbons, 500° to 700° C. (932° to 1292°
F.), are far in excess of any available at salt domes at present, however, and seem much too high to be acceptable. Further, the sulphur does not have the relationships that would be expected if it had existed in the cap rock in a molten state (above 112.8° C. or 235° F.). In connection with the supposed necessity of high temperatures for this reaction, however, it should be noted that the reaction might take place at considerably lower temperatures where a relatively long period of time has been involved, as several workers have suggested.

The data on bacterial reduction in subsurface waters have also been considered by Marx (1936), who states that bacteria are not known to exist in cap rock. Brown (1931) considered that the sulphur in the calcite was derived from syngenetic sulphur in the anhydrite, basing this conclusion upon the interpretation of anhydrite thin section showing remnants of anhydrite grains within sulphur. The relationship is that shown in plate XIX, plate XX, figure 3, and plate XXIV, figure 2, of the present paper (see Brown's fig. 2C), and is clearly that of the replacement of anhydrite by sulphur. There is a small amount of syngenetic sulphur in anhydrite that represents grains derived from the water-insoluble residue of the salt, but as Goldman (in a discussion of Brown's paper) pointed out, this cannot possibly account for the amount of sulphur present in some
cap rock. Later, Brown (1935) stated that there is insufficient sulphur in the anhydrite, even in the combined state, to account for large deposits, and suggested that the deposits are formed as a result of reduction of the anhydrite by connate hydrogen sulphide gas that was formed at the time of salt deposition, trapped, and then released when the salt was intruded. He experimented with the action of hydrogen sulphide on calcium carbonate in a solution saturated for gypsum and containing 15 percent sodium chloride, and found that sulphur formed at a temperature of 130° C. (266° F.) and a pressure of 1,300 pounds. He expressed the reaction as: \( \text{CaSO}_4 + 3\text{H}_2\text{S} = 4\text{S} + \text{Ca(OH)}_2 + 2\text{H}_2\text{O} \). However, the only connate hydrogen sulphide gas that is known is the trace found in some of the salt. Further, it is not necessary to call upon an outside source for hydrogen sulphide, as there is somewhat more sulphur in combination in anhydrite than is needed to balance the amount of calcite cap rock present. Brown's equation is of interest, however, in that it affords a means of direct replacement of anhydride by sulphur by which volume relations are maintained locally. In his earlier work, Brown (1931) turned to the action of ground waters for replacement of anhydrite by calcite. Later (1934), he seems to have abandoned this line of reasoning, as he assigns the calcite cap rock to the same origin as the anhydrite, i.e., a block of primary sedimentary material brought up on top of the
The inference is strong from the association of sulphates, hydrocarbons, calcite, and sulphur, and from the fact that hydrocarbons or carbonaceous matter are included within both the calcite and the sulphur, that the sulphur and calcite have resulted from reduction of sulphates, involving hydrocarbons. According to the theories outlined, the sulphur is deposited by oxidation of the hydrogen sulphide, and the calcite results from mingling of the calcium hydroxide resulting from reduction, and of ground waters bearing the CO₂ radical. However, any theory calling for reduction in one zone followed by oxidation in another cannot explain the direct and complete replacement of the anhydrite by calcite and sulphur. The fact remains also that while volume relations for the sulphur-bearing cap rock as a whole are about what would be expected from the molecular make up of calcium sulphate, in thin sections there is sometimes complete replacement by one of the minerals in the absence of the other. The younger sulphur, that of the veins and cavities, however, can well be deposited as a result of the oxidation of a sulphide removed from the zone of reduction.

There are several possibilities that can be suggested for direct replacement of the anhydrite. It is possible that the sulphur and calcite below the transition zone have been brought in by solutions from the transition zone — the seat
of the most active chemical change in cap rock. A solution containing sublimized sulphur and calcium carbonate could exist at depths below a few thousand feet, on the basis of the average geothermal gradient for salt domes. Direct replacement could be accomplished by this solution, but the sulphur and calcite probably would not be so closely associated as they usually are. Direct replacement by sulphate-reducing bacteria would be difficult because it would not favor the formation of pseudomorphs in which the volume relations of the anhydrite are preserved. Likewise, the type of bacteria capable of producing sulphur directly could not be expected to effect complete replacement. Most of the proposed theories for the reduction of sulphates by carbon or hydrocarbons without bacteria entail the same difficulties in replacement as the bacterial theories. Even if reduction to sulphides were followed immediately by oxidation, possibly by the oxygen of the sulphate radical, complete replacement of anhydrite would not be expected.

The reaction suggested by Brown (1955) can account for direct replacement of anhydrite, with the hydrogen sulphide being supplied by solutions working their way downward from the transition zone. Volume relations would be maintained, and the reaction would be accompanied by precipitation of calcium carbonate through union of the resulting calcium hydroxide and of carbon dioxide from the accompanying solution.
More work must be done with this reaction, however, before it can be definitely accepted.

There is a possibility that this reaction, or a similar one involving hydrocarbons, may be important in the transition zone. Before the inception of active sulphate reduction, a small amount of hydrogen sulphide is available from the petroleum, from the salt plug, and from the action of hydrocarbons on whatever sulphur had been inherited from the salt. It is possible that in the presence of so active a reducing agent as hydrogen sulphide, and with the aid of the warm waters of the salt dome, a reaction between the hydrocarbons and sulphates would be initiated that under optimum conditions would be accelerated to the point of very active reduction. Certainly the associations suggest some such reaction, and from what is known of sulphur bacteria, the conditions under which the reaction occurred are not those favorable to bacterial growth.

Another factor to be considered in this problem is the manner in which the transition zone has worked from the top of the cap rock downward, having become active some time after the formation of an appreciable thickness of anhydrite cap rock. Several explanations can be advanced for this. It is not primarily because altering solutions could enter more easily at the top, for alteration did not, in most cases, begin with formation of the cap rock. The impervious-
ness of the false cap rock, and the gumbo beds that sometimes overlie the cap rock, indicate that the zone did not encroach from the surface. Rather, transgression of the transition zone from the top of the cap rock downward indicates the rather sudden appearance of the altering solutions—petroleum and hydrogen sulphide, or possibly bacterial cultures.

To summarize this discussion, the only definite statement that can be made regarding the paragenesis of the sulphur and calcite, is that they are contemporaneous and that they have been formed by alteration of the anhydrite and gypsum. The manner in which this alteration has been brought about is not clear, but relationships suggest that it has resulted from some form of reduction. Whether the reaction has resulted from the action of bacteria, or whether it is due to the action of hydrocarbons or other reducing agents in the absence of bacteria, is not known. The bulk of the evidence seems to favor the latter explanation. In the case of vein sulphur, the reduction that probably occurred in the transition zone was followed by oxidation in another part of the cap rock. Complete replacement of anhydrite by sulphur, with the formation of pseudomorphs, however, suggests that some other reducing agent, such as H2S, may have been active, or that some reaction at present not known was involved. Calcite has probably been formed by the reaction of calcium hydroxide, released from CaSO4, with carbonate waters.
The presence at some salt domes of considerable amounts of calcite in cap rock that does not contain more than a trace of sulphur calls for explanation. Cap-rock calcite is of the same type regardless of whether sulphur is present or not; in all cases, direct evidence of its derivation by alteration of the anhydrite can be detected. As anhydrite contains about one-fourth sulphur, by molecular weight, large quantities of sulphur have been released in some form. At Winnfield, for example, there is about 100 feet of calcite cap rock, but very little sulphur, and the amount of secondary pyrite and other sulphides is far from enough to account for the amount of sulphur released. Of the hundred or more salt domes having cap rock, only 13 have been found in which there are commercial sulphur deposits, so the question appears to be one of determining the special conditions under which sulphur is retained.

The chances of sulphur escaping as hydrogen sulphide before it could be deposited are very good. Further, if the sulphur had been deposited, there is the possibility that it would be reduced to hydrogen sulphide, by hydrocarbons, and thus escape. Ahlfeld (1934) has noted that wherever there are large quantities of hydrocarbons, the possibilities of finding deposits of sedimentary sulphur are not favorable. Salt domes are veritable flumes into which water, petroleum, and gas are deflected. The breached condition of the shallow
salt domes affords an escape to the surface for these substances, and where there is active circulation, flushing of gases from the cap rock would result, except under special conditions. The cavernous condition of the calcite cap rock is due to this active circulation, and may also be due in part to removal of sulphur.

Apparently preservation of the sulphur deposit calls for some form of seal which prevents the escape of the sulphur in the form of hydrogen sulphide gas. This seal is formed in part by the false cap rock and in part by shale and gumbo, as at Jefferson Island and Lake Washington. There are indications that faulting may seal the cap rock laterally. Breaking of this seal would result in removal of the sulphur, unless the seal were immediately closed again by infiltering clays, as at Jefferson Island and Belle Isle, in the manner of the "mudding" practice employed in sulphur mining. There is also the implication that the sulphur is of quite recent development, unless the solution of the salt has been retarded by the seal and the cap rock and salt plug are in a condition of relative stability. Rapid sedimentation, with resulting deep burial, would also aid in preserving the sulphur, as Ahlfeld (1934) has suggested. The sulphur deposits of the Gulf Coast certainly are not old geologically, for in addition to the fact that sulphur is reduced by hydrocarbons
to hydrogen sulphide, and would have had repeated opportuni-
ties to escape as hydrogen sulphide at times of cap-rock
brecciation, the sulphur apparently is still being formed
from the anhydrite.

Other Minerals

The sulphates, barite and celestite, that are contemp-
orous with the anhydrite, probably have come from the
water-insoluble residue of the salt, along with the anhy-
drite, dolomite, and traces of quartz, calcite, pyrite, sul-
phur, and hauerite. Secondary barite and celestite that
occur in the upper part of the anhydrite zone and throughout
the calcite and transition zones, represent traces of these
elements released during solution of the salt and alteration
of the anhydrite, as traces of strontium and barium are
found in both of these minerals. Warm waters may have aided
in their concentration and reprecipitation. Aragonite,
strontianite, and smithsonite are also minerals that would be
expected in a rock body that has formed as a result of
solution of salt.

With regard to the secondary sulphides, the concentration
of pyrite, a common mineral in Gulf Coast sediments, in cap
rock and in false cap rock is probably due to the reaction
of H₂S with iron released during solution of the salt, as
Gulf Coast salt contains an appreciable amount of iron oxide.
Traces of other sulphides can also be assigned to this origin. The presence of appreciable amounts of galena at a few salt domes is somewhat difficult to explain as having come from the salt, although the warm salt-dome waters may also have had a concentrating effect in this case also. Lack of direct evidence is unfavorable to an outside source, such as magmatic waters, for any of the cap-rock minerals.
Summary and Conclusions
The anhydrite cap rock of the salt domes of the North American Gulf Coast region is a residual accumulation of the relatively water-insoluble materials in the rock salt of the associated salt plugs. The following evidence points to this conclusion: (1) the relatively flat-topped salt table, present at many salt domes, decapitates all of the isoclinal folds in the salt excepting those that are more resistant to solution, and these project up into the cap rock; (2) brine, with associated salt residue, occurs at the salt-anhydrite contact; (3) the minerals of the salt residues can be traced into the overlying cap rock; (4) the development of the anhydrite cap rock has been established as progressing from the salt-anhydrite contact upward; and (5) the anhydrite of cap rock has been found by comparison to be identical to the anhydrite in the salt and distinctly different from that of primary, bedded deposits.

The amount of residue in salt and the amount of salt available in salt plugs is sufficient to allow formation of the thicker cap rocks. The variable thickness of cap rock is due to conditions of accumulation, total amount of salt dissolved, and the amount of residue in the salt. Absence of cap rock at shallow salt domes is not due to lack of residual material in the salt, but to recent upthrust or to conditions unfavorable to accumulation. Typical horizontal
and other banding is due largely to the deposition of secondary minerals along shear planes or zones. Some of the horizontal banding, particularly that in the anhydrite near the salt contact, may be due to differences in composition of the salt, and to periodicity of accumulation.

The gypsum, calcite, and sulphur of cap rock have been formed by alteration of the anhydrite. The transition zone, in which the anhydrite has been altered to gypsum, calcite, and sulphur, apparently comes into existence after a considerable thickness of anhydrite has accumulated, and works from the top of the cap rock downward. Altering solutions can enter from the flanks, or laterally, and probably consist of petroleum and hydrogen sulphide, so that appearance of the transition zone may be coincident with the entrance and accumulation of hydrocarbons. Alteration is most active in the transition zone and probably consists of reduction, with attendant or subsequent oxidation. The actual steps possible are reduction of the anhydrite in the presence of excess hydrogen sulphide, with oxidation of the hydrogen sulphide either immediately, caused by oxygen from the sulphate radicle, or later, following migration of the hydrogen sulphide to a part of the cap rock where oxidizing conditions exist. Calcite could be formed by the reaction of calcium hydroxide, formed at the time of the reduction, with carbon dioxide derived from ground water. Cultures of bacteria may
cause the alteration, but bacteria are not known to occur in cap rock, and the environment under which reduction has occurred is one that would not be favorable to the activities of known bacteria.

Wherever calcite cap rock is present, it contains the distinctive dolomite rhombs (many of which are replaced), quartz crystals and rosettes, and banded structure, showing that it has been derived from the anhydrite. The calcite and sulphur that occur in veins and fill cavities are younger than where directly replacing anhydrite, but have also been derived from the anhydrite. Some of the sulphur directly replacing anhydrite would be moved as hydrogen sulphide if subjected for long to the reducing influences of an excess of hydrocarbons. Where a seal does not exist, sulphur would be lost as hydrogen sulphide, leaving behind the cavernous calcite cap rock.

Other minerals of the cap rock in addition to the anhydrite, calcite, gypsum, and sulphur, appear to have been derived either directly or indirectly from the salt.

The sequence of events that probably takes place during cap-rock formation is outlined below. Few salt domes, of course, have passed through all of the stages listed here; examples of nearly every stage can be found among known salt domes. A few such examples are cited:

1. Intrusion of the salt plug into a zone of active
water circulation, probably up to within a few hundred feet of, but not to, the surface, or if to the surface, in an environment in which the surface of the salt would soon be covered by sediments. Where intrusion did not bring the salt into the zone of active water circulation, cap rock would be thin or wanting, as at Henderson, Convent, or Timbalier Bay. Where intrusion has been recent, cap rock would also be thin or wanting, as at Avery Island, Cote Blanche, and the spines at New Iberia and Jefferson Island.

2. Rapid solution of the salt, taking place with the greatest rapidity at the apex of the cone-shaped salt plug. Cementation of the surrounding sediments would begin at this stage. Anhydrite sand would begin to accumulate in irregular pockets and solution cavities in the salt surface. Waters moving up the sides of the salt plug would effect some solution and residue would also accumulate on the flanks; false cap rock would also begin to form at the flanks. Anse La Butte is probably an example of this stage.

3. Gradual truncation of the top of the salt plug, decapitating the folds in the salt and forming a solution table, with the anhydrite sand derived from the salt accumulating upon it, relatively uncontaminated by surrounding sediments due to the covering of false cap rock. Bay Marchand salt dome may be at about this stage of development.

4. Beginning of the compaction of the cap rock as a result of occasional collapse of the false cap rock and up-
thrust of the salt, accompanied by some precipitation of anhydrite from solution and intergrowth of anhydrite grains. From what is known of Vermilion Bay salt dome, it is an example of this stage.

5. Continued solution of the salt, with the upthrust of the salt plug compensating for the salt removed, with more rapid upthrust than removal, or with upthrust lagging behind solution. The tendency toward deeper burial of the top of the salt plug, due to continued sedimentation, also would have to be overcome by upthrust of the salt. Shearing of the anhydrite as it became consolidated would result from stresses set up by upthrust and collapse. The upper part of the cap rock and that along the flanks would be repeatedly broken and recemented. Sorrento, Gueydan, and Hackberry salt domes apparently are near this stage.

6. Entrance of altering solutions and inauguration of the transition zone in which anhydrite alters to gypsum and both in turn alter to calcite and sulphur, with the relict anhydrite structure retained. This might begin early, after the formation of a relatively thin anhydrite cap rock, or might be delayed until a fairly thick cap rock had been formed. The cap rock at Garden Island Bay is at about this stage of development.

7. Transgression of the transition zone downward, escape of hydrogen sulphide or its oxidation to sulphur in
place or within the overlying cap rock, and deposition of calcite. Secondary veins of calcite and sulphur, and of pyrite, other sulphides, barite, and celestite, develop in the upper part of the calcite zone, or replace sulphur in the transition zone. Continued influx of hydrocarbons results in the reduction of sulphur and its redeposition in another part of the cap rock, or its escape. Caverns develop in the upper calcite zone, owing to active circulation of ground water, and possibly as a result of removal of sulphur, and collapse of the lower part because of solution of salt. Several of the salt domes that have commercial sulphur deposits, and others that have considerable thicknesses of calcite cap rock virtually barren of sulphur, are examples of this stage. Lake Washington is included in the former group and Hockley in the latter.

8. Cessation of cap-rock growth, due to quiescence of the salt plug and the development of a seal that retards circulation of water. Sulphur salt dome appears to be an example of this stage.

9. Final stages might be the removal of cap rock by uplift and subsequent erosion, stranding of relatively thick cap rock at a lower level by a sudden upthrust of the salt plug, or shattering of relatively thin cap rock owing to a considerable upthrust of the salt plug. Cap rock is exposed to surface erosion at Winnfield and Pine Prairie, it
has been stranded at a lower level at Jefferson Island, and apparently is shattered by uplift at White Castle.

There are a number of points in this outline that call for further study. The residual origin of cap rock appears to be well established, but exact knowledge of all the processes involved must await detailed studies of the salt, cap rock, and surrounding sediments at a number of salt domes, including the deeper ones. The material and data that are needed for making these studies are difficult to obtain, particularly in the case of the deeper domes, but with the continued intensive search for sulphur and petroleum reserves these should become available. Cores of cap rock and salt must be studied in detail whenever possible. The difficult problem of the reactions involved in the alteration of anhydrite to calcite and sulphur should be investigated. All possible combinations of the substances that might be involved in this alteration should be tested exhaustively, and cap rock and natural salt-dome waters in which there can be no question of surface contamination should be examined for bacteria. Only by careful studies of all the material available, and a consideration of every theoretical possibility, will rock bodies so remote from direct observation as salt-dome cap rock ever be fully understood.
Appendix A

Economic Geology
Cap rock is an important source of "limestone," petroleum, and sulphur in the Gulf Coast. Of these, the last is of the most importance as cap rock has furnished the major part of the world's sulphur since the year 1906, and continues to do so at the present time. Gulf Coast sulphur has attained this position because of the scarcity of other types of sulphur deposits of appreciable size, and because the mode of occurrence and the physical and chemical properties of sulphur lend themselves to the mining of these otherwise inaccessible cap-rock deposits. Petroleum is probably second in value of cap-rock products, but the amount that has been produced is very small in comparison to the total amount that has been obtained from other sources. Cap rock is important as a source of "limestone" only where other sources are not available and where the calcite cap rock lies sufficiently close to the surface to permit advantageous quarrying. Although some gypsum has been quarried at Gyp Hill, Tex., the anhydrite and gypsum are of little value because of their limited uses and because of the comparatively high cost of mining them. The hematite, limonite, and metallic sulphides do not occur in cap rock in sufficient quantities to be of economic importance.

The three economically important cap-rock products will
be discussed separately, especially with reference to their occurrence in Louisiana.

"Limestone"

There are only two Louisiana salt domes at which cap rock comes close enough to the surface to allow quarrying of the calcite portion; these are Winnfield, in the south central part of Winn Parish, and Pine Prairie, in west central Evangeline Parish. The "limestone" is exposed at the surface at both of these salt domes, and has been utilized at Winnfield since the early part of the nineteenth century. It is of much the same character at both localities, consisting of cavernous and somewhat broken coarsely crystalline calcite, with irregular light- and dark-gray, or blue and gray, bands. The quarried product is fairly uniform in composition, ranging from 92 to 98 percent calcium carbonate. Clay and sand have filtered into the cap rock from adjacent sediments in places, however, and gypsum extends well up into the calcite in some parts of the quarries.

Until recently, the chief use of the "limestone" has been as crushed rock for surfacing roads. Unsuccessful attempts have been made to use that at Winnfield, known locally as "marble" because of its coarsely crystalline character, as building stone. Rock crushers have been in operation at Winnfield since about 1900, and at Pine Prairie
since 1933. The calcite of both deposits has also been used for the production of lime. At present the quarry at Winnfield is being operated by the Solvay Process Co., Inc., who took over the deposit from the Louisiana Stone and Lime Corp., and are shipping the greater part of the output to Baton Rouge for use in their soda ash plant. Some of the rock at Winnfield is still being used for road surfacing, while almost all of that being quarried at Pine Prairie, where the Louisiana Stone and Lime Corp. operate a quarry and a crusher, is at present being diverted to this use. The Rock and Lime Corp., Inc. have kilns for the production of lime at Pine Prairie, but at present are not operating them.

Following are data on production and reserves of "lime-stone" for recent years at the two Louisiana localities:

Production (short tons)

<table>
<thead>
<tr>
<th></th>
<th>Winnfield</th>
<th>Pine Prairie</th>
</tr>
</thead>
<tbody>
<tr>
<td>1930</td>
<td>125,503</td>
<td></td>
</tr>
<tr>
<td>1931</td>
<td>577,677</td>
<td></td>
</tr>
<tr>
<td>1932</td>
<td>291,055</td>
<td></td>
</tr>
<tr>
<td>1933</td>
<td>14,543</td>
<td>16,188</td>
</tr>
<tr>
<td>1934</td>
<td>74,279</td>
<td>21,100</td>
</tr>
<tr>
<td>1935</td>
<td>250,732</td>
<td>14,186</td>
</tr>
<tr>
<td>1936</td>
<td>258,195</td>
<td>54,326</td>
</tr>
<tr>
<td>1937</td>
<td>348,385</td>
<td>65,084</td>
</tr>
</tbody>
</table>

Estimated Reserves (short tons)

- Winnfield: 20,000,000 to 30,000,000
- Pine Prairie: 10,000,000

Petroleum

One of the most interesting points in connection with the production of petroleum from cap rock is that develop-
ment of the great petroleum reserves of the Gulf Coast was initiated by the completion in 1901 of the "Lucas gusher" at Spindletop, Tex., a cap-rock producer. Discovery of the prolific Spindletop field focused the attention of the petroleum industry on salt domes, with the resultant discovery of large cap-rock production at Sour Lake, Humble, and Batson, Tex., and the intensive search for salt domes that is still in progress.

Although production has been obtained from the cap rock of several Louisiana salt domes, no fields similar to the large Texas cap-rock fields have been discovered in this State. Total production from this type of reservoir in Louisiana has been less than 5,000,000 barrels, whereas nearly 200,000,000 barrels have been produced from the cap rock of Texas salt domes. The Louisiana production has come mainly from Lake Washington, Sorrento, Starks, and Black Bayou. Cap-rock production has also been reported for Hackberry, Edgerly, Fausse Pointe, Anse La Butte, and New Iberia, and small amounts of petroleum have been found in the cap rock at Sulphur, Jefferson Island, and several others. Lake Washington has been the principal producer, with a production of about 1,200 barrels per day.

The petroleum is obtained from the upper cavernous portion of the calcite zone and the sandy false cap rock, where its escape is prevented by overlying impervious shales and clays. Cap-rock petroleum differs somewhat from that of
other sources. According to Barton (1935), that from Spindletop has an A.P.I. gravity of 19.7 degrees, lower than that from most other sources. Further, Barton notes that its A.P.I. gravity is lower for the lighter fractions and higher for the heavier fractions than in the case of other Gulf Coast petroleum, and that it has much higher sulphur and carbon-residue content.

Sulphur

Commercial sulphur deposits have been developed at three Louisiana salt domes: Sulphur, in central Calcasieu Parish; Jefferson Island, in western Iberia Parish; and Lake Washington or Grande Ecaille, in Plaquemines Parish. The manner in which the sulphur occurs in the lower calcite and transition zones of the cap rock, replacing anhydrite and gypsum, and as veins, has already been discussed in another part of this paper.

Mining is carried on by the Frasch process, a process developed by Herman Frasch at the Sulphur salt dome. In this process, the sulphur is melted in place by superheated water introduced by means of concentrically cased drill holes, and the melted sulphur brought to the surface through the same drill holes with the aid of compressed air. Several detailed descriptions of the Frasch process have been published, including recent ones by O'Donnell (1935), Marx
(1936), and Howe and McGuirt (1936). Described briefly, this method of mining involves the drilling of closely spaced wells of 8- or 10-inch diameter with the usual rotary drilling equipment. Most of these wells are drilled through the calcite and transition zones and into the anhydrite zone. An 8- or 10-inch protective casing is set at the top of the cap rock, and a casing of six or eight inches diameter, the "hot-water line," with the lower several feet perforated, is set in the bottom of the well. The "sulphur line," a three- or four-inch casing, with the lower end open, is then seated inside the "hot-water line," within the perforated portion. Tubing of an inch or an inch and one-quarter diameter, the "air line," is suspended inside the "sulphur line," extending to a point somewhat above the highest perforations on the "hot-water line."

In the mining operation, water that is under sufficient pressure to maintain a temperature of 320 to 350°F, is forced down both the "hot-water line" and the "sulphur line." The hot water gradually raises the temperature of the sulphur-bearing formation above the melting point of sulphur. As the molten sulphur is heavier than water, it collects in a pool at the bottom of the well, flows through the lower perforations in the "hot-water line" and enters the "sul-
phur line" through an opening in the seat. After hot water has been pumped into the well for several hours, the water intake is disconnected from the "sulphur line" and air under considerable pressure is turned into the "air line." There, if there is sufficient sulphur present to make the well a producer, the molten sulphur will rise inside the "sulphur line" to a point above the "air line", and the compressed air, with the aid of the mine pressure, will cause the sulphur to rise to the surface. When it reaches the surface, the molten sulphur flows through insulated pipe lines, that have steam lines running through them to nearby steam-heated collecting pans. The liquid sulphur is pumped from the collecting pans through heated and insulated pipe lines to vats — boarded inclosures in which the sulphur is allowed to cool and solidify. When it is to be marketed, the solidified sulphur is broken from the vats by blasting. The run-of-mine product is of extreme purity, averaging 99.5 percent, or better.

In the successful development of a cap-rock deposit of sulphur by the Frasch process, there are a number of factors which must be taken into consideration. As the chief use of sulphur is in the manufacture of sulphuric acid, elemental sulphur meets strong competition from sulphuric acid manufactured from pyrite and from flue gases. If the sulphur produced is to compete under present market conditions,
therefore, the deposit must be of sufficient size and concentration to permit economic development. Recovery varies with concentration, but a probable maximum recovery of about 75 percent must be taken into consideration in estimating the commercial possibilities of a deposit. The character of the cap rock, i.e., percentage of sulphur to calcite, thickness of the sulphur-bearing formation, and porosity, must be given attention. Cavernous cap rock can sometimes be successfully mined by introduction of a mud solution that closes off cavities, although this operation involves considerable expense. Depth of the sulphur-producing horizon is also of importance. If the cap rock is too shallow, there is a possibility of great loss of heat; the maximum depth at which sulphur has been mined is about 2,000 feet, but development of large deposits at greater depth should be economically possible. The deposit must also be located in a region advantageous to erection of a large plant in which the one to several million gallons of water used daily can be heated. An adequate supply of cheap fuel and of fresh water for the boilers is also necessary. Storage space and transportation are other factors which must be considered.

A total of some 41,000,000 long tons of sulphur, valued at over three-fourths of a billion dollars, has been produced from the cap-rock deposits of the Gulf Coast. This production has come from 10 salt domes, with over 90 percent from only five. The approximate total production from Louisiana
and Texas is as follows:

<table>
<thead>
<tr>
<th>Name</th>
<th>Production to Jan. 1, 1938</th>
<th>Year Opened</th>
<th>Present Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur (La.)</td>
<td>9,400,000</td>
<td>1898</td>
<td>Abandoned 1924</td>
</tr>
<tr>
<td>Bryan Mound (Tex.)</td>
<td>5,000,000</td>
<td>1914</td>
<td>Abandoned 1935</td>
</tr>
<tr>
<td>Big Hill (Gulf) (Tex.)</td>
<td>11,800,000</td>
<td>1916</td>
<td>Abandoned 1936</td>
</tr>
<tr>
<td>Hoskins Mound (Tex.)</td>
<td>5,000,000</td>
<td>1923</td>
<td>Producing</td>
</tr>
<tr>
<td>Palangana (Tex.)</td>
<td>240,000</td>
<td>1928</td>
<td>Abandoned 1935</td>
</tr>
<tr>
<td>Boling (Tex.)</td>
<td>7,580,000</td>
<td>1929</td>
<td>Producing</td>
</tr>
<tr>
<td>Long Point (Tex.)</td>
<td>380,000</td>
<td>1930</td>
<td>Producing</td>
</tr>
<tr>
<td>Jefferson Island (La.)</td>
<td>426,000</td>
<td>1932</td>
<td>Abandoned 1936</td>
</tr>
<tr>
<td>Lake Washington (La.)</td>
<td>1,137,000</td>
<td>1933</td>
<td>Producing</td>
</tr>
<tr>
<td>Clemens (Tex.)</td>
<td>100,000</td>
<td>1937</td>
<td>Preparing for production</td>
</tr>
<tr>
<td>Orchard (Tex.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>41,163,000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Production at Lake Washington, the only Louisiana deposit that is being mined at present, was 337,655 long tons during 1937. Production in Texas during 1937 totaled 2,679,950 long tons.

The reserves of sulphur for the Gulf Coast are estimated, on the basis of available data, as somewhat in excess of the total amount that has been mined to date. In considering reserves, the possibilities of future discoveries must also be taken into account. Of the hundred Gulf Coast salt domes
with cap rock, commercial deposits of sulfur have been found at 11 (including Orchard, Tex.). At least 25 Gulf Coast salt domes with cap rock have been prospected specifically for sulfur, including the following in Louisiana: Starks and Vinton in Calcasieu Parish; Black Bayou in Cameron Parish; Choctaw in Iberville Parish; Belle Isle in St. Mary Parish; Sorrento in Ascension Parish; Napoleonville in Assumption Parish; Chocahcule in Lafourche Parish; Bay St. Elaine in Terrebonne Parish; and Lake Hermitage and Potash, in Plaquemines Parish. Most of the remaining salt domes favorable to the occurrence of sizable deposits of sulfur have been prospected to some extent as a result of the drilling of oil tests. It is probable that very few favorable sulfur prospects remain to be found in the present region of production, in view of the intensive search that has been conducted for salt domes. The possibility should not be overlooked, however, that discoveries may be made in areas of the Gulf Coast that are relatively unexplored for salt domes, such as east Texas, north Louisiana, and west Mississippi. Indications are that added reserves will consist of small deposits at known, but incompletely explored, salt domes, and that discovery of large deposits must depend upon the rather unlikely possibility that more salt domes containing large deposits are yet to be discovered.
The suites of core samples described here represent one sulphur well drilled by the Jefferson Lake Oil Co., Inc., at Jefferson Island, and two drilled by the Freeport Sulphur Co. at Lake Washington. The descriptions are based upon the detailed analysis of all of the core samples with the hand lens, and of thin sections of some of the samples with the petrographic microscope. The thin sections were spaced in such a manner as to include the important changes in the section, with particular attention being paid to the transition zone and the sulphur-bearing cap rock. Photomicrographs of some of the thin sections are included in plates VI to XXVI.

Jefferson Lake Oil Company, Inc.,
Lake Peigneur, No. 36 well.11

0-604: Unconsolidated sediments composed of sand and gumbo (sticky blue-gray clay), with sandy shale and fragments of broken sandy fine-grained calcite cap rock in the lower few feet.

604-310: Brecciated dark-gray fine-grained sandy calcite cap rock, with light-gray coarsely crystalline calcite

A description of part of the cores from this well has been published by O'Donnell (1935), based on an examination of the cores with the hand lens by Dr. R. Dana Russell, School of Geology, Louisiana State University.
as the cementing material. The breccia fragments are composed of dark-gray fine-grained calcite, with abundant included grains of detrital quartz and a few grains of other detrital minerals. The appearance of this cap rock in thin section is illustrated by a photomicrograph, plate VI, figure 1. Inclusions of finely divided opaque substance, partly creamy white by reflected light (argillaceous?) and partly dull black (carbonaceous?), also occur in the breccia fragments. The coarse-grained calcite is replacing the breccia fragments. Pyrite occurs as disseminated grains and in irregular veins in both types of calcite. Subhedral quartz crystals, quartz rosettes with nuclei of opaque finely divided substance, white by reflected light, and large well-defined rhombohedral areas of calcite that are probably replaced rhombs of dolomite, bordered by irregular, simultaneously extinguishing calcite areas, occur sparingly in the breccia fragments.

From 610-624 feet the cap rock is similar to that from 604-610 feet, although broken in the upper part and containing some shale. Sulphur of the type occurring from 624-628 feet first appears in the lower part of this interval.

624-628: Very porous dark-gray broken calcite cap rock con-
taining much opaque material, reconstituted with coarsely crystalline calcite, and with abundant coarsely crystalline sulphur in veins and cavities. In the calcite of the breccia fragments, crystalline sulphur is disseminated interstitially, and microcrystalline sulphur occurs in hair-like veins. The microcrystalline sulphur of the very fine veins is nearly opaque at a magnification of 25 times (pl. X, fig. 1), but with a magnification of 400 times (pl. X, fig. 2), individual grains can be detected. The crystalline sulphur of the large veins and that filling cavities is composed of individual irregular crystals, of different optical orientation, and occurs throughout the section. Pyrite is abundant as disseminated grains and irregular veins, and comprises the greater part of the opaque substances; the remaining opaque material is like that described for 604-610 feet. Subhedral quartz crystals, and calcite areas with relict rhombohedral outlines, are also present. (See pl. VII, fig. 1).

The interval between this section and the next one for which thin sections were prepared is similar to the part just described, with some gouge, varying amounts of sulphur, and with breaks of quartz and calcite sand.
653-657: Light-gray coarsely crystalline calcite cap rock, with coarsely crystalline sulphur in veins and filling cavities. Much of this cap rock is sandy and saturated with petroleum. A few remnants of breccia fragments of dark-gray fine-grained calcite are present, with their former outlines indicated by the opaque included material and disseminated crystalline and microcrystalline sulphur. Pyrite occurs as disseminated grains and in irregular areas where it is replacing sulphur. Some marcasite is associated with the pyrite.

The interval from 657-660 feet is the same, and a foot of unconsolidate material, composed of cap-rock fragments, sand and shale, occurs below it.

670-673: Fine-grained medium-gray breccia fragments of calcite cap rock, containing well disseminated grains and very fine branching veins of crystalline sulphur and pyrite. The breccia fragments are recemented by coarsely crystalline calcite and traversed by veins of coarsely crystalline sulphur. Some of the fragments are partially replaced by the coarser calcite. Pyrite is confined almost entirely to the breccia fragments, replacing sulphur and in places forming irregular bands; a few grains of detrital quartz also occur in the fine-grained calcite.
673-675: Dark-gray fine-grained calcite cap rock brecciated and recemented with fibrous aragonite and more coarsely crystalline calcite. Pyrite and microcrystalline calcite form narrow bands in the fine-grained calcite. The pyrite also occurs as disseminated grains. The aragonite is partially replaced by coarsely crystalline calcite. An opaque white substance is included in the fine-grained anhydrite.

675-678: Gray fine-grained calcite cap rock, less brecciated than the overlying, that contains abundant crystalline sulphur. Some of the sulphur is intimately associated with the calcite, while some occurs as large veins cutting across both the fine-grained and the coarse-grained vein calcite. Pyrite is well disseminated, chiefly in the fine-grained calcite. Aragonite, almost completely replaced by calcite, broken dolomite-like rhombs replaced by calcite, broken barite crystals, and euhedral quartz crystals, are also present.

678-675: A gouge zone occurs in the upper part of this section; the lower part is a fine-grained massive medium- to dark-gray calcite, veined with white calcite and somewhat porous. Crystalline sulphur is abundant as veins, cavity fillings, and disseminated grains.
685-689: Fine-grained dark-gray calcite with numerous small cavities and with abundant crystalline sulphur as cavity fillings and in widely disseminated, in many instances rectangular-shaped, grains, groups of which are of the same optic orientation. (See plate VII, figure 2.) Similar small rectangular areas also occur in the calcite. These structures appear to be identical with the structures formed by anhydrite cleavage fragments in the lower part of the cap rock. Detrital grains and euhedral crystals of quartz occur within both the sulphur and the calcite. Dolomite-like rhombs replaced by calcite are also present. Pyrite occurs in veins and disseminated.

689-693: Light-gray fine-grained calcite cap rock somewhat brecciated and recemented by coarsely crystalline calcite. Crystalline sulphur occurs disseminated throughout the fine-grained calcite, some as rectangular-shaped grains and some as veins cutting the entire section. Pyrite occurs in fine-hair-like veins, and disseminated. There are also the dolomite-like rhombs replaced by calcite, barite crystals, and euhedral quartz crystals, including one large broken one with inclusions of anhydrite grains.
Quartz sand cemented by fine-grained calcite with veins of microcrystalline sulphur that give it a banded appearance. Fragments of dark-gray finer grained calcite, and grains of chert, feldspar, and pyrite are also present. Some of the detrital quartz grains contain inclusions of brown tourmaline.

Gray medium-grained cavernous calcite cap rock containing abundant sulphur as large veins intimately associated with the calcite. The upper part is dark gray; breccia fragments of dark-gray calcite occur in the lower part. Veins of coarsely crystalline calcite and of pyrite are also present. Pyrite is replacing sulphur. Euhedral quartz crystals and dolomite-like rhombs occur sparingly.

Fine-grained calcite, carrying abundant pyrite, which has been brecciated and recemented, as well as partly replaced, by more coarsely crystalline calcite. The creamy white and dull black opaque substances are disseminated through the calcite. Scattered through the calcite are found dolomite-like rhombs replaced by pyrite and calcite, and occasional grains of detrital quartz. Sulphur is present in this core interval as veins and cavity filling.

Similar cap rock, with the sulphur content...
variable, continues to 729 feet.

729-732: Fine-grained calcite with inclusions of finely divided black substance, traversed by numerous veins of crystalline and microcrystalline sulphur and by veins of coarsely crystalline white calcite. Sulphur of both types occurs as systems of delicately branching, arborescent veins. Where associated with coarsely crystalline calcite, sulphur veins have straight boundaries and include crystals of calcite, as shown in plate VIII, figures 1 and 2. Pyrite grains are sparsely scattered through the section, and pyrite, with calcite, has replaced the relatively numerous dolomite-like rhombs. A few euhedral quartz crystals are present.

Similar calcite cap rock continues to 742 feet, with the sulphur content variable.

742-748: Cap rock composed of alternate bands of dark-gray very fine grained calcite, and light-gray, more coarsely crystalline calcite, with crystalline yellow sulphur present in both types of calcite as discontinuous veins paralleling the bands and as cavity filling. The fine-grained calcite areas and the sulphur within these areas contain inclusions of quartz, chert, and pyrite grains. The greater part of the sulphur occurs in the fine-grained calcite
bands. This banding in the calcite appears to be a result of brecciation, the coarser calcite appearing later than the brecciation, recementing the fragments.

From 748-751 feet, the same type of cap rock continues, becoming very sandy in places.

751-755: Dark brownish gray petroleum-soaked calcite cap rock, with abundant pyrite that forms the cementing material in places, cut by veins of white calcite. Rectangular and rhombohedral, somewhat broken calcite grains, are scattered through the section. Detrital grains and crystals of quartz, as well as a fragment of silica cemented sandstone, are present. The lower part of this core is like that from 755-759 feet, with barite and sulphur.

755-759: Gray to dark-gray medium- to fine-grained calcite cap rock, brecciated and recemented with light-gray coarsely crystalline calcite. Some of the earlier calcite has the "millet seed" appearance typical of the calcite which is forming in the gypsum part of the cap rock; this relationship is brought out by comparing plate XIII, figures 1 and 2 with plate VI, figure 2. Large irregular crystals of barite which are broken and partly replaced by calcite occur in the earlier calcite (pl. VI, fig. 2).
Pyrite is very abundant as thin veins bordering breccia fragments and barite crystals and as well disseminated grains. Numerous small grains of detrital quartz, euhedral quartz crystals, and dolomite-like rhombs replaced by pyrite and calcite, are also present. The creamy white opaque substance is associated with the calcite and pyrite. Crystalline sulphur occurs in veins and fills cavities in some of the core samples, but was not found in the thin sections.

The cap rock from 759-770 feet is like that from 755-759 feet, although very sandy in places.

770-772: Light-gray calcareous sandstone composed of quartz with a few grains of feldspar, muscovite, biotite, tourmaline, pyrite, and sulphur. Some of the larger quartz grains have been fractured and recemented with calcite.

Similar cap rock continues to 774 feet.

774-778: Dark-gray fine-grained calcite cap rock, with scattered areas of coarsely crystalline white calcite as cavity fillings and in small veins. Crystalline sulphur is associated with light-yellow microcrystalline sulphur in discontinuous veins and in irregular closely associated patches, groups of which extinguish simultaneously, very like those at 685-
689 feet. These have the appearance of pseudo-morphs after anhydrite grains. Pyrite is abundant, occurring in grains up to one millimeter in diameter. Numerous small discontinuous veins, filled with opaque substance (probably carbonaceous matter), traverse the section. Some of the narrow veins of pyrite, and of the black opaque, outline areas of light-gray fine-grained calcite, suggesting the presence of incorporated breccia fragments. There are also present dolomite-like rhombs partly replaced by pyrite and calcite and surrounded by small calcite areas with the same extinction as the rhombs, and euhedral quartz crystals. A few fragmental crystals of barite, embayed by calcite, are present. A quartz rosette from this interval is shown in plate IX, figure 2.

Fine-grained calcite cap rock with variable amounts of crystalline and microcrystalline sulphur, somewhat less brecciated than the overlying, continues to 823 feet.

823-827: Dark-gray very fine-grained calcite cap rock containing a discontinuous series of thin parallel bands of microcrystalline sulphur, pyrite, and the fine-grained calcite of the matrix (pl. X, figs. 1 and 2). The bands are not over 0.1 mm. in width
and are somewhat distorted. If the discontinuity of the bands is due to brecciation, this relationship is obscured. A few small patches of more coarsely crystalline sulphur are also present. There occur, in addition, a few grains of much embayed barite, scattered dolomite-like rhombs partly replaced by calcite and pyrite, and occasional crystals of quartz.

Similar cap rock continues to 832 feet.

832-835: Highly brecciated light-gray fine-grained calcite cap rock recemented with light-gray more coarsely crystalline calcite. Abundant pyrite occurs as disseminated grains in the breccia fragments, and borders areas of coarsely crystalline calcite. Clear yellow coarsely crystalline sulphur occurs in large veins and cavities and in intricately ramifying microscopic veins, bordered by or grading laterally into the light-yellow nearly opaque microcrystalline variety of sulphur. Detrital grains and euhedral crystals of quartz are sparingly present in the calcite breccia fragments. Broken remnants of barite crystals, embayed by calcite, also occur in the fine-grained calcite.

835:838 (section a, upper part of core): Medium-gray rather fine-grained calcite cap rock containing many small
fragments of light- to dark-gray fine-grained calcite, irregular areas of microcrystalline and occasional patches of crystalline sulphur, pyrite, and detrital quartz grains. There are also present, in the calcite matrix, scattered crystals of barite, broken and embayed by calcite. The breccia fragments are irregular in shape and have the corners ground off; the light-gray ones carry microcrystalline sulphur, granular pyrite masses, barite crystals, and detrital quartz grains. The sulphur is of several generations, the oldest, of the microcrystalline type, occurs in the breccia fragments; some, also of the microcrystalline type, is contemporaneous with the matrix; and some, still younger than the matrix, consists of both the microcrystalline and crystalline types. Plate XI, figure 1, illustrates the brecciated character and also shows an area of microcrystalline sulphur; a portion of this sulphur area is shown in plate XI, figure 2, enlarged to 1000 times so that the crystalline structure of the sulphur is apparent. Some of the matrix has admixed with it abundant pyrite and the dull-black opaque substance (carbonaceous?). Those occur principally as streaks and bands, or border breccia
fragments and sulphur areas.

835-838 (section b, lower part of core): Interlocking irregular crystals of selenite, exhibiting undulatory or spotty extinction, that are being replaced by interlacing rectangular networks of small scalenohedral calcite crystals and wisp-like stringers of very fine grained calcite. It appears as if anhydrite had been partly replaced by calcite before the inception of gypsification. The replacement by calcite is nearly complete in some parts of the section. Embayed cleavage fragments of anhydrite are scattered through the gypsum. Crystalline sulphur occurs in patches and irregular veins, in many places with sharp straight borders, and includes angular areas of gypsum with associated calcite scalenohedrons, as if alteration had followed the gypsum cleavage at this point, rather than that of the anhydrite. Pyrite is fairly abundant, occurring as granular masses, as stringers, and as a replacement of dolomite rhombs. A grain of detrital quartz is present in the gypsum.

838-841: This is the same type of gypsum cap rock as that in the lower part of the preceding core, with the alteration to calcite less advanced. The calcite
scalenehedrons outline in great perfection the replaced anhydrite cleavage fragments, a few of which are still present (pis. XII and XIII). Crystalline sulphur also follows the outlines of the anhydrite cleavage fragments, or forms pseudomorphs after them. Dolomite rhombs, some replaced by calcite, and rosettes and crystals of quartz are present. The sulphur and calcite are closely associated and calcite crystals frequently occur between the sulphur and gypsum. The quartz rosettes and dolomite rhombs are identical in appearance with those occurring throughout the cap rock and in the salt, being of the same size and containing nuclei of finely divided white opaque substance (pl. XIII, fig. 2).

(Total depth, 841 feet; depth to salt in the vicinity of this well is 870 feet).

Freeport Sulphur Company,
Lake Washington, No. 1005 well

0-1298: Unconsolidated sands, silts and clays, some of which contain fossils of marine organisms, comprise this interval. Calcareous-cemented sands and shales (false cap rock) occur near the base of the section.
scalenohedrons outline in great perfection the replaced anhydrite cleavage fragments, a few of which are still present (pls. XII and XIII). Crystalline sulphur also follows the outlines of the anhydrite cleavage fragments, or forms pseudomorphs after them. Dolomite rhombs, some replaced by calcite, and rosettes and crystals of quartz are present. The sulphur and calcite are closely associated and calcite crystals frequently occur between the sulphur and gypsum. The quartz rosettes and dolomite rhombs are identical in appearance with those occurring throughout the cap rock and in the salt, being of the same size and containing nuclei of finely divided white opaque substance (pl. XIII, fig. 2).

(Total depth, 841 feet; depth to salt in the vicinity of this well is 870 feet).

Freesport Sulphur Company,
Lake Washington, No. 1005 well

0-1296: Unconsolidated sands, silts and clays, some of which contain fossils of marine organisms, comprise this interval. Calcareous-cemented sands and shales (false cap rock) occur near the base of the section.
1298-1324: Gray medium-grained calcite cap rock containing a trace of petroleum and a few thin layers of calcareous sandstone. A small amount of crystalline sulphur is present in irregular veins in the lower part.

1324-1373: Gray to greenish-gray, fine-grained calcite cap rock, somewhat brecciated in places, with crystalline yellow sulphur in veins and cavities and well disseminated. Crystals of greenish-yellow and brown sulphur are associated with the yellow sulphur in the cavities. The calcite and sulphur are arranged in horizontal, alternating bands in some of the cores. Finely crystalline sulphur coats horizontal cleavage surfaces or shear planes in the calcite, along which parting occurs quite easily. Petroleum is also present in the shear planes or zones, as well as interstitial to the calcite grains in some areas.

1373-1407.5: Gray porous medium-grained calcite cap rock, with crystalline yellow and brown sulphur in veins, filling cavities, and disseminated. Small fragments of darker gray calcite cap rock are locally present. A foot of nearly solid sulphur was encountered at about 1,390 feet.
Porosity increases toward the lower part of the interval, and the sulphur in this part occurs chiefly in veins and as cavity filling. Throughout this interval the cap rock is somewhat stained with petroleum.

1407.5-1409.5: Cavity.

1409.5-1411.5: Mottled gray and white fibrous anhydrite cap rock containing a small amount of crystalline sulphur in thin irregular veins or coating surfaces. Gypsum forms irregular veins along shear zones and replaces anhydrite adjacent to the veins. The anhydrite is composed of closely packed elongate sheared anhydrite cleavage fragments of approximately horizontal orientation, associated with smaller irregular cleavage fragments. The anhydrite grains are intergrown but show little effect of recrystallization. The mottling is due to small areas of finer grained anhydrite. Veins of crystalline sulphur appear to follow shear zones; the microcrystalline variety is also present, associated with petroleum, interstitial to some of the larger anhydrite grains. Large dolomite rhombs occur sparingly, scattered at random in the section.

1411.5-1422: A continuation of the mottled anhydrite with horizontal as well as irregular veins of gypsum.
The cap rock breaks easily along the horizontal gypsum veins, forming smooth-surfaced plates. The gypsum forms a mosaic of very irregular crystals, some that are pseudomorphs after anhydrite cleavage fragments retaining small remnants of the anhydrite. A small amount of crystalline and microcrystalline sulphur occurs in isolated irregular areas, replacing the anhydrite. A few somewhat broken and crushed dolomite rhombs are present. Petroleum occurs interstitial to some of the anhydrite grains.

1422-1427: Mottled gray and white, fibrous anhydrite cap rock, composed of closely packed anhydrite cleavage fragments of fine-sand size, with numerous larger, elongate fragments of approximately horizontal orientation. The cap rock breaks along horizontal shear planes which are slickensided, along some of which gypsum, crystalline and microcrystalline sulphur, and petroleum are found. A few dolomite rhombs are present.

1427-1431: Light-gray fibrous anhydrite, irregularly banded, that makes irregular contact with gray, crystalline calcite. The anhydrite consists of
elongate distorted cleavage fragments which have an approximately horizontal orientation, and in places are bent into microfolds (pl. XIV, fig. 1). The bands are composed of dark brownish gray calcite filled with inclusions of finely divided opaque substance (carbonaceous?), large dolomite rhombs, pyrite grains, and crystals and rosettes of quartz. The dolomite rhombs and quartz rosettes have the typical nuclei, and some of them are crushed or deformed (pl. XIV). Large dolomite rhombs also occur scattered through the anhydrite, with the fibrous anhydrite bent around them. There are also scattered areas of coarsely crystalline calcite in the anhydrite that appear to have replaced some earlier mineral, possibly barite. Crystalline sulphur outlines anhydrite grains, and also occurs in discontinuous veins and as small divergent veins in the dark-colored calcite.

1431-1440: Broken dark-gray fine-grained calcite cap rock, cut by veins of coarsely crystalline calcite and crystalline sulphur, with bands and patches of light-gray mottled anhydrite in the lower part. The calcite contains an opaque dark brown substance (petroleum?), chiefly interstitial, and has bands of darker calcite like those at 1427-
Dolomite rhombs are fairly common, and in places are concentrated along the bands; one of them contains an inclusion of barite or celestite. The anhydrite is like that at 1427-1431 feet. Anhydrite grains embayed by calcite are also present. Small sharply defined ramifying veins of crystalline sulphur cut across both the anhydrite and calcite areas, but have their best development in the bands of darker calcite. The contact of the anhydrite and calcite bands apparently occurs along shear planes. Gypsum is replacing the anhydrite in localized areas at the anhydrite-calcite contacts. The banding of sulphur and calcite is illustrated in plate XV, figure 2, and the contact of anhydrite and calcite in plate XV, figure 1. A vein of coarsely crystalline sulphur in calcite having relict anhydrite structure is shown in plate XVI, figure 1, and plate XVI, figure 2.

Gray medium-grained saccharoidal indistinctly banded anhydrite, that has good rock cleavage along horizontal planes and numerous vertical veins of gypsum, calcite, and crystalline sulphur. The anhydrite grains are tabular, elongate, and closely packed parallel to their elongation. They are somewhat interlocking, as
shown by their overlapping extinction. Some of them are crushed or bent, and where dolomite rhombs are present the anhydrite grains are bent or streamed around them. Gypsum has replaced the anhydrite along cleavage or shear planes, and bead-like scalenohedral crystals of calcite occur in the gypsum, following the outlines of the replaced anhydrite grains. Crystalline sulphur is present in irregular disconnected veins that outline or replace anhydrite crystals.

1446-1456: Light-gray fine-grained "schistose" anhydrite (pl. XVII, fig. 1) with horizontal narrow petroleum-stained calcite bands. The anhydrite breaks readily along the bands, resulting in smooth slickensided surfaces. The anhydrite occurs in elongate distorted fragments that stream around dolomite rhombs, which themselves are oriented with their longest axes parallel to the elongation of the anhydrite fragments. The rhombs are large, often with a nucleus of finely divided opaque white substance, and bordered by small calcite areas. Gypsum is replacing the anhydrite adjacent to the fine-grained petroleum-stained bands of calcite.
Mottled, medium-gray to white anhydrite, composed of large elongate cleavage fragments in a matrix of fine-grained somewhat fibrous fragments, with alteration to gypsum occurring along horizontal shear planes and irregular veins. Orientation of the smaller grains and fracturing of the larger ones along shear planes is illustrated in plate XVII, figure 2. Deformed dolomite rhombs, partially altered to calcite, occur at random through the section. The mottling is due to small well defined areas of very fine grained cleavage fragments.

Pinkish-gray saccharoidal quite massive anhydrite, with discontinuous bands of white calcite, irregular gypsum veins, and relatively wide bands of brown, petroleum-stained anhydrite. The anhydrite is composed of cleavage fragments, mostly rather short and square, little deformed, and not well oriented. The banding is horizontal and occurs along shear planes or zones.

Cavity.

Brown very fine grained porous calcite, with roughly parallel horizontal veins of coarsely crystalline and microcrystalline sulphur, and of petroleum-stained calcite containing in-
clusions of mottled white and gray fine-grained anhydrite. Scattered anhydrite grains and dolomite rhombs also occur in the calcite. The anhydrite is composed of elongate, fibrous grains of horizontal orientation that are somewhat intergrown. Crystalline sulphur occurs in large veins parallel to the anhydrite-calcite contacts, and in connected smaller veins interstitial to the anhydrite and calcite grains. Some of the sulphur veins cut sharply across both the anhydrite and calcite areas, as shown in plate XVIII, figure 1. The anhydrite contains branching veins of calcite with included sulphur, carbonaceous matter, and dolomite rhombs.

1508-1521: Gray medium-grained somewhat fibrous mottled anhydrite, with horizontal veins of crystalline sulphur. Minute branching veins of crystalline sulphur, from the larger veins, surround and replace the anhydrite grains, entirely unassociated with calcite, as shown in plate XVIII, figure 2, and plate XIX, of 20 and 200 times magnification, respectively. Dolomite rhombs, somewhat fractured, but very little altered, occur rather abundantly, scattered through the anhydrite.

1521-1536: Mottled gray anhydrite composed of aggregates
of fibrous grains and larger cleavage fragments in a matrix of fine-grained anhydrite, with bands of very fine grained intimately mixed calcite and anhydrite. Veins of coarsely crystalline calcite traverse both the calcite and anhydrite, but are terminated by some of the shear planes in the anhydrite. The calcite bands occur along older shear planes and are accompanied by carbonaceous matter and ramifying sulphur veins. Dolomite rhombs, somewhat deformed, occur at random through the anhydrite; a large subhedral quartz crystal, containing inclusions of anhydrite cleavage fragments similar to those found in the salt residues, was also noted. Gypsum is replacing some of the fibrous anhydrite along shear planes.

(Total depth, 1536 feet; depth to salt in the vicinity of this well is 1570 to 1580 feet.)

Freeport Sulphur Company,
Lake Washington, o. 59 well

0-1252: Unconsolidated sediments composed of sands, silts, and clays, some of which contain the remains of marine organisms. Several thick beds of gumbo occur in this interval, including one
from 1163-1220 feet. Calcareous-cemented sands and shales (false cap rock) occur near the bottom of this interval.

1252-1330: Medium- to dark-gray fine- to medium-grained calcite cap rock, containing a trace of petroleum and lenses of calcareous sandstone.

1330-1370: Gray medium- to coarse-grained calcite cap rock containing breccia fragments of dark-gray calcite cap rock. Crystalline sulphur occurs in veins and filling cavities, with a small amount disseminated through the calcite. Carbonaceous matter, probably petroleum, is interstitial to the calcite grains.

1370-1455: Calcite cap rock that is similar to that from 1330-1370 feet, but with less sulphur, and with tabular barite crystals lining cavities, in places apparently replacing sulphur.

1455-1480: Banded light- and dark-gray cavernous hackly calcite cap rock. Crystalline and microcrystalline sulphur occurs in veins and disseminated. Tabular barite crystals and coarsely crystalline calcite line some of the cavities. Breccia fragments of dark-gray calcite cap rock are fairly common.

1480-1510: Light-gray fairly massive calcite cap rock, with
abundant crystalline sulphur in veins and cavities. Crystalline and micro-or cryptocrystalline barite are intimately associated with some of the sulphur. Breccia fragments of dark-gray calcite are present.

1510-1525: Dark-gray fine-grained calcite cap rock in the upper part of the interval, in angular irregular contact with the light-gray, fine-grained sulphur-bearing calcite cap rock that forms the remainder of the interval. The light-gray calcite cap rock is composed of intergrown areas of crystalline sulphur and calcite, with the two minerals present in about equal amounts in places (pl. XX, fig. 1). A few of the sulphur areas contain inclusions of anhydrite cleavage fragments (pl. XX, fig. 3). Sulphur is also present in veins and filling cavities in both the light- and dark-gray calcite. Pyrite grains are sparingly present and barite crystals line some of the cavities. Dolomite rhombs and euhedral quartz crystals occur sparingly in this section of the cap rock, the dolomite being the more common. A black opaque finely divided substance (carbonaceous?) is distributed through all of the calcite, producing a darker color where it is more abundant.
1525-1530: Banded dark- and light-gray fine-grained calcite cap rock. The darker bands are about 0.5 mm. in width; the light ones are 1.0 to 5.0 cm. The dark bands owe their color to the presence of pyrite in irregular veins. A small amount of crystalline sulphur is disseminated in the calcite, like that at 1520-1525 feet. Fibrous barite, associated with pyrite, completely fills some of the cavities in the calcite. Dolomite rhombs, showing some fracturing, and a few broken celestite crystals that are being replaced by calcite, were seen scattered through the calcite.

1530-1555: A nearly continuous breccia and gouge zone, composed of porous, very soft, chalky fine- to medium-grained calcite, containing fragments of hard calcite cap rock. The breccia fragments are derived in part from the overlying cap rock. Petroleum occurs in the interstices between grains of the soft calcite cap rock, sometimes accompanied by pyrite and small galena grains. The typical dolomite rhombs are crushed or fractured, and are sometimes concentrated, along with quartz crystals, in the dark calcite bands.
Coarse calcite, and barite as tabular crystals and of the fibrous type, line some of the cavities. A small amount of associated crystalline and microcrystalline sulphur occurs in irregular cavities. Rounded aggregates of a brownish-black mineral, possibly hauerite, are disseminated in more compact calcite cap rock at 1540 to 1545 feet.

1555-1560: The upper part of this interval is a continuation of the breccia zone; the lower part is dark-gray fine-grained hackly calcite cap rock, with indistinct bands and platy partings developed along horizontal planes. The dark bands are due to the presence of petroleum in shear zones that also contain some of the large dolomite rhombs that are typical of anhydrite cap rock and of the salt residues. Well-defined veins of crystalline sulphur follow the shear zones and connect with smaller irregular sulphur veins that extend into the adjacent calcite areas. Pyrite grains are disseminated through the calcite; a few tabular barite crystals line cavities.

1560-1565: Cores were not available for this interval but it is logged as a continuation of 1555-1560 feet.
Strikingly banded cap rock composed of alternating horizontal layers of dark-gray fine-grained calcite, and white finely divided barite and associated crystalline and microcrystalline sulfur. The calcite is characterized by scattered and broken dolomite rhombs and quartz crystals like those occurring in the anhydrite and salt, and by areas in which the granular and sheared structure of the anhydrite have been preserved. A few breccia fragments of calcite cap rock similar to that overlying the extensive breccia zone are present. The barite is of the fibrous variety and, at least in part, is replacing sulfur. Thin veins of crystalline sulfur cut sharply across the calcite in places. The bands are horizontal, apparently resulting from the penetration of altering solutions and deposition of secondary minerals along shear zones in the anhydrite; there are also parallel dark-brown bands of calcite containing interstitial petroleum and pyrite, in which the dolomite rhombs and quartz crystals are definitely concentrated and are considerably broken and fractured. Crystalline sulfur has replaced areas of some fibrous mineral, probably anhydrite.
rather than barite. A few of the quartz crystals contain inclusions of anhydrite grains (pl. XXI, fig. 1). Fragmental and embayed celestite crystals occur in the calcite matrix.

1568-1580: Bluish-gray coarsely crystalline saccharoidal anhydrite cap rock, with divergent discontinuous brown to black horizontal bands, less than 0.5 mm. in width and 1 to 3 cm. apart. The anhydrite is composed of cleavage fragments that are 0.3 to 0.6 mm. in length, and of approximately horizontal orientation, in a matrix of much smaller cleavage fragments. Some areas consist entirely of the closely packed large cleavage fragments, and others of the smaller anhydrite grains. A few "stem-shaped" crystals of anhydrite, like those in the salt plug, are present. Under crossed nicols, the anhydrite grains prove to be intergrown, so the extinction of individual grains overlaps that of adjoining ones. The bands are due to veins of secondary pyrite and gray or brown opaque substance (petroleum?) that occur in shear zones (pl. XXII, fig. 1). Irregularities, such as microfolds and diverging shear planes, are closely followed by the veins. The anhydrite grains that occur
along the bands are broken and displaced. One dark band is paralleled by a light-gray band composed of small anhydrite grains that appear to be crushed and sheared. Dolomite rhombs with the characteristic nuclei are scattered at random through the section. Small areas of calcite border some of the dolomite rhombs and occasional groups of calcite scalenohedrons occur along the bands. A few euhedral quartz crystals occur scattered through the anhydrite.

1580-1714: Granular fairly massive colorless to light-gray rock salt; water-insoluble residue of 3.6 percent. The residue is composed almost entirely of poorly sorted anhydrite sand but contains about one percent of the characteristic dolomite rhombs with nuclei, a few pyrite crystals, quartz rosettes with the typical nuclei, and individual crystals of quartz.

(Total depth, 1714 feet.)
Appendix C

Bibliography
Biography
Ralph Emerson Taylor was born at Lykens, Ohio, in the year 1905. He attended grammar school at Andrews, Ind., and high school at this town and at Ann Arbor, Mich., graduating from the latter school in 1923. In 1927 he received the A. B. degree from University of Michigan, Ann Arbor, Mich., and was commissioned as a second lieutenant in the Reserve Corps of the Infantry of the United States Army. The B. S. degree in geology was given him by the University of Michigan in 1929. During the school years of 1926-1927 and 1927-1928 he acted as assistant in the Department of Geology. He worked as geologist for the Michigan Geological Survey during part of the years 1927 and 1928. In 1929 he entered the employ of the Arkansas Natural Gas Corp. of Shreveport, La., remaining with them until 1931.

He studied advanced work in geology at the University of Michigan during 1932 and 1933. In 1934 he was geologist for the Michigan Geological Survey, leaving in October to enter Louisiana State University as a graduate fellow. During that school year and the following two he carried out work for the Ph.D. degree. He joined the Freeport Sulphur Company, Port Sulphur, La., as geologist in 1937 and re-enrolled at Louisiana State University in February, 1939.
Illustrations
Figure 1. Southwest-northeast cross-section of the northeastern portion of the cap rock of Lake Washington salt dome. Blank areas represent cavities. Some of the data for this section have been taken from the records of wells just off the line of cross-section. For location of wells see figures 22-A and 22-B in Russell, Howe, and McGuirt (1936).
Figure 2. Northwest-southeast cross-section of the cap rock of Lake Washington salt dome. Blank areas represent cavities, dotted areas represent sandy portions of the cap rock. Some of the data for this section have been taken from the records of wells just off the line of cross-section. For location of wells see figures 22-A and 22-B in Russell, Howe, and McGuirt (1936).
Figure 3. North-south cross-section of the cap rock of Jefferson Island salt dome. Blank areas represent cavities. The upper part of the calcite zone is very sandy, but sandy portions are not distinguished in the diagram. Some data for this section have been taken from the records of wells just off the line of cross-section. For maps of the dome showing location of wells see figures 2, 3 and 5 in O'Donnell (1935).
Figure 4. Southwest-northeast cross-section of the cap rock of Jefferson Island salt dome. Blank areas represent cavities. The upper part of the calcite zone is very sandy, but sandy portions are not distinguished in the diagram. Some data for this section have been taken from the records of wells just off the line of cross-section. For maps of the dome showing location of wells see figures 2, 3 and 5 in O'Donnell (1935).
Fig. 1. Tabular anhydrite grains. Low index oil, plane polarized light, X 35 (East Hackberry residue).

Fig. 2. Stem-shaped anhydrite crystals. Low index oil, plane polarized light, X 44 (Sulphur residue).

Fig. 3. Quartz rosettes, with nuclei, and single crystals. Low index oil, plane polarized light, X 37 (Choctaw residue).

Fig. 4. Positive and negative rhombohedrons of dolomite, upper two with nuclei. Low index oil, plane polarized light, X 51.5 (Choctaw residue).

Fig. 5. Barite crystals with anhydrite inclusions. Low index oil, plane polarized light, X 20 (Winnfield residue).
Fig. 1. Celestite crystals. Low index oil, plane polarized light, X 44 (L. Washington residue).

Fig. 2. Celestite crystal. Low index oil, plane polarized light, X 01 (Sulphur residue).

Fig. 3. Hilgardite grain lying on good cleavage. Low index oil, plane polarized light, X 38 (Choctaw residue).

Fig. 4. Magnesite crystals. Low index oil, plane polarized light, X 38 (Choctaw residue).

Fig. 5. Dolomite rhombs reflected light, X 25 (Weeks Island residue).

Fig. 6. A. Calcite scalenohedrons, X 25 (Weeks Island residue). B. Octahedron of hauerite and pseudomorph of limonite after pyrite, X 25 (Avery Island residue). C. Boracite crystals, X 35 (Choctaw residue). All by reflected light.
Fig. 1. Danburite crystals. Immersed in low index oil, plane polarized light, X 38 (Choctaw residue).

Fig. 2. Rock salt containing anhydrite cleavage fragments and dolomite rhombs (D) with nucleus. The photomicrograph also shows anhydrite and halite cleavage, and irregular fracture lines in the halite. Nicol prisms removed, X 60 (dark band, Avery Island mine).
Fig. 1. Rock salt with inclusions of anhydrite grains and large dolomite rhomb (dark). Nicol prisms removed, X 60 (Weeks Island salt mine).

Fig. 2. Sand inclusion in salt. Nicol prism removed, X 25 (Weeks Island salt mine).

Fig. 3. Sand inclusion in salt. Nicol prisms removed, X 25 (Avery Island salt mine).
Fig. 1. Sand inclusion in salt; small irregular gray areas are calcite or dolomite. Plane polarized light, X 20 (Jefferson Island salt mine).

Fig. 2. Sand inclusion in salt, showing contact with salt containing anhydrite grains. Plane polarized light, X 20 (Jefferson Island salt mine).
Fig. 1. Brecciated sandy calcite cap rock (dark), recemented by more coarsely crystalline calcite. Plane polarized light, X 25 (Jefferson Lake Oil Co. Jefferson Island No. 36, 604-610 feet).

Fig. 2. Barite crystals partially to completely replaced by calcite, in calcite cap rock. Plane polarized light, X 25 (Jefferson Lake Oil Co. No. 36, Jefferson Island, 755-763 feet).
Fig. 1. Quartz rosette, in calcite cap rock. Crossed nicols, X 240 (Jefferson Lake Oil Co. No. 36, Jefferson Island, 624-28 feet).

Fig. 2. Rectangular sulphur (upper) and calcite (lower part of photograph) in calcite cap rock; apparently pseudomorphs after anhydrite. Plane polarized light, X 20 (Jefferson Lake Oil Co. No. 36, Jefferson Island, 625-629).
Fig. 1. Sulphur veins (black) in calcite (white and gray). Plane polarized light, X 20 (Jefferson Lake Oil Co. No. 56, Jefferson Island, 729–732 feet).

Fig. 2. Enlargement to 60 times of area in lower left hand corner of figure 1. Nicol prisms removed.
Fig. 1. Quartz rosette in gypsum cap rock. Crossed nicols, X 120 (Jefferson Lake Oil Co. No. 36, Jefferson Island, 838-841 feet).

Fig. 2. Quartz rosette in calcite cap rock. Crossed nicols, X 25 (Jefferson Lake Oil Co. No. 36, Jefferson Island, 774-778 feet).

Fig. 3. Three quartz rosettes in gypsum cap rock. Crossed nicols, X 25 (Jefferson Lake Oil Co. No. 43, Jefferson Island, 634-639 feet).
Fig. 1. Banded sulphur (gray), calcite (white), and pyrite (black). Nicol prisms removed, X 25 (Jefferson Lake Oil Co., No. 36, Jefferson Island, 323-328 feet).

Fig. 2. Black band in lower central portion of above photograph at 400 times, showing crystalline structure of sulphur (lighter portion). Nicol prisms removed.
Fig. 1. Brecciated calcite cap rock with sulphur (black). Plane polarized light, X 25 (Jefferson Lake Oil Co. No. 36, Jefferson Island, 835-838 feet).

Fig. 2. Sulphur area in lower left part of figure 1 at 1,000 times, showing crystalline structure of sulphur (black is pyrite). Nicol prisms removed.
Fig. 1. Sulphur area in gypsum, showing how outlines of anhydrite cleavage fragments have been preserved. Nicol prisms removed, X 25 (Jefferson Lake Oil Co. No. 36, Jefferson Island, 838-841 feet).

Fig. 2. Area in figure 1 at 60 times to show detail of gypsum pseudomorphs after anhydrite (white is gypsum, dark gray is sulphur). Nicol prisms removed.
Fig. 1. Dolomite rhomb in gypsum; network of calcite scalenohedrons outlines rectangular areas of gypsum suggestive of the structure of anhydrite grains. Nicol prisms removed, X 60 (Jefferson Lake Oil Co. No. 36, Jefferson Island, 838-841 feet).

Fig. 2. Same part of section as figure 1; large rhombohedral area in gypsum is being replaced by calcite (gray crystals). Nicol prisms removed, X 60.
Fig. 1. Anhydrite cap rock, with two dolomite rhombs (dark), with shear zone between them. Plane polarized light, x 25 (Freeport Sulphur Co. No. 1005, L. Washington, 1437-1431 ft).

Fig. 2. Dolomite rhomb from same area as figure 1, showing nucleus and streaming of anhydrite grains. Plane polarized light, x 100.

Fig. 3. Highly sheared anhydrite cap rock; dark band of carbonaceous matter; dolomite rhombs. Plane polarized light, x 40 (Same section of core as figs. 1 and 2).
Fig. 1. Highly sheared anhydrite with deformed band of petroleum-stained calcite, dolomite rhombs. Plane polarized light, X 20 (Freeport Sulphur Co. No. 1005, L. Washington, 1437-1440 feet).

Fig. 2. Banded brown and gray calcite cap rock with petroleum-stained bands, and irregular veins of crystalline sulphur. Plane polarized light, X 20 (Freeport Sulphur Co. No. 1005, L. Washington, 1437-1440 feet).
Fig. 1. Calcite cap rock with sulphur vein on right, petroleum-stained calcite band on left; dolomite rhombs. Plane polarized light, X 25 (Freesport Sulphur Co. No. 1005, L. Washington, 1437-1440 feet).  

Fig. 2. Sulphur area with included dolomite rhomb (at right edge of photograph), in calcite with dolomite rhombs. Plane polarized light, X 25 (Same thin section as fig. 1).
Fig. 1. Sheared anhydrite cap rock, showing alignment of grains and dolomite rhombs. Plane polarized light, X 20 (Freeport Sulphur Co. No. 1005, L. Washington, 1451-56).

Fig. 2. Shear zone in anhydrite cap rock. Plane polarized light, X 60 (Freeport Sulphur Co. No. 1005 Lake Washington, 1456-1461 feet).
Fig. 1. Closely banded, fine-grained calcite cap rock, with sulphur vein (upper left), and scattered dolomite rhombs. Plane polarized light, X 20 (Freeport Sulphur Co. No. 1005, L. Washington, 1497-1508 feet).

Fig. 2. Sulphur (dark) in anhydrite cap rock. Plane polarized light, X 20 (Freeport Sulphur Co. No. 1005, L. Washington, 1516-1521 feet).
From same thin section as figure 2, plate XVIII, showing replacement of anhydrite by sulphur (dark gray to black). Nicol prisms removed, X 200.
Fig. 1. Disseminated sulphur (dark) in calcite cap rock. Plane polarized light, X 50 (Freeport Sulphur Co. No. 59, 1520-1525 feet).

Fig. 2. Dolomite rhombs, and quartz crystal (lower right) in calcite cap rock. Plane polarized light, X 68 (Freeport Sulphur Co. No. 59, 1565-1568 feet).

Fig. 3. Remnant anhydrite grains in sulphur (dark), from the calcite zone of cap rock. Plane polarized light, X 150 (Freeport Sulphur Co. No. 59, 1520-1525 feet).
Fig. 1. Quartz crystal (white), containing inclusions of anhydrite, in calcite cap rock. Crossed nicols, X 56 (Freeport Sulphur Co. No. 59, 1565-1568 feet).

Fig. 2. Anhydrite cap rock with area of finer-grained anhydrite. Dolomite rhombs (dark) occur in the coarser anhydrite. Plane polarized light, X 48 (Freeport Sulphur Co. No. 59, 1560-1580 feet).
Fig. 1. Anhydrite cap rock with shear zone along which pyrite (black) has been deposited. Plane polarized light, X 80 (Freeport Sulphur Co. No. 59, 1568-1580 feet).

Fig. 2. Primary bedded anhydrite from Sligo (north Louisiana), depth about 4,600 feet. Plane polarized light, X 400.
Fig. 1. Quartz rosette in anhydrite cap rock. Crossed nicols, X 110 (Jefferson Lake Oil Co., miscellaneous core from Jefferson Island).

Fig. 2. Sulphur pseudo-morph after dolomite in calcite cap rock. Plane polarized light, X 55 (Freeport Sulphur Co. No. 66, L. Washington, 1570-1575 feet).
Fig. 1. Large anhydrite grains (black), of same extinction position, with gypsum entering along cleavages. Crossed nicols, X 60 (Jefferson Lake Oil Co., miscellaneous core from Jefferson Island).

Fig. 2. Sulphur (dark) and gypsum (white), with remnants of anhydrite cleavage fragments in the gypsum. Plane polarized light, X 120 (Freeport Sulphur Co. No. 3, L. Washington, 1400+ feet).
Fig. 1. Gypsum with remnants of anhydrite cleavage fragments, Crossed nicols, X 40 (The Texas Co. No. 7, Garden Island Bay, 1915-1916 feet).

Fig. 2. Contact of "chalcedonic" anhydrite and cap-rock anhydrite (on right), Plane polarized light, X 80 (The Texas Co. No. 7, Garden Island Bay, 2107-2117 feet).
Fig. 1. Residue of anhydrite grains from Jefferson Island salt (dolomite rhomb in center). Plane polarized light, X 25. The grains are immersed in a low-index oil.

Fig. 2. Loosely compacted anhydrite grains. Anhydrite cap rock from Bayou Bouillon salt dome. Plane polarized light, X 32.
EXAMINATION AND THESIS REPORT

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