Salt Dome Caprock—A Record of Geologic Processes

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ABSTRACT

The presence of caprock on Gulf Coast salt domes is evidence of dissolution of salt over long periods of time. It is reasonable to assume that the thickness of the caprock provides a measure of dissolution in the geologic past. This record can be used, with caution, as a basis for determination of present hydrologic stability. The character of the anhydrite at the salt-caprock interface should provide more definitive evidence in this regard. Caprock thickness not only establishes the amount of salt removal, it also indicates the quantity of sodium chloride added to underground waters responsible for dissolution. Complementary studies of caprock and chemical geohydrology may contribute to a better understanding of both geologic elements. The thickness of caprock is also potentially useful in studies of tectonic stability. Calculated growth rates of domes must incorporate average rates of caprock formation. Rates of growth determined from the stratigraphic record must be increased in proportion to the amount of dissolution recorded by caprock thickness. Older caprock studies were focused on the sequential development of the entire caprock or on later phases. The uses of caprock data for salt dome studies, outlined above, are contingent upon a proper understanding of the accumulation and diagenesis of anhydrite which constitutes the basal part of salt dome caprock. Continuing research is required to advance knowledge of early caprock genesis.

INTRODUCTION

If caprock represents the end product of a residual accumulation of anhydrite particles from a salt stock, it constitutes a valuable record of the history of dissolution of the salt stock. Although this mode of origin of caprock is now generally accepted and has a high probability of being essentially correct alternative explanations have been proposed. Four principal theories of origin were summarized by Rogers (1918). Among these were the residual accumulation hypothesis and the precipitation in place hypothesis. The idea that caprock could form by precipitation in place of calcium sulphate from migrating ground water was reviewed and critiqued by Taylor (1938). His work complementing that of Goldman (1933, 1952) served to advance the theory of the formation of caprock by residual accumulation of anhydrite resulting from salt dissolution. An excellent short review of this modern version of caprock formation from the initial accumulation of anhydrite through its final chemical and physical modifications is given by Murray (1966). Murray's summary was later presented in graphic form by Martinez (1974).

GENESIS OF ANHYDRITE CAPROCK

The various processes of modification of anhydrite caprock, including accumulation of native sulphur deposits, are all of great scientific and economic importance. However, the phase which is critical to a correct interpretation of salt dome history is the initial accumulation of anhydrite. Positive evidence in favor of the residual theory offered by Taylor (1938) included:

1. The presence at the salt-anhydrite interface of brine associated with the water-insoluble minerals of the salt,
2. The existence of a relatively flat-topped solution table that decapitates the salt folds,
3. The similarity in composition of the salt residues and the anhydrite caprock and,
4. The great irregularity in the development of caprock.

Taylor found no other explanation acceptable at that time.

Walker (1972, 1974, and 1976) reexamined the origin of anhydrite caprock, with the aid of modern geochemical techniques. His study was prompted by the extraordinary amount of salt dissolution required to account for large thicknesses of caprock, as much as 1,500 feet thick, by residual accumulation of anhydrite originally dispersed throughout the salt stock. He found evidence that he considered to be incompatible with the residual accumulation hypothesis. Characteristics cited as constituting such evidence were as quoted directly below:

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

On the basis of his work, Walker proposed a combined residual accumulation-precipitation in place explanation. In essence, he believed that a large part of the calcium sulphate in the anhydrite caprock was precipitated from brines containing calcium sulphate that originated from dissolution along the flanks of the dome by upward moving waters. The contribution of anhydrite by residual accumulation at the upper surface of the dome was thought to be involved but only to a minor extent. The work by Walker, along with his data and observations has added very valuable new information to the fund of knowledge of salt dome caprock. However, his proposal that anhydrite caprock has been essentially precipitated in place is not convincing. It is difficult to visualize the exact process by which salt is removed by dissolution with a simultaneous precipitation of anhydrite on a large scale as postulated by Walker. Such an explanation is not consistent with observations of brine containing anhydrite sand at the caprock-salt interface. If the anhydrite were precipitated concurrently with dissolution of the salt, there should be some indication of this in this youngest stage of caprock formation. Such evidence is lacking. An appreciable thickness of loose or poorly cemented sand at the contact without evidence of precipitated anhydrite indicates a lengthy period of dissolution without simultaneous precipitation of $CaSO_4$. Furthermore, the entire process depends on undersaturation of the rising brine in NaCl and saturation of $CaSO_4$. It is difficult to see why this unique condition would necessarily exist.

One of the early arguments favoring the residual accumulation hypothesis is the common occurrence of a solution table at the upper part of the salt stock. The large amount of dissolution required to form such a feature is much more compatible with the residual accumulation theory than with an explanation dependent on large scale precipitation of anhydrite. The cross section of the Benthe salt dome near Hannover, Germany shown in Figure 1 is an example of the extensive dissolution required to decapitate large scale folding. The thickness of the resulting caprock is indicated.

Trace element differences between caprock and salt residue anhydrite as well as morphological differences in the anhydrite itself observed by Walker do raise questions concerning the validity of the residual accumulation theory. However there are alternative explanations such as diagenetic changes after release of the anhydrite from the salt. In any event the essential simplicity of the residual accumulation theory as opposed to others is in itself compelling.

PROPOSED INFLUENCE OF SALINITY ON ANHYDRITE–GYPSUM CONVERSION

Previous explanations of the development of zonation of caprock from the initial residual accumulation of anhydrite seem to have overlooked an apparent paradox. If the basal anhydrite zone resulted from dissolution of the salt, why was it not hydrated to gypsum by the same solution at the time of residual accumulation rather than at some later stage? If this is due to depth-temperature relationships, as one can infer from Goldman (1933, 1952), why is gypsum found in the transition zone above the anhydrite? One explanation is that this hydration occurred after upward movement of the anhydrite caprock brought it into a lower temperature field. An alternative explanation follows which is considered to be more acceptable. The common relationship of gypsum in the transition zone overlying anhydrite is considered to be due to hydration of the anhydrite by percolating water. Anhydrite-gypsum transitions have been demonstrated to be a function of salinity as well as temperature (Goodman, 1954). Experiments by Goodman established that gypsum is the stable form of calcium sulphate regardless of concentration up to approximately 30°C. He also found that at temperatures of 66°C to 74°C, anhydrite is the stable form for concentrations as much as 5 times normal sea water. Above that concentration hemihydrate was found to be stable. The demonstrated stability of anhydrite as it accumulates from dissolution of salt to form caprock suggests that the failure to convert to gypsum (or hemihydrate) at this step in the process is due to the extreme salinity of the water which results from salt dissolution. A hypothetical sequence of caprock development which illustrates this interpretation is shown in Figure 2. Some distance above the interface salinity would be expected to decrease allowing conversion of anhydrite to gypsum.

Thus characteristics of salt dome caprock may furnish important evidence of stability relations between anhydrite and gypsum. Moreover this observation at the interface makes it clear that the failure of anhydrite to convert to gypsum in the salt stock does not necessarily indicate a lack of trapped brines in the salt.

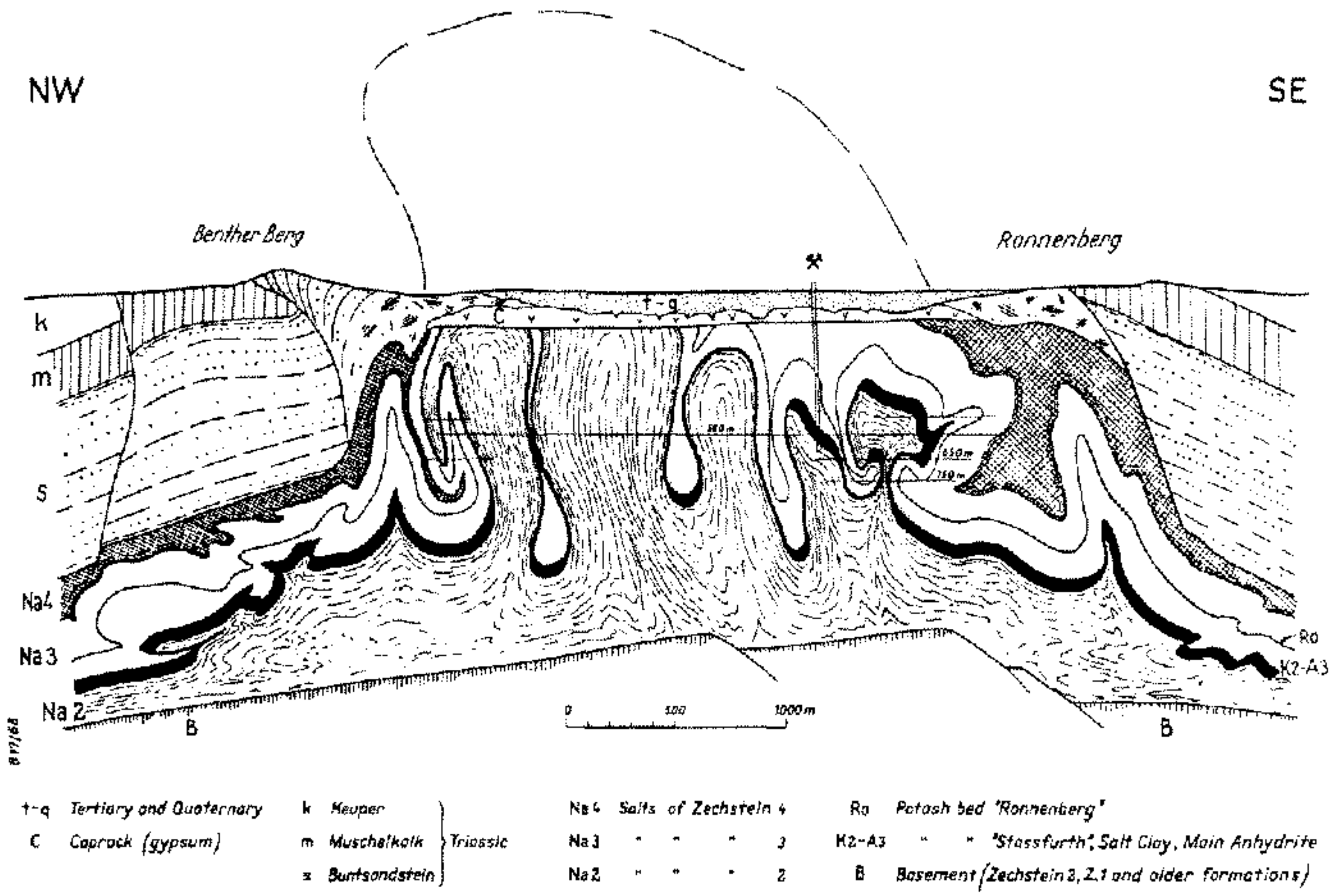

Figure 1. Salt dome of Benthe/Hannover. From G. Richter-Bernburg, International Symposium, Geology of Saline Deposits, Hannover, Germany, 1968.

The conclusion that gypsum does not form at the caprock-salt interface because of the high salinity of the brines is not invalidated because of its virtual absence on some domes. In such instances, it may well be that another condition essential for hydration of anhydrite is not present. There must also be sufficient permeability of the anhydrite caprock to permit passage of water to effect hydration. It is to be expected that the fracturing and brecciation which normally provides permeable channels may not exist on some domes possibly because of a lower than normal growth rate or special characteristics of the intruded material.

It is somewhat more difficult to account for a caprock which has a gypsum zone resting directly on the salt with or without anhydrite above. This may be explained by a flow pattern in the aquifer, probably with a higher than normal velocity, which has the effect of shifting the critical salinity line shown on Figure 2 down nearly to the caprock-salt interface. However, the important point is that conditions do exist which prevent hydration of anhydrite in the basal part of the caprock where it is intimately associated with circulating waters that are dissolved in the salt.

RELATION OF CAPROCK THICKNESS TO DISSOLUTION AND GROWTH OF SALT DOMES

Bearing in mind the ramifications outlined in the preceding paragraphs, it is reasonable to assume that the thickness of the caprock provides a measure of the amount of dissolution in the geologic past. It is obvious that the reliability of caprock thickness as an indication of dissolution is dependent on a correct understanding of its mode of origin. The hypothesis of "residual accumulation" is adopted here. The following discussion is contingent upon the correctness of this decision. In any event the scale of dissolution thus interpreted will be a maximum amount. In an analysis of the hydrologic stability of salt domes, this approach will provide the most conservative interpretation.

An understanding of the growth and dissolution history of salt domes as deduced from the record provided by caprock can provide an important aid in the analysis of rates of growth of salt domes as well as associated structural and geomorphic features.

Martinez (1974) called attention to the scarcity of published data of subsidence over U.S. salt domes as a result of

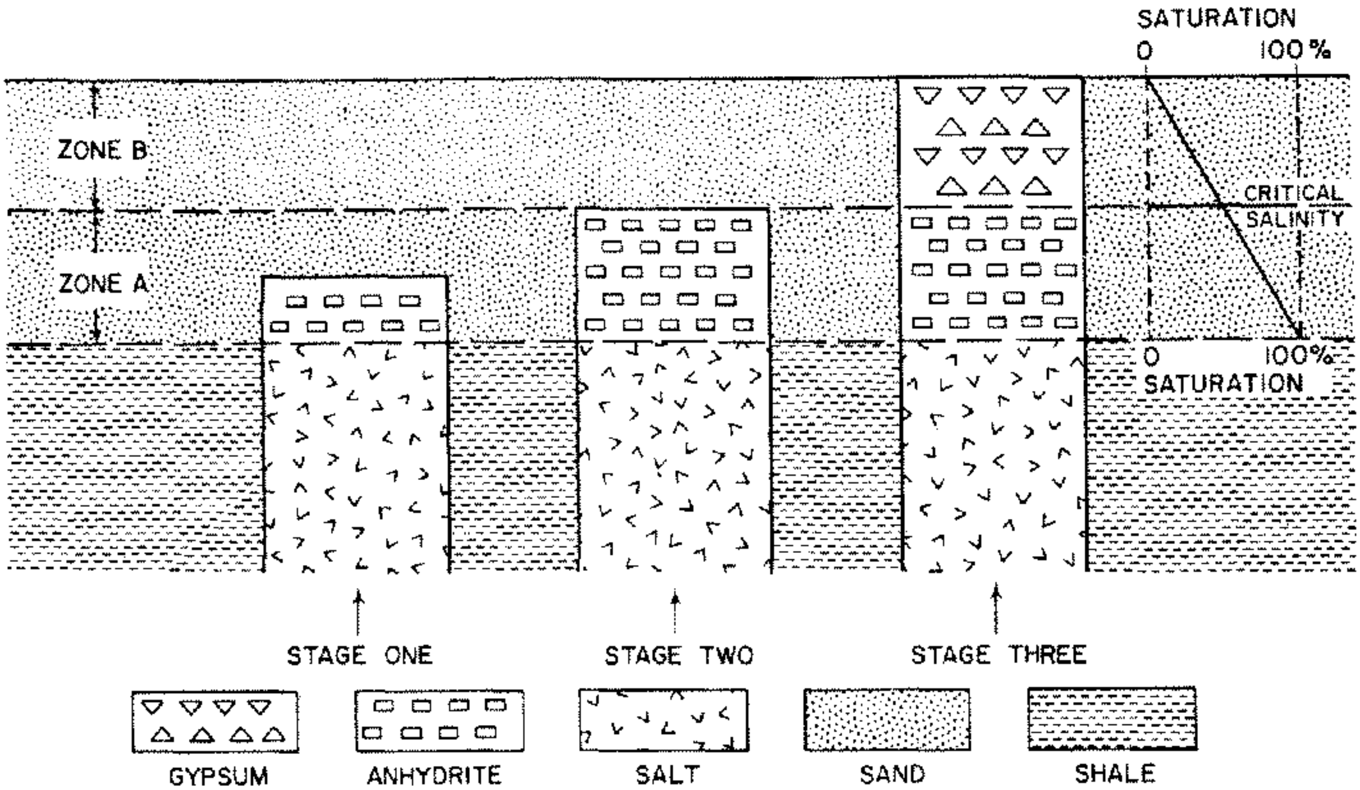

Figure 2. Postulated effect of salinity in delaying conversion of anhydrite to gypsum.

salt dissolution. Solution collapse features are common over salt domes in Germany according to Borchert and Muir (1964). Lakes and thick, circular, or elliptical bodies of lignite are found above some of these domes. The only two subsidence features cited by Martinez (1974) were the lake overlying the Jefferson Island dome in Louisiana and a subsidence feature over the Chestnut dome also in Louisiana. Since that time, the common association of surficial subsidence features with salt domes in the North Louisiana Salt Dome Basin has been reported by C.R. Kolb (*in* Martinez, et al., 1977). He considers them to be a result of salt dissolution. C.G. Smith (*in* Martinez, et al., 1976) has listed several domes with and without topographic lows in the Northeast Texas Salt Dome Basin.

The presence of topographic lows or highs or the absence of either of these features can be explained in principle by certain processes of growth as modified or not by dissolution. Martinez (1974) following ideas proposed by Goldman (1931) drew an analogy between salt dome growth, as modified by salt dissolution, and the flow of a glacier of ice. The advance or retreat of the toe of a glacier is dependent on the relative rates of flow and melting. Similarly, the vertical movement of the upper surface of a salt stock depends on the relative rates of growth and dissolution. A steady state can be brought about by an equivalence of these two processes in either instance. Figure 3 illustrates diagrammatically the structural and geomorphic effects of several different combinations of hypothetical conditions of growth and dissolution.

Figure 3A, Case 1, represents a condition of equilibrium in which the top of the salt remains in place at the plane of dissolution "D" as the salt stock continues to move upward. This plane of dissolution is the base of an aquifer containing moving water of a salinity which will dissolve salt. Minor uplift persists due to formation and upward movement of the caprock. It is to be noted that for this set of conditions the upper part of the aquifer and overlying units up to and including the surface is arched upward. The base of the aquifer which coincides with the plane of dissolution is not disturbed. The upper part of the caprock is oldest and the base is youngest. As long as the plane of dissolution does not move downward, surface subsidence cannot occur. Thus, if it could be demonstrated for an actual dome, that the base of the caprock coincides with the contact between an aquifer and an aquiclude, one could conclude that active subsidence and major uplift is unlikely. Without uplift and without subsidence the dome would appear to be tectonically stable even though the stock itself is still rising vertically. This apparent lack of movement is due to the steady state which is a result of the equilibrium between upward growth and dissolution.

Stage 1 of Case 2 shown in Figure 3B represents a situation in which the top of the stock has moved upward past the base of the aquifer. For this period of time the rate of

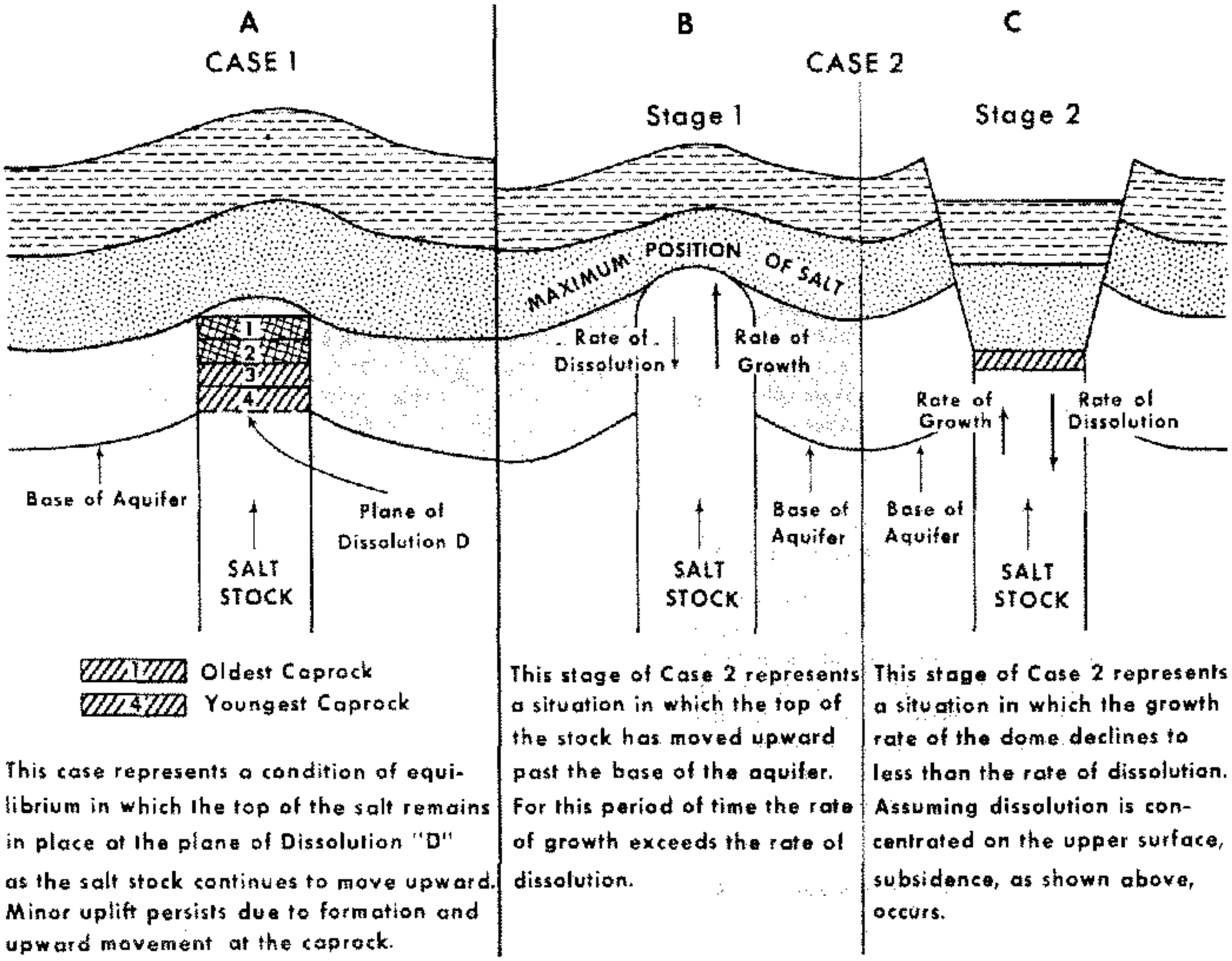

Figure 3. Growth versus dissolution in a rising salt stock.

growth has exceeded the rate of dissolution. A stock that has experienced this rate of growth may or may not have developed a caprock. It could be expected to experience a significant amount of dissolution in the future with concommitant subsidence of the overlying units.

This stage might be followed by Stage 2 shown in Figure 3C, which represents a situation in which the growth rate of the dome declines to less than the rate of dissolution. Assuming dissolution is concentrated on the upper surface, subsidence as shown above occurs. If dissolution occurred around the cylinder of salt as well, subsidence would still occur but the pattern would be more complex. A caprock would be expected to develop along with dissolution. The period of time represented by final growth of the dome would be indicated by the youngest beds that are upturned on the periphery. Dating of the latest period of subsidence might be accomplished by examination of possible collapse features in the down dropped plug. Sinkholes similar to those found overlying limestone or gypsum beds would not be expected to occur. The basis for this conclusion is that the salt stock itself would not be fractured so that ground waters could not percolate through the salt. Dissolution can only occur on the upper surface or the periphery. Any depression produced on the top of the salt, unless it is part of a linear path of dissolution, would be self-limited in downward growth by density isolation (stagnation) of saturated brine in the bottom of such a depression.

Two other possibilities are not illustrated in Figure 3. One of these is for the stock to stabilize in a position of equilibrium with its top surface at the uppermost level shown in Figure 3B. The ensuing events would be similar to those shown for Case 1 in Figure 3A. Finally, growth could continue to exceed dissolution as in Stage 1 of Case 2 shown in Figure 3B. If caprock had been formed it could be subject to sufficient stress from movement ahead of the plug and become quite brecciated and faulted.

All of these postulated examples of the results of growth and dissolution of a salt stock might have occurred at an early period of growth of the dome as it approached an erosion surface now recorded in the geologic record as an unconformity. Dissolution would be most likely to occur at such near surface conditions.

This model is not expected to be particularly useful as a predictory tool but should prove to be an aid in the interpretation of geohydrologic, structural, and stratigraphic data developed in a salt dome investigation.

In evaluating the potential utility of salt domes for the isolation of radioactive wastes both the hydrologic stability and the tectonic stability of these structures must be considered. The degree of development of caprock on salt domes provides a geologic record of the past history of dissolution and thus gives a basis for determining amounts of long time hydrologic stability and assessing the importance of dissolution in estimating growth rates.

DEGREE OF HYDROLOGIC STABILITY AS DEDUCED FROM CAPROCK DATA

A model (Fig. 4) was proposed by Martinez (*in* Martinez et al., 1975), contrasting conditions for maximum hydrological stability and instability. One of the indicators of instability incorporated in this analysis is the presence of caprock. Another is the presence of a plume of saline ground water "downstream" from the dome. Whereas caprock provides historical evidence of dissolution, a saline plume demonstrates active dissolution. These two conditions are not necessarily mutually exclusive. In fact, they probably represent a continuum of events. The presence of an anhydrite sand at the base of the anhydrite caprock would strongly suggest that the saline plume is a modern indication of the long period of dissolution demonstrated by the caprock. If this is correct, there should be a positive correlation between salt content of the aquifer and the amount of salt that must have been removed to produce the thickness of the caprock found on a particular dome. This, of course, may be very difficult to determine because of dispersion over such long periods of time. Positive proof of the absence of such a correlation would suggest significant dissolution of salt as it penetrated a deeper and older aquifer. C.G. Smith (1976 and *in* Martinez et al., 1976) recorded the presence of saline plumes in the Wilcox formation which were associated with the Bullard, Hainesville, Steen, and Whitehouse salt domes. Based on aquifer permeability, potentiometric slope, and thickness, Smith estimated rates of salt dissolution for these domes. In 250,000 years (a critical period for isolation of radioactive wastes) he concluded that a thickness of 75 feet would be removed from the top of the Bullard dome, 60 feet from the Hainesville dome, 50 feet from the Steen dome and 20 feet from the Whitehouse dome. If these rates of removal have persisted throughout the period of caprock formation, an extrapolation will provide an estimate for the duration of time involved in the development of caprock. Based on this assumption and a further assumption of 5% content of anhydrite in the salt, the 225 foot thick

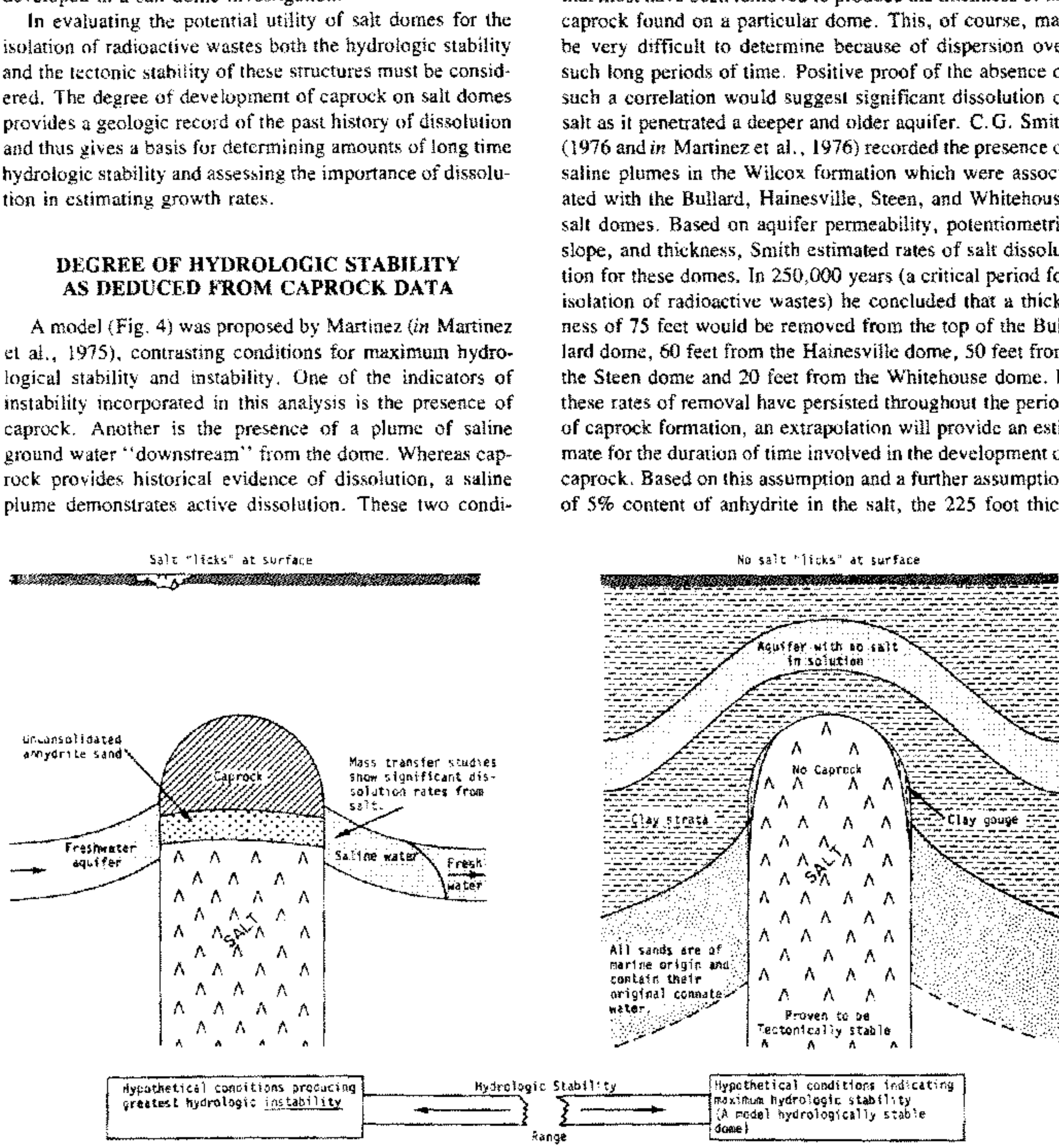

Figure 4. Contrasting conditions for maximum hydrological stability and instability. From Martinez (*In* Martinez et al., 1975).

caprock of the Steen dome has required 22.5 million years to accumulate. The total thickness of caprock on the Whitehouse dome is not known. The minimum demonstrated thickness of 67 feet would have required 16.75 million years for its accumulation. Based on the time scale of Kupfer (*in* Martinez et al., 1976) which places the end of the Wilcox as 50 million years ago, the caprock on the Steen dome began to form 27.5 million years after the close of Wilcox time and that on Whitehouse began to form as much as 33.25 million years after the close of Wilcox time and possibly much sooner. Thus the rate estimates by Smith for these two domes is not inconsistent with evidence afforded by caprock. Caprock thickness on the Bullard dome is not well established and not known for the Hainesville dome.

It is premature at this time to carry this foregoing discussion further. The intent of this presentation is to indicate the potential value of including the evidence afforded by caprock in estimates of hydrologic stability of salt domes. It does seem clear that the condition of the base of the anhydrite just above the caprock-salt interface can provide a direct indication of any possible active dissolution. If the basal anhydrite is a loose or poorly cemented sand, one could reasonably conclude that the salt stock is being presently dissolved. Conversely, if the basal anhydrite is well cemented, dissolution is probably inactive. This argument is reinforced by the observed fact that anhydrite sand pumped to the surface in solution mining becomes well cemented within a few years (Fig. 5) (Martinez, *in* Martinez et al., 1975).

According to Taylor (1938) anhydrite sand has been encountered next to the salt in a number of instances. This condition was found on the following domes: Belle Isle, Choctaw, Darrow, White Castle, Sorrento, Gueydan, and Calcasieu Lake, La. and Hockley, Lost Lake, and Hawkinsville, Texas. The latter three were originally reported by Hanna (1934). It does not necessarily follow that the entire surface of the dome is undergoing dissolution at the same time for Taylor also pointed out that in a few wells at some of the above domes and in the shaft at Hockley, Texas (Teas, 1931) caprock was determined to be resting directly on solid salt.

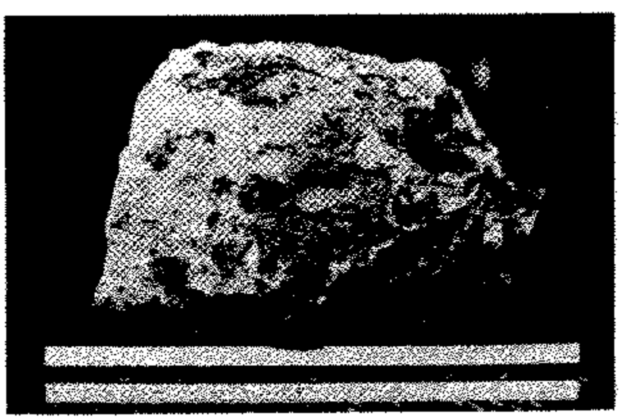

Figure 5. Rock formed at surface from anhydrite sand pumped from a solution mine in the Bayou Choctaw dome, Iberville Parish, Louisiana. From Martinez (*In* Martinez et al., 1975).

Taylor also cited the presence of brine in association with anhydrite sand at or near the contact as reported by Goldman (1933) for the Hockley dome in Texas and for the Winnfield dome in Louisiana; and reported by Hanna (1934) for the Grand Saline dome in Texas. Goldman (1933) reported that the brine in the Grand Saline caprock at the salt contact was under considerable pressure. He also stated that this same condition existed on the Winnfield dome where the pressure was equivalent to a column of water from the anhydrite sand extending up to 70 feet above the surface of the ground. Such pressure is possibly the driving force for salt water springs which commonly are found over salt domes. It is by no means certain what produces this pressure. One possible source is release of trapped gas from the salt itself by dissolution. Martinez and Thoms (*in* Martinez et al., 1977) based on information provided by Mr. Francis Falcon, listed a number of domes which were said to contain oil and gas in the salt. More recent evidence of gas in the Sorrento dome provided by Mr. William F. Sporleder was also reviewed in the report by Martinez et al. (1977). It is generally accepted that methane as well as CO_2 does occur in salt albeit in small quantities. However, dissolution of salt in amounts required to produce substantial thickness of caprock may result in accumulation of trapped gas in the caprock under substantial pressure.

USE OF CAPROCK DATA IN AN ANALYSIS OF TECTONIC STABILITY

It was suggested by Martinez (1974) that caprock may serve as a "speedometer" to indicate relative rates of growth of salt domes located near each other with their upper surfaces at the same elevation but differing in thickness of caprock.

William A. Huckaba in a report by Netherland, Sewell & Associates, Inc. (1976) made estimates of growth rates of some domes in the Northeast Texas Salt-Dome Basin. He computed "uplift-vs-time" values from comparative thickness measurements of time equivalent units over domes and in the basin. Huckaba recognized that it is also necessary to factor into this calculation that part of the growth rate not recorded in the structural and sedimentological record because of salt dissolution. He computed this component from caprock thickness data based on assumptions of the period of dissolution and anhydrite content of the salt. He found rates computed on that basis to be much greater than those calculated as "uplift-vs-time" values.

In the same report by Netherland, Sewell and Associates, William R. Muehlberger concurred with Huckaba's approach. Muehlberger also considered that an analysis of caprock thickness and anhydrite content of the salt gives an indication of probable rate of vertical movement of salt domes.

Kumar (*in* Martinez et al., 1977) described in detail the approach required to determine growth rates of salt domes by measuring the magnitude and the duration of the uplift. He explained a number of the assumptions required in this kind of calculation and recognized the potential value of using the relationship between the thickness of caprock and the amount (thickness) of salt dissolved from a salt stock in developing estimates of salt dome growth rates. However, Kumar did not use this relationship in his analysis of 18 of the 19 salt domes in the north Louisiana salt dome basin because he did not consider sufficiently precise data on caprock thickness and dome salt chemistry to be available. Huckaby's data, nevertheless, indicate that rates computed on this basis may be considerably higher than those determined from uplift data. This demonstrates the need to develop the quality of information required to include the dissolution component if growth rate estimates are attempted.

CONCLUSIONS

It is evident that salt dome caprock preserves a record of geologic processes. The interpretation of this record is extremely difficult and is not likely at the present time to provide unique and unequivocal solutions. Conclusions developed from an analysis of caprock can vary widely depending on the hypothesis accepted for its origin. Furthermore, even when thickness data and anhydrite content of the salt stock are known, other significant assumptions are required to estimate such items as dissolution and growth rates.

Despite these negative factors, if the most reasonable hypothesis of caprock origin, residual accumulation, is accepted, it becomes possible to make initial estimates of rates of dissolution and growth of domes. It is possible that further research will provide a basis for refining estimates of this kind in the future.

DISCUSSION

R. Kuhn:

Comment. I would like to note here one process, which is going on during the formation of the caprock: that is the increasing of the volume by the transition of anhydrite into gypsum. This process may press together the infiltration ways of water and therefore let stop the formation of further gypsum (of course only, if the water infiltration doesn't flow!).

ACKNOWLEDGEMENT

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