ORIGIN OF BEDDED SALT DEPOSITS:
A CRITIQUE OF EVAPORATIVE MODELS AND
DEFENSE OF A HYDROTHERMAL MODEL

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THESIS

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ABSTRACT

Current models for the deposition of large bodies of salts, based upon classical evaporative techniques, are inconsistent with field observations and experimental data. The desiccated, deep-basin model recently advanced to explain salt deposits in the Mediterranean Basin has some major shortcomings. The model illustrates how a common uniformitarian bias toward the evaporative process dictates the interpretation of many features and data.

A new model for the deposition of salts, termed the "hydrothermal model," is consistent with known field observations such as the tremendous lateral extent and thickness of deposits, their occurrence and distribution throughout the world, and their unique composition including the monomineralic nature, ionic concentrations, and relative abundance. Volcanic, tectonic, structural, stratigraphic, heavy metal, and hydrocarbon associations with salt deposits also support the hydrothermal model.

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Chapter One

INTRODUCTION

Salts represent some of the most common commodities today, including table salt, wallboard, and fertilizers. They are abundant in the rock record on continents worldwide. They are easy to recognize and describe, and yet their origin has been a subject of much discussion for hundreds of years. Theory upon theory has been offered. Whenever one theory is advanced to explain their deposition, another problem or unique feature comes to light which necessitates a modification of the theory.

The problem does not lie in explaining how to get the salts. That can easily come about by merely evaporating sea water (hence the term "evaporite" in describing this whole suite of minerals). The real problem arises in trying to explain some of the major features of salt deposits by a depositional model. It is one thing to talk about the formation of merely a few inches or feet of salts and an entirely different problem to explain the origin of deposits several thousand feet thick. Table 1 lists many salt deposits giving content and thicknesses of the deposits. As one

Table 1. Selected Salt Deposits of the United States.

Strata System	Area	Formation or Interval	Thickness of Section (ft)	Type
Silurian?	Michigan Basin	Bass Island, Salina	3,000	S,H
	West Virginia	Salina	800	S
Mississippian	Williston Basin	Otter, Charles	1,000	S
Pennsylvanian	Paradox Basin, Utah	Paradox	4,000	S,H,B
	Gypsum Basin, Colorado	Maroon	500+	S
Permian	Southeastern New Mexico	Rustler, Salado, Castile	4,500	S,H,B
	Texas Panhandle	Pease River, Clear Fork, Wichita	2,000	S
Jurassic?	Gulf Coast	Louann, Werner	1,500±	S,H
	Central Utah	Arapien	1,000	H
Cretaceous	South central Florida	Comanchean	6,000	S

Thicknesses are approximate and include interbedded sediments. Type of salts are calcium sulfates, including anhydrite and gypsum, S; halite, H; and bedded bittern salts of potassium and magnesium, B (Modified from Stewart, 1963, p. Y27).

can readily see, there are deposits of salts which stagger the imagination.

Furthermore, as also seen in Table 1, large deposits often include principally one mineral to the exclusion of the others. Concerning a large deposit of gypsum, Bateman (1942, p. 181) reports:

> Since the evaporation of 1,000 feet of sea water yields only 0.7 foot of gypsum, then the evaporation of 425,000 feet, or a depth of 80 miles, of sea water, would be required to yield 300 feet of anhydrite. As this is ridiculous, it follows that new supplies of sea water must have been added to the basin during evaporation, and the residual liquors became concentrated in subbasins.

The thickness of the deposit is only one problem. An additional concern is the whereabouts of the other types of salts that "should" be there if the deposit formed by the evaporation of seawater. This monomineralic deposition has stymied students of geology for years. In the experiments and observations of modern salt deposition, a definite order of precipitation giving several salts is noted. This is drastically different from the record of past deposits.

The problem of determining how these major salt deposits originated stems from an attempt to explain past geologic features by present day processes. This uniformitarianism forms the underlying principle and philosophy of most of today's geology. The philosophy is inherent in the genetic term "evaporite" used to describe the various salts. The logic of uniformitarianism tells us that since some salt is formed by the process of evaporation of water today, the giant deposits in the geologic past were probably also formed that way and hence should be called "evaporites."

The following example illustrates the problem. Suppose we see a man who is digging a hole with a shovel. Can we assume the next time we see a hole somewhere else, that the same man with the same shovel also dug this hole? Of course we cannot. There are other individuals who can dig a hole and other operations which would result in a "thing" called a hole. In the same way, other methods besides evaporation can produce the so-called "evaporite" minerals.

Because the bias concerning the origin of salt is inherent in the term "evaporite," its use in this paper will be in quotations to emphasize this bias. Other times these deposits will merely be called salts.

In this study, various classical models for the origin of salts will be discussed along with their strengths and failures. The underlying bias referred to above, along with the secondary assumptions, will be demonstrated in discussions of one of the newest theories of salt deposition, the desiccated deep-basin model, as well as in discussion of problems assoociated with the theoretical and experimental geochemistry of salt deposition.

A new model for the deposition of salts, the "hydrothermal model," will be presented as an alternative to the classical evaporative models. This model will be shown to be consistent with known field data and to alleviate many of the "problems" other models cannot solve. It is hoped that this model will cause geologic thinking to progress in a new, fresh, direction since the old direction involving evaporative flats and basins has become stagnant.

Chapter Two

EVAPORATIVE MODELS FOR DEPOSITION OF SALT

Many depositional models have been proposed in attempts to explain the origin of salt. Most postulate one of two main depositional environments: either the mud flats (sabkhas) along coastal tidal zones and inland lakes, or deeper water basins. Both rely on concentration of salts through evaporation. Proponents of one are often bitterly opposed to the other. The main theories will be discussed here, along with their strengths and weaknesses.

Basinal Deposits

The concept of basinal evaporite deposits has been used, overused, and often greatly misused in explanations of various salt deposits. The beginning of the modern barred basin models was first put forth by Bischof in his 1854 publication of Elements of Chemical and Physical Geology. He suggested the deposits may have formed in a basin behind a bar over which the sea poured during high tide seasons. The model was later revitalized in the last quarter of the nineteenth century by Ochsenius, whose famous barred basin model has since dominated the thinking of most geologists. His theory has led to numerous publications adopting the same or a slightly modified plan for evaporite deposition. In his 1888 model, he describes a barred basin:

> When a nearly horizontally running bar cuts off a bay from the sea, so that only as much sea-water runs in over it as is compensated by evaporation from the surface of the lagoon, and the so partially separated portion receives no large additions of fresh --, i.e. rain or running water a deposition of salt takes place in the way to be described. (Ochsenius, 1888, p. 181)

He then goes on to describe the order of deposition of salts as the seawater becomes more and more concentrated.

In essence the traditional view of a barred basin is a body of water cut off in whole or in part from the open marine environment by a reef, shelf or sand bar. The water trapped in the basin is concentrated by evaporation until the salinity is sufficient to precipitate "evaporite" minerals. Periodic or perhaps constant recharging of the basin with water from the outside environment, provides more material for precipitation resulting in many feet of deposition.

Shortly after workers tried to match the theory to the actual data, they realized a major problem existed. Ochsenius' theory in their estimation could not explain the deposits having a great thickness of a single mineral to the exclusion of other minerals that "should" have also been deposited. Gypsum deposits hundreds of meters thick would demand the evaporation of an unreasonably tall column of water, implying an extremely deep basin. What happened to the precipitation of the other salts then?

In 1915, Branson published a modification of the Ochsenius bar theory to try to account for the monomineralic deposition common to many of the large salt deposits. About the same time, it was noticed that the ratio of sodium chloride to calcium sulfate in normal seawater is about 30:1; yet in the Castile Formation of Texas and New Mexico, it is about 0.25:1. This puzzled workers for years. Therefore, King (1947) put forth his reflux model. He suggested that while the thick deposits of one "evaporite" mineral were accumulating, the more soluble salts escaped as a dense countercurrent of thick brine beneath the inflowing seawater. This idea (or a very similar one) is currently held to by many barred basin advocates.

Schmalz (1969), discontent with the idea of salt forming in shallow basins, argued that basins had to be very deep in order to account for the saline giants such as the Zechstein (in Germany and the Netherlands) and the Castile. For him, it was very unreasonable to assume that the basin could be subsiding at exactly the precise rate to allow continuation of salt deposition. He summarized evidence suggesting that salt accumulated in a deep basin with deep water.

There have been so many variations of bars and basinal deposits, that later workers found it extremely helpful to provide a classification (Krumbein and Sloss, 1963; Schreiber, 1978; Sloss, 1969). Several types of basins have been suggested based either upon their environmental relationships with stratigraphic sequences, or upon the tectonic setting. These can be grouped into three main types: basins of the craton proper, basins of the stable continental margin, and basins of the rifted continental margin.

The last major type of basin suggested is that associated with rifted continental margins due either to diverging or converging lithospheric plates. These are extremely deep oceanic basins. An example given of a basin due to convergence is the Mediterranean Sea (Hsü, 1972) and that of divergence is in the Red Sea and along the margins of the south Atlantic Ocean (Kinsman, 1974). Deposits in these types of basins have rather recently been suggested because of the efforts of the oceanic researchers from Wood's Hole and Scripps Institution of Oceanography as well as geophysical exploration companies. This is the new hot spot for active research.

Although each of the major models appear to be quite different in approach, they all depend upon the concentration of seawater by evaporation and deposition as the waters reach sufficient salinities. Problems with all of these basinal models are perhaps best illustrated by the paper written by Woolnough (1937). Although Woolnough is a supporter of the barred basin hypothesis, his approach is not one of most traditional geologists. He recognizes the inadequacy of the "Doctrine of Uniformitarianism" in the explanation of geologic formations which include major salt deposits, major coal measures, major fresh water series of sediments, and source rocks of oil deposits. In general, he does not want to give up the doctrine, but to modify it:

> The writer would therefore ask to be permitted to advance three postulates: (1) the geological processes active in the world at the present day represent only a fraction of the processes which have acted, throughout geological history, in modifying the earth's crust; (2) existing phenomena are capable of extension, both qualitatively and quantitatively, to account for results which defy explanation by the strict application of the Doctrine of Uniformity; (3) processes may be envisaged which have no counterpart at present, provided that the assumptions so made are not contrary to the fundamental laws of nature, and that there can be found objective instances explicable by such assumptions only and by no recognized and accepted phenomena. (Woolnough, 1937, p. 1105)

In regard to the origin of salt, he states:

> The writer was engaged for a number of years in an intensive investigation of salt deposits, in the course of which he studied the literature carefully, and visited arid regions where, if anywhere, such deposits should have been observed in course of formation. In no instance were conditions encountered which could conceivably have produced any of the *major* primary salt deposits of the geological past. *Some* circumstances or set of circumstances, entirely lacking under present day conditions, *must* have been operative when such major salt deposits were generated. (p. 1104, emphases his)

Woolnough's main thesis in the paper is that ideal conditions for barred basins existed in the past to a lot greater extent than they do today. The conditions as he sees them would be just right for the deposition of the salt as well as oil formations, black shales, and foraminifera:

> The main thesis of this paper is an amplification of the "Bar Theory" of Ochsenius. It is suggested that, when all implications of this theory are considered, the possibility is indicated of existence in the geologic past of "barred basins" of dimensions and characters entirely unrepresented at the present day. (p. 1101)

Woolnough lists what he considers to be modern enclosed basins of very large proportions. He includes the Mediterranean Sea, Black Sea, Red Sea, Persian Gulf, Baltic Sea, Caribbean Sea, Gulf of Mexico, Hudson Bay, Gulf of St. Lawrence, Sea of Japan, and other enclosed basins of the East Indies. These vary in their degree in which they are cut off from the main open ocean. He sees all of these except for the Black Sea as having what he calls a balanced faunal assemblage. His idea is that unless the basin becomes even more isolated and conditions are severely altered, the development of basinal deposits will not happen.

Woolnough's willingness to consider the unusual in geologic processes is rare but perceptive. He undoubtedly would be open to many of the ideas put forth in this paper.

Sabkhas

During the last 15 years the concept of the sabhka has been used extensively as a blanket explanation of many of the ancient evaporites. This suggestion has been made as a result of detailed study of recent deposits of salts accumulating along such areas as the Trucial Coast on the south side of the Persian Gulf and the Laguna Madre mudflats of southwest Texas (Masson, 1955).

The sabkha environment is the supratidal desert environment of either coastal margins or large inland lake margins. The term, sabkha, is Arabic and refers to flat salt-crusted deserts. It was first used in the present sense to describe the coastal desert supratidal plain along the Trucial Coast. Kinsman (1969) defines it as a fairly level, salt-encrusted surface that only occasionally is inundated. He refers to coastal and continental sabkhas:

> Coastal sabkhas are supratidal surfaces formed by depositional offlap of marine sediments, and the associated evaporites are precipitated from seawater derived brines. Continental sabkhas comprise continental or earlier cycle marine sediments, and the associated evaporites are precipitated from evaporated continental waters (Kinsman, 1969, p. 830).

The coastal sabkha, then, has its groundwaters principally derived from the sea, while the groundwater for the inland sabkha is predominantly terrestrial. The Trucial Coast Abu Dhabi sabkha is diagrammed in Figure 1.

Sabkha deposits were first described by Masson (1955) in a study of the Laguna Madre mudflats. Others quickly followed suit (Fisk, 1959; Kerr and Thompson, 1963). Shortly following the first recognition of the supratidal depositional environment, the Trucial Coast deposits were reported (Wells, 1962; Curtis, Evans, Kinsman and Shearman, 1963; Butler, 1969). The first two of the reports on the Trucial Coast linked both dolomite and anhydrite deposition to evaporites. These reports spurred many others on to consider this sabkha environment. As a result, the literature became full of this cure-all for problems associated with salt deposition (Gray, 1967; Goldberg, 1967; Roehl, 1967; Butler, 1969). As is usually the case with a new, fruitful idea, it

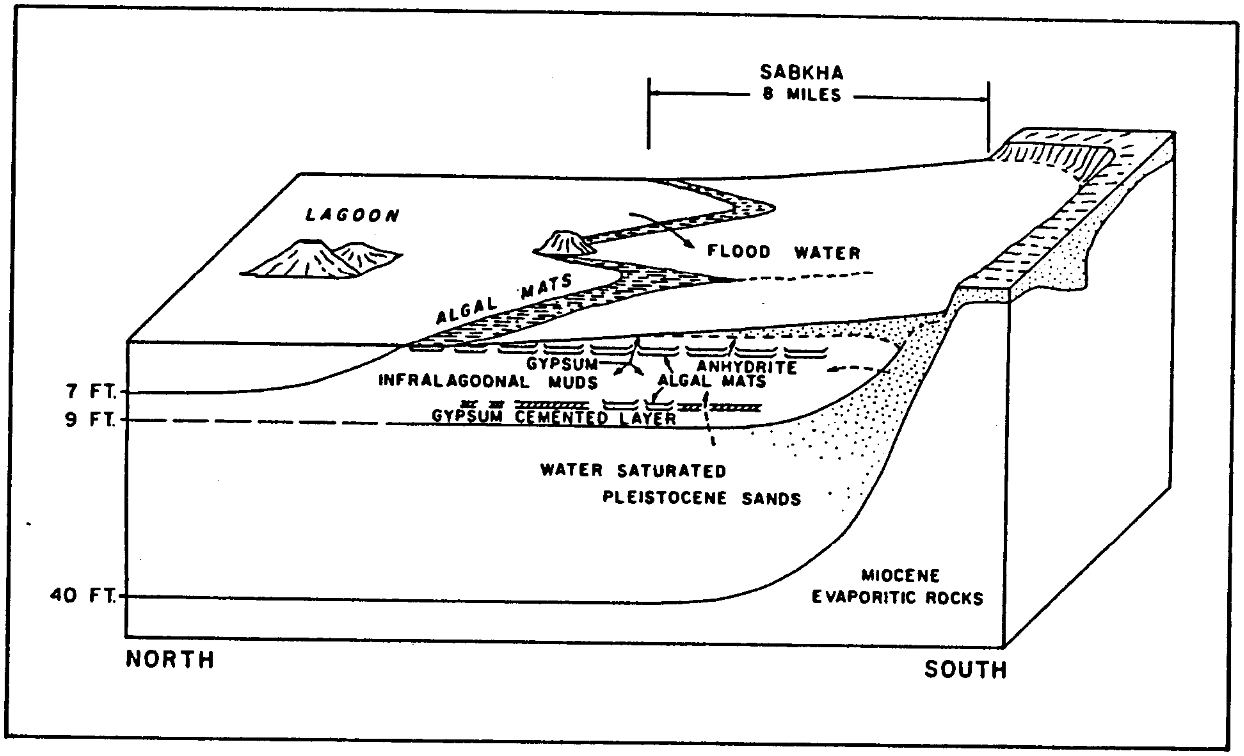

Figure 1. Stratigraphy of the Abu Dhabi Sabkha. (Schematic cross section.) (From Butler, 1969, p. 72.)

became abused and everything was tied into the sabkha process. We are still weeding out many overenergetic attempts at model fitting.

In the state-of-the-art summaries, Birnbaum and Presley (1980) emphasize the necessity of watching carefully for overuse of the sabkha model:

> There has of late been a rush -- a stampede to apply sabkha interpretation . . . Sloss (1977) identified the "sabkha syndrome" which, when applied to displacement sulfates of the supratidal flats of the Persian Gulf may be roughly defined as the stampede to attribute ". . . all ancient modular-mosaic, enterolithic, and the chicken-wire anhydrites to prograding supratidal environments on the margins of regressive seas." There must be continual re-evaluation to prevent over-use of the sabkha analog. (p. 305)

With this in mind we will carefully analyze one major sabkha interpretation in the next chapter, and discuss in detail the evidences of the sabkha environment that have influenced so many researchers in recent years.

Chapter Three

THE DESICCATED DEEP-BASIN MODEL: A SPECIFIC EXAMPLE OF UNIFORMITARIAN ASSUMPTIONS

A whole new topic of speculation opened up in 1961 when oceanic researchers noted diapiric structures typical of salt domes on geophysical reflection profiles in the Mediterranean Sea. Armed with many pet theories and coring machinery to prove their theories, the investigators aboard the Glomar Challenger steamed into the Mediterranean. Coring of the strata confirmed the presence of "evaporites." Seismic reflection profiles indicated the layer of salts to be as much as 2500 meters thick. What, then, is a huge layer of salt doing below sediments at the bottom of a 3000 meter deep ocean basin? Some said, "Aha! This proves the deep basin hypothesis for salt origin." Others, who held to the sabkha model didn't give up. They pointed to features of the deposit they recognized as sabkha facies.

Hsü *et al*. tried to resolve the apparent dilemma by suggesting the deposit was of sabkha origin, resulting from the total (or nearly so) drying up of the Mediterranean Sea (Hsü, 1972; Hsü, Cita, and Ryan, 1973; Hsü, 1983a; Hsü, 1983b). They claimed that evidence for a deep basin did not necessarily require that the basin contained deep water. This new model can be termed the "deep basin--shallow water" hypothesis, or in Hsü's words, the "desiccated deep-basin" model. This is in distinction to the "deep basin--deep water model proposed by Schmalz (1969). See Figure 2 for a comparison of these models. Although having such a huge basin drying up may seem bizarre, the theory is gaining many advocates and has been suggested as an explanation of many of the ancient large saline deposits (Hsü, Cita, and Ryan, 1973) including the famous Zechstein (Friedman, 1972). This model will be carefully discussed since it will probably be looked upon as a leading theory in years to come.

Hsü (1972) along with Hsü, Cita and Ryan (1973) published several lines of reasoning leading to their desiccation hypothesis. These are listed and will be discussed individually.

The first point Hsü _et al_. make is that the basin responsible for the deposition of the salts under the Mediterranean Sea was indeed a deep one. They summarize the arguments given by Schmalz (1969) such as the unreasonable idea that rates of subsidence coincided exactly with rates of salt deposition, the occurrence of "varves" in evaporitic sequences,

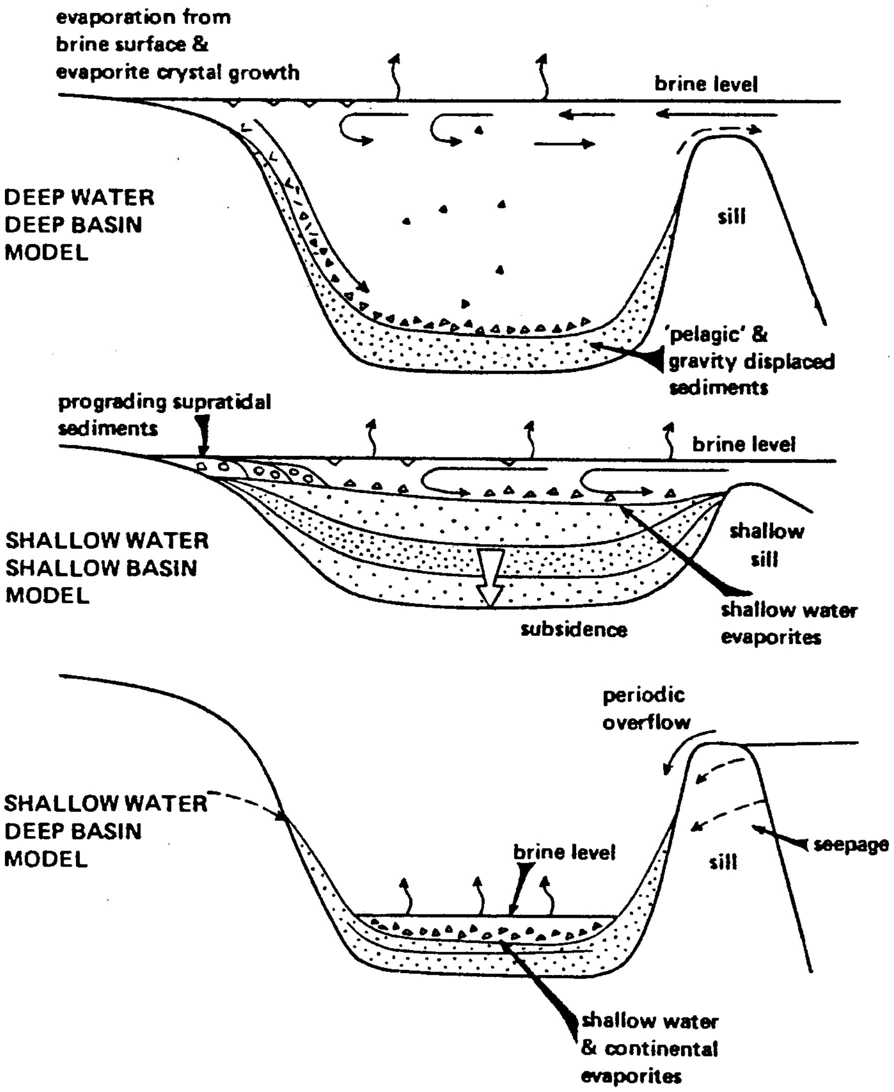

Figure 2. Depositional Models for Basinal Evaporites. (From Kendall, 1978, p.135).

paleogeographical reconstructions, and interlayering with euxinic sediments such as black shale. They also cite the discovery of salt under the Gulf of Mexico which is underlain by thin oceanic crust as evidence of deep basinal deposition.

Paleontological evidence derived from cores taken from the bottom of the Mediterranean was also included as evidence of a deep basin. It is known that calcium carbonate becomes more soluble in water as the water becomes colder and deeper. The mineral, aragonite, of the calcium carbonate group tends to dissolve more rapidly than the mineral, calcite, of the same group. Therefore, the lack of aragonitic tests on foraminifera agrees with the considerable depth of deposition. Also, the particular fossils comprising the oozes between sterile salt deposits indicated that these oozes were normal marine and suggested great depth of water at least for non-evaporative stages. This will be discussed later.

After claiming the sufficiency of this evidence to indicate deep basin deposition, Hsü *et al*. then suggest that these are not necessarily criterion to base the assumption that the water in that basin had to be deep:

> Thus it seems that we have considerable evidence for the postulate of evaporite deposition in ancient deep basins. However, none of the criteria discussed above could be

> construed as an explicit indicator that these salts were deposited in deep waters. (Hsü, *et al*., 1973, p. 1209)

It seems that once a geologist becomes a sabkha advocate, he continues in spite of overwhelming circumstances. Hsü *et al*. then offer petrological, geomorphological, geochemical, and paleontological evidence that the actual environment on the bottom of the Mediterranean Sea was that of a sabkha. A critical analysis of the evidence proposed for the sabkha environment follows. Beginning with the petrologic features, we will show that the data argue strongly against the desiccated deep-basin model.

Petrological Evidence

The petrologic features Hsü *et al*. point to as evidence of subaerial exposure include nodular and chicken wire anhydrite with stromatolitic laminations, desiccation cracks, and possible indicators of halite diagenesis. Interpretations of these features, however, were made with some rather rash judgments and were made consistent with their assumptions and with many who went before.

The first point to make is that once a feature of a particular environment is recognized, its presence elsewhere does not mean it is from the *same* environment. Analogical reasoning can break down as pointed out earlier in the example of a man digging a hole. Many environments and processes in geology can and do produce the same features. After nodular and chicken wire anhydrite with stromatolitic laminations were first described from the coastal modern environment, it seemed like everything that vaguely resembled this material suddenly represented sabkha deposition. The literature became full of evidence of ancient sabkhas. The association of these features with the sabkha environment is illustrated by Friedman (1973):

> The nodular anhydrite, particularly with the typical "chicken-wire lattice structure " . . . is indicative of subaerial exposure of soft sediments in which the nodules are formed by displacement of the host sediment. (p. 703)

He continues:

> With the discovery of modern anhydrite nodules in the Persian Gulf, comparable to those found in the rock record, the interpretation has become generally accepted that nodular anhydrite is an indicator of subaerial origin in tidal flats of arid regions, generally known as sabkhas. (p. 705)

The discovery of these features in cores from the bottom of the Mediterranean Sea was also given the blanket treatment of proof positive that the bottom of the sea was at one time a sabkha environment (Hsü, 1972; Hsü, Cita, and Ryan, 1973; Friedman, 1973).

There is a tremendous variation from one specimen of nodular or chicken wire anhydrite to another. It is very likely that some other process was responsible for the observed characteristics in some of these. The author is familiar with at least two other occurrences that resemble the nodular and chicken wire form. One is in nephrite jade, the other in turquoise. That found in the jade is uncommon and highly prized; however, many are familiar with the beautiful "spider-web" look of high quality turquoise jewelry. Neither of these minerals are said to be of sabkha origin, but reflect conditions of formation or of metamorphic alteration. On the surface without any prior knowledge, these could easily be incorrectly interpretted.

Dean et al. (1975) also recognize the difficulty with the trend to ascribe all these features to the sabkha:

> The common nodular habit of anhydrite similar to the nodular anhydrite in modern Persian Gulf marginal sediments, has played a key role in the interpretation of older deposits as paleosabkhas. Also, laminated carbonate and sulfate sediments with dark organic interlaminae or films have served as criteria for peritidal or intertidal sedimentation under algal mat control. Not all laminated sediments originated as algal mats in shallow or intertidal environments, and the nodular habit of anhydrite is a normal diagenetic fabric not indicative exclusively of the subaerial sabkha environment. (p. 367)

They conclude that nodular anhydrite is not diagnostic of supratidal environments but of increasing salinity and can be formed subaqueosly in water of great depth or shallow.

In some salt deposits, laminations comprised of alternating bands of anhydrite, calcite, and halite have been interpreted as an indication of deposition in still, quiet water that is unaffected by wave action (Kendall, 1978). These laminations can often be traced or correlated over great distances (100 kilometers in the Castile anhydrite of Texas and New Mexico, and over 200 kilometers in the famous European Zechstein (Dean *et al*., 1975). Some researchers term some of these as stromatolitic laminations and interpret their origin to be due to periodic seasonal changes which result in deposition of great quantities of algae. Some refer to them merely as algal mats and presume they originated in intertidal and even supratidal zones.

Harris (1973) points to the possibility that organic laminations result from fluctuations in salinity of the water. This need not involve seasonal changes at all but could reflect many rapid salinity changes. There is much debate as to what these laminations actually represent. The deposition in intertidal zones for these large deposits with the laminae is ruled out because as Dean *et al*. (1975, p. 369) point out, "even the most regular individul mats in intertidal environments cannot be correlated for more than a few hundred meters." Harris (1973) reports the possibility that algal laminations are accumulations of phytoplankton which resemble algal laminations. In Chapter 6, it is suggested that these laminations could also be due to the sulfur reducing bacteria in deep water associated with hot hydrothermal solutions. Suffice it to say here that these types of laminations are found in some modern deposits, but the sabkha process does not account for the 2000 laminations found in the German Zechstein salt formations or the 200,000 laminations reported by Dean _et al_. (1975) of the Castile.

Note is made by Hsü, Ryan, and Schreiber (1973, p. 710) that "the desiccation crack is additional evidence of subaerial exposure." In many instances the presence of these desiccation cracks are categorically interpreted as "proof of periodic subaerial exposure." Again, this evidence sounds impressive; however, it does not look so good upon closer inspection. Figures depicting the desiccation cracks were given by Hsü, Ryan, and Schreiber (1973, pp. 709 and 711). One's mental picture when the word desiccation crack is mentioned is the classic dried and curled up mud that leaves an almost unmistakable mud flat impression. This is not so with these reported "desiccation cracks." In the first figure, the crack is at most 1 to 2 mm wide and 4 to 5 cm deep. The second figure has much smaller dimensions. The "desiccation cracks" are less than 1 mm long and no more than 1/40 of a millemeter wide! These features do not look at all like desiccation cracks but are most likely of totally different origin. In another core, a similar "desiccation crack" is observed (Nesteroff, 1973, p. 679). This crack follows the laminations which are highly contorted and, in this case, is clearly not a desiccation feature. Considerable information has been appropriated from so little speculative evidence. This is not in keeping with sound scientific judgement.

Plummer and Gostin (1981), Harris (1973), and Burst (1965) also warn of the misidentification of features interpreted traditionally as those representing desiccation cracks and then consequently of mistakes in interpreting the environment of subaerial exposure. It would sound as though they must have studied the case concerning the man and the hole. Plummer and Gostin conclude:

> Shrinkage cracks can form not only at the sediment-air interface by desiccation processes but also at the sediment-water interface or substratally by synaeresis processes." (p. 147)

Burst (1965) also concludes after experimentation that shrinkage cracks form subaqueosly and are due to fluctuations in salinity. Care then, has not been taken in interpreting so-called desiccation cracks. These features have been used much too liberally to imply sabkha environments. How many mistakes in interpreting paleoenvironments have been made by the abuse of "desiccation" features?

Evidence of halite diagenesis is given to support the desiccated deep-basin sabkha hypothesis. This includes the partly dissolved and recrystallized salt crystals as well as structures commonly termed "hopper" crystals. These are pyramid shaped crystals which were reported by Dellwig (1955) to have formed at the surface of a brine pool. Although it is possible to explain the unique shape of the crystals by the process Dellwig reports, it is <u>not the only</u> process which will give the same characteristic shape. Raup (1970) generated hopper crystals by brine mixing totally independently of surface concentration (see Chapter 5). Another possible mechanism for the formation of "hopper" crystals could be growth of crystals at the interface of distinct thermoclines having very distinct salinity levels as are reported for the Red Sea brines. This would make an excellent research project. Dissolution and partial recrystallization of salt crystals can be accomplished by many mechanisms including crystals falling down through water having different salinity and temperature. Of course many of the traditional methods of diagenetic alteration can achieve the same end result.

It should be noted that part of Hsü's argument for the sabkha environment rests on the "validation" of establishing a correlation between the core holes from the bottom of the Mediterranean and the formations found adjacent to the sea. The researchers then used information relating to those terrestrial deposits in support of their model for the desiccating Mediterranean. Debenedetti (1982) objects to this method especially on the basis of so little information. He points out that the total volume of the cores was merely a few cubic meters. That only represents an area of about 800 square centimeters. This is hardly enough information to derive inferences about the origin of the deposit encompassing 2 million or more square kilometers and definitely not enough information to derive its correlation with the deposits adjacent to the sea. The method is similar to the old story of the blind man describing an elephant by feeling only the tail. In the present case, the data is much less, and the interpretations are much greater.

Another problem inherent in the sabkha model of "evaporite" deposition is the lack of terrigenously derived material within the salt deposit. As would be expected, modern sabkhas certainly contain a great deal of terrigenous material (Butler, 1969); yet most of the major salt deposits are relatively pure. This argues against a sabkha genesis and will be discussed later as substantiation of the model to be proposed.

Geochemical Evidence

Another "proof" for the sabkha model that is used by Hsü to arrive at a complete desiccation of the Mediterranean is offered by the stable isotope compositions of the salts:

> Geochemical evidence points in the same direction: stable isotope compositions of the Mediterranean Evaporites are comparable to those of modern playa evaporites, and are very distinct from those of modern marine evaporites. (Hsü, 1972, p. 386)

This author does not feel as content with the isotopic studies as Hsü apparently does. Even Hsü's colleagues note a discrepancy between some of the isotopic data and the paleontologic data (Longinelli and Cita, 1973). It is generally held that stable isotopic values reflect the temperature of formation of minerals with the isotopes in them. Generally, the colder the water, the more depleted the mineral is in the heavier oxygen and carbon isotopes. Since ocean water tends to become colder with depth, the isotopic ratios are used not only to determine surface temperature of the water but also the depth of the water. There are many other variables that enter in which cause the general use of isotopic studies to be questionable. For instance, Mason (1966) shows snow at the South Pole to be much more depleted in O_{18} than snow in Chicago which in turn is more depleted in O_{18} than rain in Chicago. Rankama (1954), however, shows a marked difference between old snow and new snow as well as between thawed snow and unthawed snow. Some other variable besides strictly temperature enters in.

Studies in the Red Sea seemingly show an opposite effect. Craig (1969) reports isotopic ratios of waters in the Red Sea at various depths. The isotopic ratio of heavy carbon shows a depletion of C_{13} with a greater depth. The diffference between samples just above the brines and in the brines, however, indicate that hot water brines are quite depleted in C_{13}. Even within the brines, there is a large difference between isotopic constituency. The small changes in isotopic values which Hsü considered as proof of his hypothesis could actually be reinterpreted as an indication of great variability in water temperature as a result of periods of hydrothermal activity. Therefore, the stable isotope evaluations do not necessarily suggest a sabkha environment.

The type of calcium sulfate which was found is anhydrite, or the high temperature variety, instead of gypsum. This is erroneously offered as proof of the sabkha environment rather than deposition in a basin containing deep, cold water:

> Furthermore, the presence of anhydrite implies crystallization temperatures higher than those of deep-ocean waters. For those schooled in carbonate sedimentology, there was no longer any doubt that the evaporites were formed under a sabkha or in shallow waters. On the other hand, those who were familiar with studies of the Red Sea brines found the evidence less than compelling. (Hsü, Cita, and Ryan, 1973, p. 1205)

This clearly shows the concept of having only one model in mind and looking only at that side of the data which seems to support that model. The data seems to indicate that the sulfate found was formed at temperatures higher than normal seawater. There are, however, many other mechanisms which can provide the sufficiently high temperatures. To Hsü's credit is the inclusion of the statement that those people familiar with the Red Sea brines did not agree with his interpretation, but he should have considered other mechanisms involving hydrothermal brines which could achieve the same suite of indicators (see Chapter 5).

In discussing sabkha deposits along the Trucial Coast, Butler (1969) points out that another factor involved with sulfate deposition is the salinity control:

> . . . gypsum occurs in contact with brines with average chlorinity less than 145‰ and anhydrite with average chlorinity greater than 145‰. . . Thus anhydrite is the stable calcium sulphate mineral in the sabkha brines where chlorinity exceeds 145‰. (p. 79)

Thus, we have at least two controls on the type of sulfate which will be formed: temperature and chlorinity. Both of these factors can be expected with the deep, hot-water mechanism to be discussed in Chapter 5. Bischoff (1969) reports that anhydrite beds up to 20 centimeters thick of deep water origin were found in association wih the hot brines in the Atlantis II Deep of the Red Sea. Hsü incorrectly dismisses this as a possibility in accounting for the Mediterranean deposits.

Some researchers (e.g. Butler, 1969) believe that the tremendously large deposits of anhydrite are not primary, but are instead, a diagenetic product of gypsum. Many of the deposits, however, give every appearance of being primary. There would be no question of their primary nature except that in any kind of "natural environment" (observed or set up in the laboratory), the type of sulfate that is invariably precipitated is gypsum, not anhydrite. The question then arises: how can very thick primary deposits of pure anhydrite have formed in the past?

Again the sabkha model can explain some smaller isolated deposits, but is of no use in explaining the tremendously large deposits.

Having analyzed the "proof" of a sabkha origin for the "evaporites" and found them not to indicate a sabkha environment, we now turn to the geomorphologic and paleontologic evidence for desiccation of the Mediterranean.

Geomorphological Evidence

Hsü (1972) points to the submarine canyons in the Mediterranean basin as evidence that the sea level was much lower than it is today. Nesteroff, one of Hsü's colleagues aboard the Glomar Challenger, disagrees with this interpretation. He instead considers the existence of the submarine canyons to be indicative of tectonic action and still holds to a shallow basin model with subsequent vertical displacement. According to Nesteroff:

> More generally, every single problem of base level, whether concerning the erosion of the canyons, the formation of karsts or the making of the Nile or Rhone Miocene Valleys (see Chapter 44.4), may be explained when one assumes the existence of a shallow basin that was subsequently subjected to considerable subsidence in the Plio-Quaternary. (1973, pp. 692-693)

One other geomorphologic feature which Hsü *et al.* claim supports their desiccation hypothesis is that of the "bull's-eye" pattern of deposition within the

Mediterranean basin. Carbonates are supposedly on the outside of the ring, gypsum next, and halite at the center. They report:

> But we were lucky indeed that we chanced upon halite at one of the few places in the Mediterranean where it could be reached by the drill string. The salt crystals from beneath the abyssal plain *confirmed* the "bulls-eye" distribution pattern of the Mediterranean evaporite and provided a logical explanation of why diapirs had only been detected under the abyssal plains . . . (Hsü, Cita, and Ryan, 1973, p. 1208, emphasis mine)

The presence or absence of the "bulls-eye" pattern does not prove the desiccation hypothesis as Hsü *et al*. claim since other models would give the same results. However, since they do use this as substantiation, they should point out that the "*confirmation*" of the pattern is based upon rather scanty evidence. Besides seismic profiles, the "proof" of the "bulls-eye" pattern is based upon *only three core holes*:

> When a marine basin is isolated and becomes desiccated, the deposits are configured in a "bulls-eye" pattern, with halite in the center, followed by aureoles of anhydrite and gypsum. In view of the few sites and the structural complexity of the basins, it is difficult to say whether Messinian formations exhibit a "bulls-eye" pattern or not. *The three drillings, however might indicate it* . . . (Nesteroff, 1973, p. 690, emphasis mine)

That is not very much information to base a pronouncement of "confirmed" as in the earlier quote, especially considering the size of the basin in question of nearly 2.5 million square kilometers! This author asserts that much more data would have to be gathered.

Debenedetti (1982) brings to light a different problem associated with the "bull's-eye" pattern:

> The salts might well have accumulated over a smaller area of the floor, but in this case speculations about either "bull's-eye" or "tear drop" patterns would be even more futile. (In any case, the proportion of the volume of the different salts resulting from the evaporation of sea water is different from that represented in the drawing of the "bull's-eye" pattern imagined by Hsü et al. . . . Contrarily to the drawing, halite and other chlorides form by far the greatest part (95.59%) while the part of the carbonates is only 0.24% and that of gypsum 4.1%.) (p. 97)

Thus the proportion of the salts which naturally evaporate out from the total evaporation of sea level would be much different than what some of the Glomar Challenger's research shows.

According to Hsü et al. (1973), the Mediterranean Sea must have totally dried up at least 11 times! Even this value assumes the traditional viewpoint that brine concentration had taken place by periodic or steady input of "fresh" seawater. In essence, considering the overall shape of the basin and the shrinkage of the volume of the basin after evaporation has begun (which it appears that Hsü et al. overlooked), it would take many more than 11 complete refillings. Debenedetti computes that after 12 evaporation and refilling episodes, the total thickness of the salts over the 2.5 million square kilometer basin bottom would have been only 260 meters thick. Using this figure and the supposed thickness of the underlying salt of 2000 meters over one-third of the basin, as Hsü _et al_. report, it can be calculated that there must have been at least 30 episodes of evaporation and subsequent refilling.

One of the most obvious objections to the desiccation hypothesis is that under the conditions put forth by Hsü _et al_., the Mediterranean could not dry up.

> At a certain depth below the original sea level the net evaporation loss would be entirely annulled, the reduced evaporation being compensated by the contemporaneous constant meteoric inflow. In concequence [sic] , the part of the basin below this critical depth would remain permanently full of residual brine. (Debenedetti, 1982, p. 92)

Debenedetti bases these conclusions on the work of Harbeck (1955) which addresses the reduction of evaporation rates with increased salinity, as well as upon the reduction of the evaporation surface area of the water during the "desiccation" process.

Regardless of the problem of the Mediterranean not being able to dry up at all under conditions approaching those in the modern Mediterranean, let's look at just one more "proof" of the desiccation theory that is offered. This is the paleontological data.

Paleontological Evidence

Hsü's team reports layers containing abundant fresh or brackish water diatoms alternating with layers containing very deep water organisms. Conditions apparently flip-flopped quite rapidly.

> . . . changes from evaporitic conditions to marine conditions, and vice versa had been rapid and sudden. The paleontological criteria argued strongly against the deep water model: How could we suddenly flush away all the brines of the Mediterranean and refill the deep hole with normal marine waters? At the same time, the facts also spoke against the shallow-basin, shallow-water model, for the oozes must have been deposited in an open sea of considerable depth where a normal marine planktonic fauna and flora could flourish. (Hsü, Cita, and Ryan, 1973, pp. 1205-1206)

They further point out:

> The presence of benthonic forms, such as the ostracods in Hole 129A, left no doubt that the fresh brackish water extended, at least at times, thousands of meters down to the bottom. (p. 1213)

Several considerations, then must be contemplated: the presence of either fresh or brackish water organisms, the rapid flip-flop from open marine conditions to "evaporite" stages, and the sterility of the "evaporite." The first is the only one of the three which seems to support the model in question. The others speak strongly against their model of desiccation. How, then, do brackish or fresh water organisms get on the bottom of the Mediterranean Sea without total desiccation? A few questions and related comments apply.

How sure is the identification of the species involved as "fresh" or "brackish"? These are microscopic organisms with very minute differences between the fresh and saline varieties. Can a dead or extinct organism's affinity for water salinity even be known? Perhaps the greatest objection to the pronouncement of fresh water affinity is the fact that relatively recently many diatoms which were thought to be fresh water varieties have been found to be living in a saline environment. Also, some varieties thought to be salinity or depth dependent have turned out to be temperature dependent. Available key nutrients also play a major role.

At the museum at the Scripps Institution of Oceanography, there is a display of the very deep water fauna associated with the hydrothermal vent systems. At depths of 2.5 kilometers, fauna typical of a shallow photic zone was found complete with its own elaborate ecological system. It was noted that even at this depth, those organisms typical of great depth were absent. This indicates temperature and possibly nutrient control are key factors. Could diatoms also be temperature and nutrient controlled, and could their presence be used as an indicator of warm brines or other hot water associated with hydrothermal activity? This would make an excellent research project. The presence of "fresh" or "brackish" forms is a matter still open for discussion and should not at this time be used conclusively as a paleohydrologic indicator.

It was suggested that changes from evaporitic to deep open marine conditions were rapid. If the evidence is interpreted correctly, then some serious objections to the desiccating hypothesis arise. Hsü, Cita and Ryan report:

> The available stratigraphic record clearly indicates that a deep marine Meditteranean basin existed prior to, during, and immediately after the epoch of evaporite deposition. . . . Pelagic oozes of later Miocene age have been found intercalated between the anhydrite at Site 124 and between the halite at Site 134. Finally the sediments directly overlying the evaporite are pelagic oozes. (1973, p. 1210)

In the same paper they report:

> In addition, we found an open marine foraminiferal ooze between two halite layers, with no transitional shallow-marine deposits. (p. 1208)

The ocean water was deep before, during, and after the deposition of the evaporites with no indication of a transition from the desiccated basin to the very deep oceanic conditions. This seems very strange indeed, especially in light of the idea that the basin totally desiccated many times. Conditions had to have been just perfect.

Enough water had to come across the "Gibralter Waterfall" to fill the basin very rapidly, yet not enough water to cause flood type erosion, since there is no evidence of major flood erosion in that area. The amount of water needed to fill the basin in 100 years without loss by evaporation was calculated to be at least 100 times the amount going over Victoria Falls of Zambesi (1000 times more than Niagra) and quite possibly as much as 170 times this famous site! Small floods involving a whole lot less water have been known to cause tremendous erosion. A good example is the flood which formed the channeled scablands of eastern Washington and cut out major river canyons (Bretz, 1969). This projected amount of water would definitely leave significant and unmistakable geologic landform erosional features.

Besides this point, in order to get very deep water dwelling organisms back into the Mediterranean, the channel that is opened must have been very deep. This very deep breach most certainly would have brought much more flood waters into the Mediterranean than was calculated.

Cita (1973, p. 1046) and Hsü, Cita, and Ryan

(1973, p. 1205) report that the evaporites were "sterile" even though the associated sediments above and below had an abundance of marine fossils. Modern sabkha salt deposits are fairly "full" of organic remains. The conditions of deposition, therefore, were probably not the same as a sabkha environment as proposed for the desiccated basin hypothesis.

It has now been shown that the desiccated basin hypothesis has some major problems. Even if it was possible for the Mediterranean Sea to dry up (and that doesn't appear to be the case), some very unusual (unbelievable) circumstances had to have happened contrary to reason and evidence. The proposed indicators of the desiccated basin sabkha environment were found not to give evidence for the hypothesis. Some very large inferences have certainly been made from very scant data.

As Hsü points out, his hypothesis is "outrageous."

> It must of course seem somewhat farfetched to imagine the Mediterranean as a deep, dry, hot hell. We ourselves were reluctant to come to that conclusion until all other explanations had failed; the facts left us with no alternative. As Sherlock Holmes once remarked: "It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth." (1972, p. 36)

This author contends there is a better alternative than Hsü's "outrageous" hypothesis.

Perhaps the chief problem with the desiccated deep-basin model comes from its unwarranted assumption that all "evaporite" deposits must come from slow processes involving the evaporation of seawater. How _is_ salt deposited on the bottom of the ocean? The traditional thinking, which has changed little over the last 130 years, says it comes about by evaporation. All present models therefore, center around different methods of evaporating water. Each one can explain some facets of the problem or some localized small modern deposit, but none can fully explain the features found in some of the large deposits of the geologic past.

Since each model is based on evaporation and each is inadequate, rather than devise a new model based on the assumption of evaporation of sea water, why not discard the assumption of traditional evaporation and propose a new model? That is one objective of this paper. For those who still cling to the evaporation process as traditionally viewed, the next chapter should point out that even theoretical and experimental geochemical mechanisms involved with evaporation fail completely.

Chapter Four

THEORETICAL AND EXPERIMENTAL GEOCHEMISTRY OF SALT DEPOSITS

A study of the theoretical and experimental geochemistry of salt deposition makes it evident that traditionally accepted evaporative models for salt deposition fail. For these geochemical considerations, a standard work has been consulted: Introduction to Geochemistry by Konrad B. Krauskopf (1967). All references and quotes in this section were taken from this book unless otherwise mentioned.

In a chapter entitled "Evaporites," Krauskopf addresses the "problem" of evaporites by analyzing the data with regard to salts carried in streams, in lakes and in the seawater. He compares this with actual geologic deposits. Compositions of each are considered in light of a basinal evaporative model and many discrepancies are noted. We need to be fully aware that Krauskopf in this chapter is totally committed to the traditional evaporative barred basin model as can be seen by the following quotation:

> Geologically the problem is simply one of reconstructing conditions under which an arm of the sea can be sufficiently isolated to permit long-continued evaporation without too much mixing with the rest of the ocean. (p. 326)

Many of the discrepancies he mentions, then, are a result of this bias. His final conclusion after listing so many problems is to figure a way to salvage the evaporative model by a process of diagenetic alteration rather than disregard sacred uniformitarian assumptions inherent in the barred basin model.

The first note Krauskopf makes is to show the inadequacy of the theoretical model to predict the results of evaporation:

> . . . we shall find that the chemistry of these substances [evaporites] must be treated from a different point of view. The solutions involved are concentrated, which means that solubility products are of little help because they are no longer even approximately constant, and activity coefficients are generally not predictable; two or more salts commonly crystallize simultaneously; and the situation is complicated by the existence of many double salts and many possible hydrates, which crystallize or recrystallize in response to minor changes of temperature and composition. <u>There is little fundamental theory here to guide us</u>. (p. 319, emphasis mine)

After dismissing the theoretical considerations as unreasonable, he then goes on to the experimental observations and uncovers many more "problems." Utilizing computations of the total salt content in stream water, he notes that 80 tons of material is dissolved per square mile of land surface per year. Considering just the dissolved salts (not including clastic material), an average rate of lowering the continent is one foot in every 30,000 years. Although not mentioned in his text, one can compute that within just a few million years, all of the continents could be washed into the sea. Where, then, is there time for even the most recent geologic era?

The composition of seawater and lake water is then discussed. After asking if the oceans' composition and volume had remained constant throughout geologic time, an assumption is made based upon traditional uniformitarian interpretations:

> For the present we shall adopt the simplest asumption, that the composition of seawater has not changed greatly since the beginning of the Paleozoic era. (p. 326)

The 600 million years assumed here should be more than adequate time for the sea to have reached an equilibrium between dissolved sediment carried to the sea and deposition coupled with what is lost from the sea by other processes. Krauskopf notes that this equilibrium apparently has not been reached and goes to great lengths to explain this major problem. Just what happens to the concentration of chlorine, sodium, calcium, potassium, magnesium and sulfate?

> Can we conclude, then, that the five ions just mentioned have simply been accumulating in the sea all through geologic time? Do their present concentrations represent merely the total amounts so far dissolved by the weathering of rocks? This conclusion hardly seems likely, because the relative amounts of the ions are so different from their relative amounts in stream water. (p. 324)

After coming up with possibilities for the loss of potassium, calcium and magnesium (although with no raw data to substantiate the possibility), he dismisses this part of the problem. His conclusions on this section are:

> To summarize this discussion, the ocean appears to have achieved a state of balance between supply and removal for at least three of its six most abundant ions: potassium, magnesium, and calcium. The other three, sodium, chlorine, and sulfate may also have reached a state of balance, but present data do not exclude the possibility that their concentrations are slowly increasing. (pp. 325, 326; chemical abbreviations for ions used in original)

Krauskopf should not skip over this point so lightly; however, with his long age uniformitarian presuppositions, he is forced to do so. One overlooked possibility is that the present ocean basins have not had enough time to reach equilibrium. The data from these considerations indicate the ocean basins are quite young. Perhaps the assumption leading to long age geochronolgy needs scrutinizing so that less hand-waving is needed to explain away the data.

In turning to the data actually observed in the deposits themselves, Krauskopf enumerates many associated problems. He notes that salt deposits of the Stassfurt series (Zechstein 2) in Germany are thick enough to require the evaporation of a layer of seawater about 100 km high. He then circumvents the difficulty by elaborating on the barred basin concept.

Another difficulty is the discrepancy between what should be precipitated and what is actually found:

> A further difficulty in correlating the Stassfurt sequence with salts that might be expected from seawater arises when a calculation is made of the relative amounts of different salts that would form if present-day seawater were evaporated to dryness . . . Comparision of the figures with rough estimates of relative amounts in the Stassfurt deposit shows obvious discrepanies, in that the calcium sulfate content of the natural salts is too high and the proportion of potassium and magnesium salts too low. (p. 329, chemical abbreviations used in original)

Krauskopf also notes the difficulty in explaining the great variation in natural deposits. Besides the existence of large variations within deposits laterally, one deposit differs greatly from another in overall composition. The sequence of beds frequently differs and often different beds contain completely different "evaporites." Considering the fact that some beds such as the Devonian beds of western Canada have practically no magnesium sulfates at all, he realizes that the overall composition is "even farther from the theoretically expected composition than is that of the Stassfurt deposit" (p. 330). Further problems arise in comparison of experimental and theoretical data:

> The relations shown . . . are the result of

> many years of work by van't Hoff and his colleagues, plus refinements by other workers. They are not, however, the results that one obtains immediately by evaporation of solutions containing the ions of potassium, magnesium, sulfate, chlorine, and sodium, as Usiglio discovered long ago. . . . The difficulty is the *old bugaboo* of experimental geochemistry, *the slowness* of reaction rates. (p. 343, 343; emphasis mine; chemical abbreviations used in original)

Concerning the sequence of minerals, Krauskopf says:

> Of all the marine salt beds that have been studied in detail, the Stassfurt deposit comes closest to matching theoretical predictions, and even here the fit is evidently unsatisfactory. (p. 346)

Krauskopf also indicates the common problem associated with the tremendous amount of anhydrite that is found rather than gypsum. Presently only gypsum is being precipitated in evaporative environments. In theory, anhydrite should precipitate first in most cases with water temperature above 25 degrees Celsius; however, experiments do not support this. Even though geologic evidence seems to indicate that large anhydrite deposits are primary, Krauskopf and many other geologists have tried to explain their origin as a diagenetic product of gypsum.

> . . . laboratory attempts to precipitate anhydrite under *simulated natural conditions have uniformly failed.* *Even at fairly high* temperatures and high salt concentrations, where anhydrite is unquestionably the stable form, metastable gypsum always appears as the first precipitate. This fact, together with the absence or near absence of primary

> anhydrite *in present-day evaporites*, has led most geologists to conclude that the anhydrite of marine evaporites is entirely secondary. (p. 344, emphases mine)

Remember, Krauskopf is committed to the traditional barred basin evaporative model in the broad context of slow, long age, uniformitarian geologic processes. As stated before, he eventually offers a solution to the difficulties with the depositional model by changing the deposit after deposition, i.e. diagenetic alteration. This alternative is reasonable *in light of the assumption he has made*. In view of the fact of the inadequacies of the model to explain the true facts, he has *no other choice*. His pre-conceived idea logically dictates how he, as well as other geologists with the same presuppositions, must treat the data.

The general model of barred basin evaporites also dictates the experimental conditions which will be tried under *simulated natural conditions*. It is also under these assumed conditions that experimentation "proved" that anhydrite must not have been primary, but secondary. Krauskopf's "natural conditions" (as well as all others who are chained to the same initial assumptions) will be comparable to the climate, water chemistry, and rates near known *existing* basins with varying temperature and salinities. Conditions such as very high pressures and temperatures (greater than

100 degrees Celsius) are generally not considered for deposition -- they just cannot be made to fit the model.

Based on experimental evidence, van't Hoff concluded that the basin in which an arm of the Zechstein sea evaporated must have had a temperature within 17 degrees of the boiling point of water. Now having temperatures of <u>83 degrees Celsius</u> (or 181 degrees Fahrenheit) just doesn't fit the generally accepted idea --after all, very few geologists believe the Permian ocean was that hot. At this point it would be obvious to pursue a different line of reasoning. Instead of assuming the atmospheric environment was tepid, why not look for reasons why the water in certain areas might be quite hot? This is usually not considered since it does not fit the traditional model. It is very obvious that the phrase "under simulated natural conditions" is dependent upon what natural conditions could exist within the tight confines of the theory that one is committed to.

The question then arises: Are there natural conditions that could give extreme hot water temperature over a broad area? The answer is easily visualized in terms of underwater volcanic and intrusive actions. As pointed out in Chapter 5, these conditions can result in a "catastrophic" deposition of very thick beds of salts over a very large area. One problem this model will have immediately in becoming accepted is the bias against catastrophic processes being responsible for what most have regarded as very slow deposition. Krauskopf uses the phrase, "the old bugaboo," in reference to the inadequacy of modern laboratory chemistry to give insight into geologic process which has supposedly operated over millions of years. Here, then, is the problem which parallels the example of the man digging the hole as mentioned earlier. We see reactions leading to salt accumulations in many areas of the world. Then we assume that <u>all</u> salt deposits accumulated by the same slow processes even though the ancient deposits look very different from modern ones. This thinking results from full acceptance of uniformitarianism. Modern processes seem now to operate at a very slow rate. This does not at all mean that extensive ancient deposits were also the result of the same processes.

Ager recognizes the difficulties in his book, <u>The Nature of the Stratigraphic Record</u> (1981). He first points out the bias against the catastrophic process, and then refers to rates of deposition:

> In other words, we have allowed ourselves to be brainwashed into avoiding any interpretation of the past that involves extreme and what might be termed

> "catastrophic" processes. However, it seems to me that the stratigraphical record is full of examples of processes that are far from normal in the usual sense of the word. In particular we must conclude that SEDIMENTATION IN THE PAST HAS OFTEN BEEN VERY RAPID INDEED AND VERY SPASMODIC. This may be called the Phenomenon of the Catastrophic Nature of much of the Stratigraphical Record. (pp. 46,47, emphasis his)

Like Ager, we must be willing to abandon traditionalism when viewing ancient process--especially in dealing with salt deposits. Geochemistry has not been able to explain the data either theoretically or experimentally. Why? It is because it is very difficult for most to abandon the traditional uniformitarian model of evaporative basins for the major salt deposits and consider a catastrophic model instead.

Chapter Five

THE HYDROTHERMAL MODEL FOR THE DEPOSITION OF LARGE SALT BODIES

The data from salt deposits suggest a model unlike the traditional evaporative models that have been widely accepted during the last 130 years. The process described herein does not call for tremendously long ages for the deposition of the salts. In fact the process at times would proceed so rapidly that one would not likely find a fossil in the salt layer, but might find them between episodes of salt deposition. The proposed model is termed the "hydrothermal model." This model is proposed to answer questions left unexplained by the evaporative models.

The geologic setting for the model requires:

1. A period of intense undersea volcanic or igneous intrusive activity
2. Widespread hydrothermal vent systems through which much water circulates
3. A basin for deposition of no specific water depth although large deposits require large basins

Derivation of the salts for deposition is by a combination of two mechanisms:

1. Enrichment of the salts in seawater by the circulation of normal seawater through the hydrothermal vent system
2. Direct addition of salts by magma effluence containing large proportions of salt mineral ions

The resulting hot waters enriched in salt ions would then stratify in layers near the bottom of the basin such as has been observed at the bottom of the Red Sea (Bischoff, 1969).

Salt can be deposited by the following mechanisms:

1. Precipitation as the saline waters ascend and are cooled by the colder seawater above
2. Precipitation of salts that are less soluble in hot saline water, such as calcium carbonate and calcium sulfate, due to the heating from hotter waters coming up from below or from variations in magmatic activity
3. Precipitation resulting from the pressure release as the brine mass rises
4. Precipitation resulting from a change in the Eh of the system

5. Precipitation resulting from a change in the pH of the system
6. Precipitation resulting from a process of brine mixing where two brines of different salinities react as described by Raup (1970) and Wilcox and Davidson (1976)

Figure 3 diagrams the hydrothermal model. There are many variations that could be presented but the one illustrated gives a good overall idea of the mechanisms suggested.

A volcanic origin for salt deposition has been suggested previously. Prior to 1925, most of the models concerning volcanic origin related to salt domes. Their unique shape gave most investigators the idea of a volcanic origin, although some good supportive points were raised. DeGolyer (1919) gave a good history of ideas relating to the volcanic origin of salt domes.

Rode (1944) offered a model for a submarine volcanic origin of rock salt deposits. He thought they were formed as a result of intense folding of strata which upturned, fractured, and raised. This left a series of longitudinal lakes. Volcanic activity occurring at the bottom of each lake (as a result of the tectonic activity) added salts to the

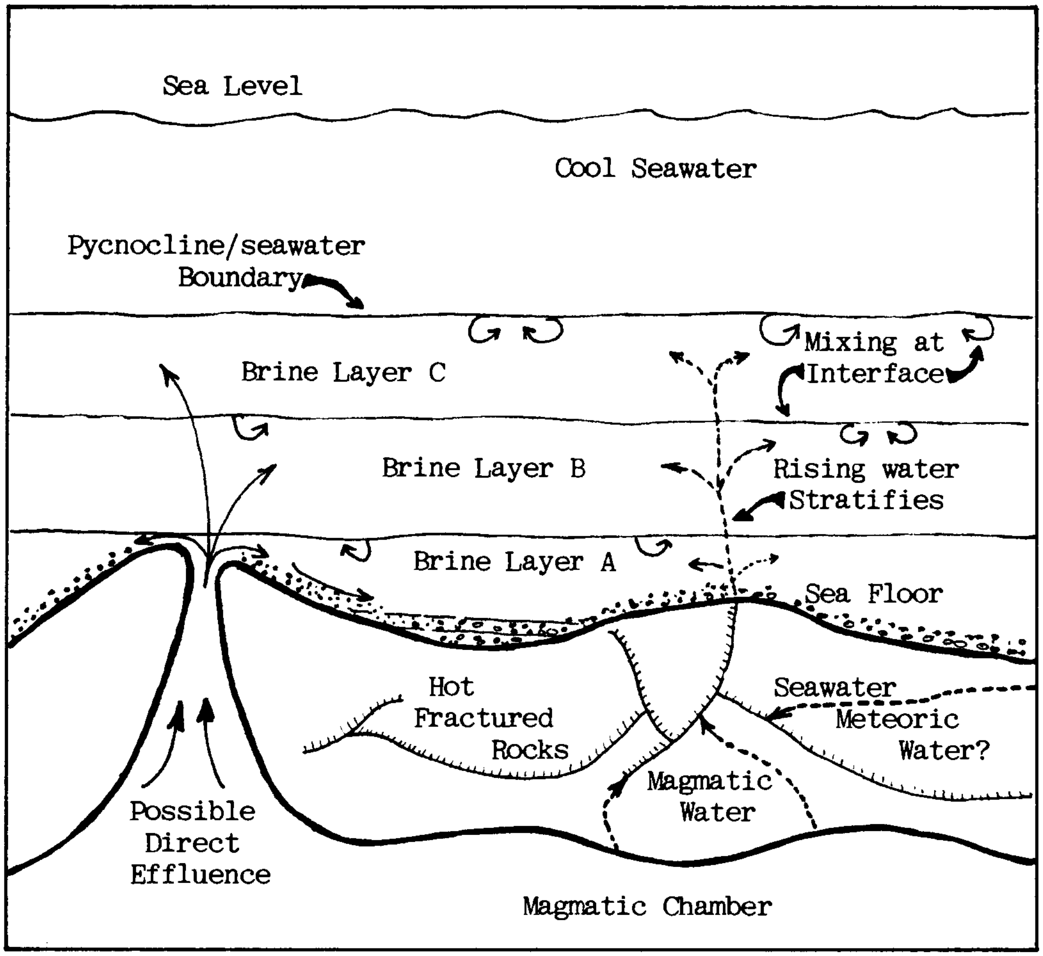

Figure 3. The Hydrothermal Model of Salt Deposition.

1. Increased volcanic and magmatic activity leads to widespread hydrothermal vent systems.
2. Enrichment of seawater is by direct magmatic effluence or by circulating seawater through hot fractured rocks of hydrothermal vent systems.
3. Hot brine either precipitates immediately as it responds to changes in thermodynamic conditions, or it stratifies, forming a pycnocline (brine layers A, B, C).
4. Precipitation of salts that are less soluble in cold water, such as halite, occurs as brine layers are cooled by the colder waters above the pycnocline.
5. Precipitation of salts that are less soluble in hot water occurs as brine layers are heated from below. This includes anhydrite, gypsum, and limestone.
6. Precipitation by Raup's mechanism (1970) occurs as layers of brine mix. This can involve entire layers or can be confined to the interfaces as a result of convective heat.
7. Precipitation occurs as ions in brine layers react with normal, oxygenated, seawater.

lake and produced intense heat which boiled the water and caused salt to be deposited.

Ford (1975) suggested that the salt deposits originated as a result of the universal flood. He suggested that pre-existing salts, that were originally created, were mobilized by heat associated with volcanics and pressures exerted by increased sediment load. The concentrated brine, or perhaps molten mass, is then envisioned to have spilled out filling areas of low topographic expression.

Part of the present model has been alluded to by Nevins (1974). He references Sozansky (1973), a Russian geologist whose model parallels the hydrothermal model in its documentation for a volcanogenic origin of "evaporites." Sozansky suggests:

> Salt deposits in deep oceanic areas are considered to be deposits from hot brines originating at great depths in the earth during tectonic movements. This is in agreement with the concept that the salinity of ocean water is the direct result of the degasification of the earth's interior. (p. 589)

The present model offers a mechanism for catastrophic deposition of salts and allows for the possibility of greater application to other strata which comprise a good share of the rock record. It also provides an explanation for associations with mineral and hydrocarbon formation, and provides a new basis for evaluating discrepancies in geo-chronology.

At the present time, this hydrothermal process is not occurring at a sufficient intensity to explain the origin of the saline giants. This is of little concern, since we are not necessarily tied to uniformitarian assumptions concerning depositional environments and rates. However, even though it is not necessary to document each major point of the model in observed phenomena occurring today, it should be recognized that each portion of the model does have an analog that can be observed in process today. The only difference is in the intensity of the process. This is assumed to have been much greater in the past, as many geologic features indicate. The fact that volcanic activity and general igneous intrusion has been much greater in the past is well documented:

> During past geologic ages, lava flowed much more freely than now; it not only spouted from craters, but also pushed upward from immense cracks in the planet's crust. Earth's most stupendous rock formation, stretching for more than a thousand miles along the shores of Canada and Alaska, was squeezed out in such a fashion. Oozing lava built great plateaus which now cover 200,000 square miles in Washington, Oregon, Idaho and northern California. An even larger eruption created India's famous Deccan Plateau, whose once molten rock extends as much as 2 miles below the surface. Argentina, South Africa and Brazil have similar plateaus. (Webster, 1957, p. 5)

There is also geologic evidence that massive outpourings of hydrothermal solutions have occurred on the ocean floor as assumed by the proposed model. Not only do extensive terrigenous volcanics imply the possibility of increased hydrothermal activity, but extensive basalt flows have been found on the sea floor (Davis, 1982). Also, chert beds in the Franciscan Formation of California show catastrophic deep water deposition of silica gel from solution (Bailey, Irwin, and Jones, 1964). Such precipitation would be impossible in the modern ocean if accomplished by slow exhalative processes. Only a rapid outbreak of solution could supersaturate the ocean water and prevent diatoms and radiolaria from removing the silica. The increased intensity of volcanic and hydrothermal action in the past is an evidence for a unique period in earth history which had rates and intensities of processes significantly greater than observed today.

If some of the same processes which are operating today were intensified as they were in the geologic past, major deposition of salts would result. As an example, seawater is concentrated at the bottom of the Red Sea as it circulates through vent systems. In this particular case, the resulting brines become very rich in metallic ions and then stratify into distinct pycnoclines (Turner, 1969).

Table 2. Summary of the Observations of Temperature and Gravimetric Salinity as Functions of Depth in Atlantis II and Discovery Deeps. (After Turner, 1969, p. 165.)

	Atlantis II Deep				Discovery Deep			
	Depth Range (m)	Thickness (m)	Temp. (°C)	Salin. (‰)	Depth Range (m)	Thickness (m)	Temp. (°C)	Salin. (‰)
"Normal water"	Above 1,984		22	41	Above 1,986		22	41
	1,984				1,986			
Upper interface		25				37		
	2,009				2,023			
Intermediate layer		28	44	135		4	36	127
	2,037				2,027			
Lower interface		5				15		
	2,042				2,042			
Bottom Layer	Below 2,042		56	257	Below 2,042		45	256

Table 2 gives the salinity and temperature of several of these layers. As seen from the table, each of these pycnoclines contain brines with temperature increasing as the depth increases. The individual layers exhibit quite distinct levels of salinity which increase with depth. Boundaries between the layers are very well defined as evidenced by the ability of seismic reflection profiles to distinguish the different interfaces. It should be noted that these stratifications do not exist under all of the Red Sea but only in several of the deepest pockets. Intensification of the same processes involved here, however, could lead to very thick and extensive layers of brine which in turn could lead to very widespread and massive salt deposits.

One might argue that these waters in the Red Sea are loaded with heavy metals and that metal sulfides are being precipitated along with minor amounts of anhydrite rather than great thicknesses of pure salts. Although this is a good point, the actual composition of the brines would be dependent upon several factors. One of these would be the particular stage of hydrothermal activity. Depth of the magmatic chamber resulting in differences of composition and temperature of the solutions would also be a factor. It is recognized that each of these is responsible for the deposition of different minerals in common hydrothermal mineral enrichments and ore deposition in veins. This same mechanism would apply to the enrichment of the "evaporite" suite of minerals.

Is there an association of heavy metal sulfides with salt deposits or does this stand as an objection to the proposed model? In reality, there is an association. It is very common to find sulfur comprising up to 30 percent of the caprock in salt domes. The occurrence of galena, sphalerite, and manganese sulfides in the caprock series is also reported by Jensen and Bateman (1981). Stewart (1963) examines a suggestion that a middle Devonian barite, pyrite, sphalerite deposit at Meggen, Westphalia is an evaporitic deposit owing its unique composition to the addition of barium, iron, and zinc from hydrothermal springs in the basin of deposition. Although Stewart disagrees with the mechanism for deposition, the report still indicates a close correlation with the metal sulfides.

The famous Kuperschiefer deposits of Germany and the Netherlands which are extraordinarily rich in metallic sulfides cover 3550 square kilometers at an average thickness of about a half meter. It is interesting to note that this deposit is overlain by the famous Zechstein salt series. We also note that the deposition of gypsum and anhydrite is an important part of the model for the Kuroko ore type of deposition which explains sulfide deposition in association with shallow marine volcanism (Ohmoto and Rye, 1974). Dolomite, a mineral deposited from solution at higher temperatures, is also found in association with certain strata-bound deposits said to have a syngenetic origin such as the sulfide deposits of the Mafulira in Zambia (Jensen and Bateman, 1981). Renfro (1974) reports that stratiform metalliferous deposits which are overlain by "evaporite" deposits account for approximately 30 percent of the world's copper production. These metal deposits generally extend into the overlying salt deposits. The best conclusion from all this is that metal sulfide deposits are not only closely associated with "evaporite" deposition, but are syngenetic with the salts.

In recent years, it has been recognized that many deposits besides the sulfide deposits result from hydrothermal activity. Formation of the Franscician chert and shale interlaminations (Bailey, et al., 1964), and a substantial deposit of talc at the bottom of the Gulf of California (Lonsdale et al., 1980) are both considered to be of hydrothermal origin. If silica rich solutions are commonly associated with hydrothermal systems, then their precipitation during hydrothermally enriched salt deposition would be a logical explanation for the origin of bedded chert deposits in hydrothermally deposited limestone and dolomite.

One of the other mechanisms for ionic enrichment suggested by this model is the direct effluence of "evaporite forming" salts or ions. Rode (1944) mentions enrichment of sodium chloride, hydrochloric acid, sulfuric acid, hydrogen sulfide, ammonium chloride, and carbon dioxide due to volcanic exhalations. A rather unusual occurrence is that of what was termed a "natro-carbonatite" lava flow reported by Du Bois _et_ _al_. (1963):

> The inference is that the lava was formed under PT conditions which very probably included an atmosphere of carbon dioxide which, in turn, permitted the formation of a new carbonate mineral. This is believed to be a complex carbonate of calcium and sodium with perhaps some potassium. Because of its rapid alteration to calcite and trona by atmospheric water and carbon dioxide, its existence has probably escaped notice in the past.
>
> In view of the extraordinary nature of this new lava, it is proposed to call it "natro-carbonatite." (p. 446)

Besides this carbonatite lava from northern Tanganyika, several other similar lava flows have been reported in Uganda (von Knorring, 1962; von Knorring and Du Bois, 1961).

A volcanic lava flow of pure sulfur has also been reported in Japan:

> Watanabe recorded remarkable eruptions of molten sulfur from Siretoko-Iosan volcano in Japan in 1936 during which time pure sulfur flows with a temperature of 120° C, cascaded down the valley to form a deposit 1500 meters long, 20 to 25 meters wide, and 5 meters thick. (Jensen and Bateman, 1981, p. 566)

Volcanic lava also involving pure sulfur has been reported on Io, one of the moons of Jupiter. It is concluded that specific volcanic outpourings which are known to be in operation very recently could very well provide the necessary elements to the seawater which results in massive precipitation of "evaporites."

It is suggested that the salts could have precipitated either directly, due to cooling ascending water, by releasing the pressure of the system, by changing the pH or Eh of the system, or by a process of brine mixing. The first mechanism can be clearly seen as a realistic route for the deposition of some of the "evaporite" minerals. Calcium sulfates and carbonates, however, both become more soluble as the seawater becomes colder (Blount and Dickson, 1969; Marshall, _et al_., 1964; Bischoff, 1969). For the carbonates and sulfates, then, deposition can come from the nearly saturated upper waters as the hotter water below increases their temperature. Bischoff (1969, p. 396) suggests a mechanism for the precipitation of anhydrite in the Red Sea not as a result of further heating, but by ionic transfer of sulfate ions at the pycnocline interface with seawater. Either of these mechanisms can be responsible for the deposition of extensive massive layers of either carbonates or sulfates to the exclusion of all other "evaporites" depending on the ionic composition of the brines.

Bailey _et_ _al_. (1964, p. 96), citing work from several geochemists, show solubilities of silicas to vary tremendously with pressure as well as temperature. From the data, one will note that the solubility at what is termed the "critical temperature" varies by approximately 300 ppm (or about 25-30 percent) for a pressure differential of 200 bars (equivalent to a depth of water change about 2000 meters). This alone could result in a substantial deposition for saturated solutions erupting from the sea floor. This not only accounts for silica deposition associated with carbonates, but provides an additional mechanism for salt deposition.

Likewise, a variation in the pH or the Eh of the system can affect precipitation. The results of changing these variables are not altogether clear. A pycnocline rich in sulfide ions, however, could be rapidly precipitated by mixing with oxygenated water (a change in Eh). This would cause the sulfides to be oxidized, producing sulfate ions. If this happened rapidly in a pycnocline containing large quantities of calcium, a massive layer of calcium sulfate would be produced. If the water was hot, anhydrite would be deposited.

It is also conceivable that deposition of alternating calcite, anhydrite, and halite laminations in the Castile of Texas and New Mexico could result from the mechanisms described above. In Chapter 3, it was noted that both temperature and salinity control anhydrite precipitation. Variations in <u>either</u> one of these controls (as well as others) can cause deposition of one mineral in preference to another. Brines saturated with sulfate, bicarbonate, and calcium ions could precipitate either carbonate or sulfate depending upon the temperature and salinity. As one is precipitated, the composition and salinity changes slightly. Also the temperature of the water is changed somewhat by the process of precipitation because of the heat of crystallization. Each of these factors can produce the right controls to have another mineral precipitated. This particular domino effect can happen repeatedly, giving rise to a tremendous number of thin or thick laminations in a very short period of time.

Another mechanism that could be responsible for the precipitation of the salts is the method of brine mixing as substantiated and described by Raup (1970). Originally suggested as an additional mechanism to precipitate salt in a standard barred basin, this has a tremendous potential in the present model. The mechanism was first suggested by Briggs (1957) as theoretically possible. Raup added experimental data by mixing both artificial and natural seawater brines of varying concentrations. The six most important conclusions, based upon his experimentation, are listed by Raup:

> 1. Salt precipitation can occur in a marine evaporite basin by mixing brines of different composition and specific gravity.
>
> 2. Precipitation occurs without further water loss by evaporation.
>
> 3. Precipitation can occur from brines that were undersaturated before mixing.
>
> 4. Brine mixing would cause the most salt to be deposited in the deepest parts of the basin, although all parts of the basin could receive such deposits.
>
> 5. Sylvite could be precipitated as a primary mineral.
>
> 6. Hopper crystals (cubic and tabular) can form as a result of brine mixing in water of any depth. (1970, p. 2258)

It is important to emphasize that the solutions do not have to be saturated, as Raup has shown. Further experimentation by Wilcox and Davidson (1976) gave similar results but indicates that even less saturation than Raup's solutions might give even greater yields.

The experimental production of sylvite was also very significant since its deposition has not been explained by any of the evaporative processes, yet sylvite is common in "evaporite" deposits. Raup's conclusions on hopper crystal formation are also very significant, as discussed in Chapter 3. The presence of this type of crystal has been taken as "proof" of an intertidal environment. This can no longer be taken as a conclusive indicator of this environment, since brine mixing can produce these crystals at any depth. It is also speculated that these crystals could be produced at the interface between pycnoclines or at the pycnocline and normal seawater boundary. This is a good area for research.

How would large layers of brine covering a vast area and occupying a great volume begin to mix? The following possibilities are offered:

1. Precipitation of the lowest layer causes it to be less dense than the layers above. This causes an unstable arrangement and hence the waters would overturn. This has supposedly happened rather recently in the Dead Sea (Steinhorn and Gat, 1983). Such massive

turnover would definitely cause a tremendous amount of mixing.

2. Water currents associated with a major catastrophe would also cause mixing. These would be caused by major underwater volcanic activity, a massive earthquake resulting in major turbidite flows, or catastrophic flooding.
3. Rapid precipitation of any layer would trigger a tremendous amount of water current which would cause mixing of the brines. The process would be perpetuated by continued precipitation as a result of the original mixing process.
4. Convection currents due to heating from below would cause mixing within layers. This has been reported by Turner (1969) in his discussion of the effect bottom heating has in producing Red Sea pycnoclines. The heating not only can produce or enhance layers, but convective stirring can also cause precipitation by Raup's mechanism.

Each point of the hydrothermal model for the deposition of large salt bodies, can be observed in process today. By merely allowing for increased intensities of the processes in the geologic past, (which is supported by geologic evidence), the hydrothermal model can realistically explain the origin of the saline giants. The next chapter will demonstrate that the model is consistent with each of the observations of field data that all models for "evaporite" deposition must address.

Chapter Six

CORRELATION OF THE HYDROTHERMAL MODEL WITH FIELD OBSERVATIONS AND DATA

Evaporative models for salt deposition have sounded good, but their correlation with known data and field observations has led to a virtual "dead-end." The purpose of this section is to demonstrate that the proposed hydrothermal model is consistent with known field data concerning salt deposition and that it alleviates many of the problems that are so frequently alluded to in discussions of "evaporites" in the literature.

Ford (1975) listed 11 field observations that needed to be addressed in the generation of a model of salt deposition. His points are incorporated and somewhat altered in this expanded list of field observations. These observations of salt deposits fall into five main categories:

1. Size and Distribution
2. Composition
3. Volcanic, Tectonic, and Structural Associations
4. Hydrocarbon and Heavy Metals Association
5. Stratigraphical Relationships

Each point is listed and will be discussed as it relates to the proposed model.

Size and Distribution of Salt Deposits

Size

Observation: Salt deposits vary in size from very small deposits all the way up to those that cover several million square kilometers. Some of these reach thicknesses of 1 to 3 kilometers (Jensen and Bateman, 1981, p. 200-203; Kirkland and Evans, 1973, p. 343).

Comment: In a hydrothermal system with related volcanic exhalative activity and stratification of waters as seen in the Red Sea, we would expect to find tremendous variation in the size and thickness of the deposits. The maximum lateral extent and thickness of the deposit would be limited only by the size of the basin.

Geologic Distribution

Observation: The occurrence of salt deposits are not limited to any strata system. They are found in strata systems Cambrian to Recent including limited deposits in the Precambrian (Kozary *et al*., 1968).

Comment: We would expect to see salt deposits in strata of any geologic system with the proposed model. Deposition of a saline giant probably represents a unique period of earth history with extensive volcanic, igneous intrusive, and hydrothermal activity and possibly reflects a period of major structural instability.

Geographical Distribution

Observation: Major salt deposits and diapiric structures occur over much of the earth including high latitude deposits in Canada, Eurasia, and within the Arctic Circle (Meyerhoff, 1970; Halbouty, 1967).

Comment: Salt deposits in the high latitudes or even within the Arctic Circle pose no problem since this model does not depend upon evaporation in an arid region. This might explain distribution of salt which otherwise is left unexplained even by recent models of continental drift and plate tectonics.

Observation: Salt deposits have been discovered below sediments in the Gulf of Mexico, in the Mediterranean Sea, and in several localities in the depths of the Atlantic (Hsü, 1972; Ewing *et al*., 1962; Ewing *et al*., 1969)

Comment: Seismic profiles originally showed the presence of diapiric-like structures in these localities. On this basis, Ewing *et al*. postulated that the Gulf of Mexico structures were salt domes and the underlying salt layer was a continuation of the already extensive Louann salt deposit. This would extend the Louann salts under the entire Gulf of Mexico Basin. Later drilling apparently confirmed the hypothesis that salt was located at such tremendous depth.

These discoveries have led researchers to think that these basins have become separated from the rest of the sea to become an evaporative basin. The unreasonable idea that the entire Mediterranean Sea was desiccated making the bottom a hot, dry desert was discussed in Chapter 3. This supposedly took place 11 times in order to explain the geologic features of this extremely deep salt deposit beneath the Mediterranean sediments. Has the Atlantic Ocean evaporated many times also? The hydrothermal process does not require evaporation and as such does not require such unreasonable conditions. Observable processes of hydrothermal activity intensified somewhat in the past would account for these deposits.

Composition of Salt Deposits

Chemical Composition

Observation: The chemical composition of the salt layer should reflect the general constituency of the water from which it originated. The proportions of salts precipitated are no where close to what theoretical and experimental geochemical methods would predict based upon uniformitarian theories (Krauskopf, 1967, p. 319-353). Some salt deposits contain great thicknesses of primarily one mineral to the exclusion of all others. Sozansky (Porfir'ev, 1974) also notes the absence in large deposits of some of the more soluble salts such as magnesium sulfate which generally form in modern evaporative lagoons.

Comment: Very thick beds of anhydrite are found with no associated halite deposition. Conversely thick beds of halite are found with no sulfate layer. These beds which are interlayered with "non-evaporative" series can reach a total thickness in excess of 2000 meters such as in the "Comanchean Series" of south central Florida (Stewart, 1963, p.Y27; Jensen and Bateman, 1981, p. 200). To account for a 300 meter thick deposit of anhydrite under traditional evaporative models, 1400 times as much water or 420 kilometers would have to be evaporated (Stewart, 1963, p. Y2). The problem is explaining what happened to all the other minerals that should have been precipitated.

Depending upon the thickness of the brine layer, the stage of the hydrothermal activity, and the duration of that stage, deposits of predominantly one mineral can become very thick. Waters saturated with specific ions could be precipitated in vast quantities very rapidly by the direct addition of ions. Another possibility with the hydrothermal model for explaining monomineralic deposits involves the temperature and salinity controls which were discussed in the preceeding chapter. The proper temperature and salinity at times would favor the deposition of only one mineral. Since water does not have to be evaporated in this model, the total constituency of seawater is not a concern. The composition of the salts should reflect instead the composition of the enriched solutions.

Table 3 summarizes ionic ratios of seawater, of hot springs solutions, and of ancient salt deposits. Although the results are inconclusive, some trends can be observed. In most every case, the observed data for salt deposits more closely reflect hot springs water composition than typical ocean water. This is also true for stable isotope composition. This supports the concept of salts precipitating rapidly as salt enriched solutions ascend from hydrothermal springs. Much variation exists between different hot springs solutions, as well as between different salt deposits, as one should expect considering the type of processes involved. The source of the hot springs, the wall rock composition, and stage of hydrothermal activity are all factors.

Table 3. Ionic Ratios of Common Salt Forming Ions from Ocean and Hot Springs Water Compared with Average Paleozoic "Evaporite" Rocks (modified after Austin, 1974, unpublished).

	Ca/Na	Mg/Ca	K/Ca	Sr/Ca	$HCO_3^=$/ Cl	F/Cl	Br/Cl	S^{32}/ S^{34}	C^{12}/ C^{13}	$SO_4^=$/ Cl
Ocean Water Salts	0.038	3.2	0.95	0.020	0.0074	0.00007	0.0034	0.04591	89.2	0.14
Average "Evaporite" Rock	3.31	0.21	0.19	0.013	0.63	0.0041	0.0003	0.04551	88.6	5.62
Hot Springs Salt	0.64	0.215	0.35	0.008	5.0	0.01	0.0023	0.04555	88.8	87.6

SOURCES OF DATA:

Ocean water and hot springs salts: (White, Hem and Waring, 1963, p. F59). Average is of 51 hot springs and geysers which are considered to contain volcanic waters.

Average "evaporite" rock: Data from Stewart (1963, pp. Y33-Y36). Average Paleozoic "evaporite" rock composition calculated from 11 representative Late Paleozoic samples. Average was weighted to 60% halite-rich, 35% anhydrite-rich, and 5% sylvite-rich according to their abundances in ancient sedimentary strata.

Sulfur isotope ratios: (Holser and Kaplan, 1966, p. 94). Average salt rock sulfur isotope is the average for Permian anhydrites.

Carbon isotope ratios: (Mason, 1966, pp. 244, 245).

Because of the variation in composition, it has been frustrating arriving at meaningful interpretations from many sources which deal with these considerations. Often the data presented are averages from other data that are no longer available for study. Most of the data have been synthesized already and reflect biases inherent in evaporative models. A more detailed analysis of the data is needed starting from unbiased raw material before concrete conclusions can be made. This is beyond the scope of this paper. Suffice it to say that the overall trend of the data supports the hydrothermal origin of salts much better than an origin by evaporation of seawater.

Observation: Some of the mineral associations of the salts indicate a high temperature of deposition such as primary anhydrite, primary dolomite, and kiesserite with langbeinite or sylvite (Krauskopf, 1967; Stewart, 1963; Jensen and Bateman, 1981).

Comment: Van't Hoff calculated that the temperature under which some of the salts such as kieserite with sylvite formed must have been in excess of 83 degrees Celcius (Krauskopf, 1967). That temperature of water is not likely to occur in a modern natural environment! Further evidence for hot solutions is provided by Krauskopf in the same publication, where he describes the dolomite "problem." The reason he terms it a problem is because laboratory experimentation has not been able to produce primary dolomite except under conditions of extremely hot water -- very close to the boiling point. The rock record, though, shows tremendously large deposits of dolomite many of which have good evidence that they originated as primary deposition.

Blount and Dickson (1969) suggest the presence of anhydrite in ore bodies to be evidence of the previous existence of unusual temperature, pressure, and compositional conditions. Conditions necessary for the deposition of this entire suite of minerals require extremely high temperatures. This type of temperature is not common in any of the modern analog evaporative settings. A hydrothermal setting, however, can have the extremely high temperature and pressure conditions which would be necessary for the deposition of these minerals.

The German Zechstein salt deposits contain a large amount of kiesserite with langbeinite which requires a high depositional temperature. The hydrothermal model, therefore, would be the only realistic model for its deposition as well as for the deposition of large deposits of primary dolomite and anhydrite. It is no longer necessary to claim that these deposits must be products of diagenesis (as is the practice even when the evidence indicates primary deposition). The hydrothermal model gives these directly as primary minerals.

Purity of Salts

Observation: Salts are relatively pure. A lack of terrigenously derived sediments prevails in ancient deposits (Debenedetti, 1982).

Comment: Certainly an enormous basin existing for millions of years would collect substantial terrigenous clastics. The lack of these sediments would indicate that the salts formed rapidly. Formation of the salts by the present model in deeper basins would account very nicely for the absence.

Fossil Composition

Observation: The distinct absence of fossils is noted in many large, ancient salt deposits. Other deposits have abundant fossils, but only between layers. Some deposits contain marine and terrestrial fossils (Kudryavtsev, 1971; Porfir'ev, 1974).

Comment: In most lagoonal situations, there should be an enormous amount of organic debris fossilized in the salt deposits. Again we see that the rapidity of deposition of the salt by the proposed process can account for this observed fossil sterility. Fossils between the layers would be much more likely to occur as has been observed by Hsü, Cita, and Ryan (1973). Other salt deposits of minor importance undoubtedly are the product of traditional evaporation, which results in the inclusion of large quantities of organic material. It is not known which deposits in geologic history contain fossils in the actual salt, or in laminations between layers, and which ones do not. This is a good subject for further research.

Composition of Salt Domes

Observation: Most salt dome structures contain pure halite. Some have a sulfate core while other salt domes appear to be pure sulfate (Jensen and Bateman, 1981).

Comment: Salt domes could have formed by many of the structural mechanisms put forth to date. It is possible, however, that they are associated with the actual discharge vents of the hydrothermal system which remained active long after the original large salt deposit was made.

Volcanic, Tectonic, and Structural Associations with Salt Deposits

Association with Volcanics

Observation: Salt deposits are frequently associated with volcanics (Sozansky, 1973; Porfir'ev, 1974).

Comment: Sozansky reports that in most salt-bearing basins, volcanic rocks of predominantly mafic composition are found in the salt-bearing sections. He lists 27 major salt deposits located on 5 continents which contain volcanics. Nesteroff, Wezel, and Pautot (1973, p. 1034-1035) also report volcanics associated with Mediterranean "evaporites." The types of volcanics reported would not be found in deposits formed by evaporation. Their presence has been explained as merely a coincidental association, possibly due to graben faulting and related volcanics. The widespread association with volcanics appears to go far beyond coincidence. In the hydrothermal model, volcanism is the primary cause for salt deposition, not just a coincidental associated effect.

Tectonic and Structural Associations

Observation: Salt deposits are frequently associated with rifting, mountain building, and faulting (Pautot, 1970).

Comment: Salt solutions appear to emerging along tectonically active regions according to Pautot. Salt springs exist in the rift valley of east Africa. Rifting, mountain building, and faulting are all activities one would associate with an intense period of volcanism and hydrothermal activity as assumed by the hydrothermal model.

Hydrocarbon and Heavy Metals Association with Salt Deposits

Association with Hydrocarbons

Observation: Salt deposits are frequently associated with large deposits of hydrocarbons (Buzzalini, 1969).

Comment: According to Buzzalini, almost every major oil producing province of the world is associated either directly or indirectly with salt deposits. Recent discoveries by oceanographic researchers give a good clue as to why the hydrothermal model of salt deposition would also be closely related to the production of hydrocarbons.

The formation of hydrocarbons has been observed in operation today as a result of hydrothermal activity. Researchers discovered a natural petroleum refining center while studying hydrothermal vents associated with sea floor spreading centers in the Guaymas Basin in the Gulf of Mexico (Simoneit and Lonsdale, 1982). Apparently, organic material (which is surprisingly abundant at the 2000 meter level) enters the vent system at one location and emerges at another nicely refined as petroleum products. Analysis of the constituents of the hydrocarbon ooze from the hydrothermal site yields several important findings that are significant to the present discussion

(Simoneit and Lonsdale, 1982):

a) The hydrocarbons have a pyrolitic origin from organic matter possibly derived nearby with rapid removal and quenching at the sea bed.

b) The aromatic to aliphatic ratio is typical of many crude oils.

c) Some of the constituents such as the triterpenoids are "surprisingly mature."

d) The hydrocarbons did not migrate, but were generated nearby.

e) The hydrocarbons were definitely very young as determined by the presence of certain olefins and lipids.

William Smithey, a biologist with Scripps Institution of Oceanography indicated (personal communication, 1983) that these findings shatter the traditional view that oil was exclusively produced by the decay of land plants and animals over millions of years. If the frequency and intensity of volcanic and hydrothermal activity was greater in the past, the same processes observed in the Guaymas Basin could have resulted in the mass production of oil which is so frequently found with salt deposits.

This hydrothermal model for salt deposition not only contains a mechanism for the generation of great quantities of oil, but can also account for the process by which the reservoir rock was deposited. Micritic limestone and dolostone are frequent reservoir rocks, the origin of which can be explained easily as a chemical precipitate during various stages of hydrothermal salt deposition. This can occur at the same time hydrocarbons are being produced.

Associations of Heavy Metals with Salt Deposits

Observation: Salt deposits are frequently associated with sulfur and heavy metal sulfides. Both are encountered capping salt domes and are also found underlying (and sometimes in) major salt deposits (Jensen and Bateman, 1981; Renfro, 1974).

Comment: This type of association would not be expected by evaporative basin models. Observations from the Red Sea as well as observations around active deep sea hydrothermal systems indicate that sulfide deposition should be expected in hydrothermal systems. This close association with salt deposits has been thoroughly discussed in the last chapter.

Stratigraphical Relationships of Salt Deposits

Relationship to Deep Water Deposits

Observation: Pelagic oozes are found above and below sterile salt layers with no transitional deposition (Hsü, Cita, and Ryan, 1973).

Comment: This is strong evidence for the hydrothermal model. The oozes represent periods of quiescence between episodes of hydrothermal activity in which deep water deposition occurred. The lack of transitional facies indicate the water was deep at all stages of deposition.

Observation: Salt deposits are commonly associated with euxinic sediments (Woolnough, 1937; Schmalz, 1969).

Comment: Euxinic sediments would result from the very deep waters and related sulfur reducing bacterial activity such as those associated with modern hydrothermal vent systems.

Multiple Laminations

Observation: Multiple laminations exist in some salt deposits. Over 200,000 laminations exist within 447 meters of stratigraphic sequence which are correlateable over 110 kilometers in the Castile in Texas and over 200 kilometers in the German Zechstein (Dean *et al.*, 1975).

Comment: The mechanisms for lamination formation has already been discussed in the preceeding chapters. It has been pointed out that many laminations can be produced in a very brief period of time. They are the product of chemical changes of the hydrothermal system.

Organic carbonate laminations, besides being due to responses of the organic community to these changes, can result from the activity of sulfur reducing bacteria either acting during short periods of hydrothermal quiescence in the sediment water interface or possibly substratally in the interface between carbonates and sulfates. The presence of vast mats of bacteria which could be responsible for this has been noted by oceanographic researchers on the Glomar Challenger in the Guaymas Basin in the Gulf of California (Simoneit and Lonsdale, 1982; Jannasch and Wirsen, 1979). These mats apparently thrive in the hot hydrothermal waters. Is it possible that similar broad mats when buried in deposits of gypsum, anhydrite, or dolomite would give the same appearance as the stromatolites which are usually interpreted as algal mats from a sabkha environment? This might be a more reasonable explanation for deposits which otherwise have all the evidences of deep water deposition.

Synchronous Deposition

Observation: Cases are known with evidence of synchronous deposition of carbonates and other salts (Sloss, 1969, p. 777).

Comment: A unique bentonite was traced from carbonates through anhydrite to salt in the Detroit

River Formation of the Michigan Basin. The chief mineral of bentonite is montmorillonite. It has been suggested to be a product of the cooling of brine rich in iron and chlorine with partial oxidation, and has been shown to be associated with the Red Sea thermal brines (see Degens and Ross, 1969, p. 399). Bentonite is also a weathering product of volcanic ash which would also result from the volcanic activity. The mechanisms proposed here would be the most logical for the deposition of the thin bentonitic layer associated with the salts.

Association with Red Beds

Observation: Salt deposits are often associated with red beds (Krumbein and Sloss, 1963).

Comment: Red beds are usually thought to be associated with continental deposition. It has been the practice for some time to ascribe every red bed in the geologic record to continental deposition. As Krumbein and Sloss point out, the association is one only of color and not of sediment constituency. Actually, the color could easily be derived from the iron associated with hydrothermal activity. Hematite in cherty iron formations is commonly attributed to volcanic exhalative processes. Ohmoto and Rye (1974) and Jensen and Bateman (1981) include the iron as a part of the description of the general model for

Kuroko type ore deposits which the hydrothermal model actually encompasses.

Summary of Field Observations

Every one of the field observations concerning salt deposition is nicely explained by the proposed hydrothermal model. Many of these have been either poorly explained by existing models or not explained at all. This model is put forth for the purpose of generating some new thinking about the origin of salt that is not bound by the shackles of the traditional evaporative hypotheses.

Chapter 7

CONCLUSIONS

Models for the deposition of large salt bodies, based upon evaporative mechanisms, have been shown to contain unresolvable difficulties. Recognizing that the main problem with all of these models was the underlying assumption that evaporation of seawater was responsible for the salt formation, a new model, not based upon standard evaporative methods, was suggested. Data in support of the model was presented and correlation with known field data was demonstrated. The hydrothermal model that has been proposed in this paper is the product of the synthesis of many observations of salt deposits and of processes seen in operation today. The field observations, which have rendered many models useless, are very well explained by the hydrothermal model. Geologically, it appears sensible and reasonable; better yet, it explains the known data.

The important steps in the hydrothermal model are:

1. Increased volcanic and igneous intrusive activity leads to widespread, active hydrothermal vent systems.

2. Tremendous amounts of hot brines are produced by either the enrichment of seawater in hydrothermal vent systems or by the direct addition of salts by volcanism and magmatic hydrothermal fluids.
3. Hot brine either precipitates immediately as it responds to thermodynamic changes of temperature and pressure or it stratifies into laterally extensive, thick layers.
4. Brine layers precipitate whether or not they are fully saturated. Saturated solutions high in the ions of sodium and chlorine precipitate as the layer is cooled by the colder seawater above the pycnocline. Layers high in sulfates, calcium, and carbonate ions precipitate when the pycnocline is heated from below since calcium sulfate and calcium carbonate are less soluble in hot water. Also, changes in pressure as a brine layer rises, or changes in the Eh or the pH of the system can lead to massive precipitation. Undersaturated solutions precipitate rapidly by a process of

brine mixing.

This model is possibly fully or partly responsible for the accumulation or deposition of the following:

1. Large deposits of salts including gypsum, anhydrite, halite, and potash salts
2. Large deposits of micritic calcium carbonate, dolostone, and dolomitized carbonates
3. Hydrocarbons (including their reservoir rock)
4. Metallic sulfide mineral deposits
5. Bedded chert and banded iron deposits

Many field observations are explained with this new model that are either poorly explained or not explained at all by evaporative models:

1. Hydrothermal solutions best explain the presence of minerals which are thought to be formed at higher temperatures such as kieserite, langbeinite, dolomite, and anhydrite.
2. The monomineralic deposition involving great thicknesses of either halite or anhydrite is consistent with the model.
3. The great number of repeated laminations in the Zechstein and Castile are the

product of many factors including rapid changes in temperature and salinity controls acting repeatedly at or near the bottom of the depositional basin.

4. Volcanic activity and igneous intrusion which is thought by some to be incidental, without causal association with salt deposition, is shown instead to be the principal cause of salt deposition.
5. The lack of terrigenously derived material in salt beds has always been a good argument for deposition in a deep basin containing very deep water. Even in shallower depositional environments, brines would not mix with currents of fresher water containing suspended terrigenous material. The catastrophic nature of the precipitation process described for this model explains this lack, as well as the lack of marine fossils in salt deposits, much more thoroughly than do slow, evaporative processes.
6. Since salt deposition by the hydrothermal model does not depend upon

evaporation in an arid region, there is no problem explaining the occurrence of salts in extremely high latitude regions such as those found within the arctic circle.

7. Tremendous deposits of salts lying below sediments under the depths of the Mediterranean Sea and the Gulf of Mexico can be explained easily by this model and do not require the unreasonable assumption that these ocean bodies totally evaporated many times.

Some very interesting side features come out of a careful study of the hydrothermal model. Assumptions involving indicators of depositional environments and the length of time needed to deposit very thick layers of salt will have to be discarded:

1. Formation of hopper crystals and what appear to be algal mats can be formed in very deep water. These are usually thought to indicate sabkha facies deposits.
2. Many red beds, which have been frequently interpreted as continental deposits, owe their red color to the presence of iron derived from iron-rich

hydrothermal solutions. They do not indicate continental deposition unless other diagnostic features are present.

3. Precipitation of salt deposits proceeds very rapidly. Deposits once thought to take literally millions of years to form can now be interpreted in terms of extremely short time intervals.

The Catastrophic Nature of the Geologic Record

Much of the geologic record which was thought to have taken so long to form such as the micritic limestones, the dolostones, the radiolarian cherts, and salt deposits appear to have formed quite rapidly. It has also been recognized that much of the remainder of the geologic record shows definite signs of having been deposited rapidly. Actually, a rather recent awakening is being observed as more and more geologists are beginning to see that the present is not the key to the past as the basic uniformitarian model of geology has stipulated for many years. A renewed look at catastrophic processes is resulting.

Ager, who holds to most of the standard evolutionary ideas, points out in his book, The Nature of the Stratigraphical Record (1981), that the geologic record is much like a soldier's life--predominated by long periods of boredom with sudden periods of terror. For example, Chadwick (1978) reports on the movement of very large boulders as a result of water action. These he terms megabreccias, which are sedimentary deposits in which angular fragments of rock in excess of one meter in diameter form a conspicuous component. He reports many boulders in excess of 10 meters in diameter. One must certainly consider the process that "floated in" that size of material as a catastrophe. Chadwick's conclusions are:

> The presence of various kinds of megabreccias in the geologic column, showing in some cases the transport of extremely large clasts, indicates energy levels on a scale that staggers our imagination. Their common occurrence in major portions of the geologic column of some localities indicates significant catastrophic activity in the past not readily explainable in terms of contemporary processes. (p. 44)

Austin (1984) has compiled a comprehensive bibliographic review of catastrophic processes that have been reported in the scientific literature. The list is quite extensive. In light of observations showing the catastrophic nature of the geologic record, we are forced to invoke a series of catastrophies (or more sensibly one major catastrophe with several minor catastrophies resulting) in order to interpret what is actually observed in the record. It is clear that uniformitarian assumptions are not supported by the geologic record. In particular, the traditional uniformitarian model of deposition of salt beds based upon the evaporation of seawater does not explain the data.

Correlation with Biblical Data

The new model proposed, termed the "hydrothermal model," is not based on uniformitarian assumptions. It is instead based on logic and observation, which suggest processes analogous to those operating today, but operating at intensified levels on a very broad scale in the past. It is consistent with the rest of the catastrophic nature of the stratigraphic record and is entirely consistent with the unique conditions associated with a universal flood.

Until the last 150 years, geology had classically been interpreted in light of this one global catastrophe -- the Noachian Flood. This model has never been proven false. It has merely been set aside for a period of time because it became popular to believe in uniformitarianism. Therefore, for the last century, almost all field research has been interpreted in light of this popular assumption. Whitcomb and Morris in their classic book, The Genesis Flood (1961), give substantial evidence for the authenticity of the global flood both scripturally and scientifically. The findings of this research support their conclusions.

Genesis 7:11 (NASV) states, " . . . all the fountains of the great deep burst open, and the floodgates of the sky were opened." Psalm 104:8 reads, "The mountains rose; the valleys sank down to the place which Thou didst establish for them." With the "fountains of the great deep" breaking up, underground water activity, and volcanic and tectonic activity as described here in the Bible, what better conditions could be provided for the deposition of salts? A tremendous amount of erosion and deposition would have occurred. Coupled with increased volcanism, a tremendous amount of salt-forming material would have been added to the hydrologic system. This period of time, as described in the Bible, was certainly a unique period of geologic history which most certainly must have shaped the entire rock record.

The notion of a global flood clearly does not fit uniformitarian assumptions; but then, neither do the data from scientific observations of salt deposits. Uniformitarian assumptions, as an explanation of geologic features, in general, do not agree with scientific observation. Modern geologists need to reinterpret their view of earth history. Only then can meaningful advancements in the field of geology be made.

REFERENCES CITED

Ager, D. V., 1981, The nature of the stratigraphical record, 2nd. ed.: New York, John Wiley and Sons, 122 p.

Austin, S. A., 1974, Ionic ratios, unpubl.

Austin, S. A., 1984, Catastrophes in earth history: a sourcebook of geologic evidence, speculation and theory -- technical monograph 13: El Cajon, Calif., Institute for Creation Research, 318 p.

Bailey, E. H., W. P. Irwin, and D. L. Jones, 1964, Franciscan and related rocks, and their significance in geology of western California: Sacramento, Calif. Div. Mines and Geol. Bull 183, 177p.

Bateman, A. M., 1942, Economic mineral deposits: New York, John Wiley and Sons, 898 p.

Birnbaum, S. J. and M. W. Presley, 1980, Evaporites: Jour. Sed. Petr, v. 50, no. 1, p. 305-306.

Bischoff, J. L., 1969, Red Sea geothermal brine deposits: their mineralogy, chemistry and genesis, p. 368-401, in Degens, E. T. and D. A. Ross, 1969, Hot brines and recent heavy metal deposits in the Red Sea: a geochemical and geophysical account: New York, Springer-Verlag New York Inc., 600 p.

Blount, C. W. and F. W. Dickson, 1969, The solubility of anhydrite ($CaSO_4$) in $NaCl-H_2O$ from 100° to 450° C. and 1 to 1000 bars: Geochmica et Cosmochimica Acta, v. 33, p. 227-245.

Branson, E. B., 1915, Origin of thick gypsum and salt deposits: Bull. Geol. Soc. Am., v. 26, p. 231-242.

Bretz, J. H., 1969, The lake Missoula floods and the channeled scabland: Journ. Geol., v. 77, no. 5, p. 505-543.

Briggs, L. I., 1957, Quantitative aspects of evaporite deposition: Michigan Academy Sci. Papers, v. 42, p. 115-123.

Burst, J. F., 1965, Subaqueously formed shrinkage cracks in clay: Jour. Sed. Petr., v. 35, p. 348-353.

Butler, G. P., 1969, Modern evaporite deposition and geochemistry of coexisting brines, the sabkha, Trucial Coast, Arabian Gulf: Jour. Sed. Petr., v. 39, p. 70-81, 89.

Buzzalini, A. D., 1969, Evaporites and petroleum: introduction: Amer. Assoc. Petr. Geol., v. 53, no. 4, p. 775.

Chadwick, A. V., 1978, Megabreccias: evidence for catastrophism: Origins, v. 51, no. 1, p. 39-44.

Cita, M. B., 1973, Inventory of biostratigraphical findings and problems, p. 1045-1065, _in_ Ryan, W. B. F., Hsü, K. J., _et al_., 1973, Initial reports of the deep sea drilling project, v. XIII: Washington, U. S. Govt. Print. Office.

Craig, H., 1969, Geochemistry and origin of the Red Sea brines, p. 208-242, _in_ Degens, E. T. and D. A. Ross, 1969, Hot brines and recent heavy metal deposits in the Red Sea: a geochemical and geophysical account: New York, Springer-Verlag New York Inc., 600 p.

Curtis, R., G. Evans, D. J. J. Kinsman, and D. J. Shearman, 1963, Association of dolomite and anhydrite in the recent sediments of the Persian Gulf: Nature, v. 197, p. 679-680.

Davis, E. E., 1982, Evidence for extensive basalt flows on the sea floor: Geol. Soc. Amer. Bull., v. 93, p. 1023-1029.

Dean, W. E., G. R. Davies, and R. Y. Anderson, 1975, Sedimentological significance of nodular and laminated anhydrite: Geology, v. 3, p. 367-372.

Debenedetti, A., 1982, The problem of the origin of the salt deposits in the Mediterranean and of their relations to the other salt occurrences in the Neogene formations of the contiguous regions: Marine Geol., v. 49, no. 1-2, p. 91-114.

Degens, E. T. and D. A. Ross, eds., 1969, Hot brines and recent heavy metal deposits in the Red Sea: New York, Springer-Verlag New York, Inc., 600 p.

Dellwig, L. F., 1955, Origin of the Salina salt of Michigan: Jour. Sed. Petr., v. 25, p. 83-93, 95-102, 107-110.

Du Bois, C. G. B., *et al.*, 1963, Natrocarbonatite lava from Oldoinyo L'engai: Nature, v. 197, no. 4866, p. 445-446.

Ewing, J. I., J. L. Worzel, and M. Ewing, 1962, Sediments and oceanic structural history of the Gulf of Mexico: Jour. Geophys. Res., v. 67, no. 6, p. 2509-2527.

Fisk, H. N., 1959, Padre Island and the Laguna Madre Flats, Coastal South Texas: Nat. Acad. Sci -- Nat. Res. Counc., 2nd Coastal Geog. Conf., p. 103-151.

Ford, D. L., 1975, Origin of evaporites: unpubl., 13 p.

Friedman, G. M., 1972, Significance of Red Sea in problems of evaporites and basinal limestones, Amer. Assoc. Petr. Geol. Bull., v. 56, p. 1072-1086.

Friedman, G. M., 1973, Petrographic data and comments on the depositional environment of the Miocene sulphates and dolomites at sites 124, 132, and 134, western Mediterranean Sea, p. 695-708, *in* Ryan, W. B. F., K. J. Hsü, *et al.*, 1973, Initial reports of the deep sea drilling project, v. XIII: Washington, U. S. Govt. Print. Office.

Goldberg, M., 1967, Supratidal dolomitization and dedolomitization in Jurassic rocks of Hamakhtesh Haqatan, Israel: Jour. Sed. Petr., v. 25, p. 760-773.

Gray, R. S., 1967, Cache Field -- a Pennsylvanian algal reservoir in southwestern Colorado: Amer. Assoc. Petr. Geol. Bull., v. 51,

p. 1959-1978.

Halbouty, M. T., 1967, Salt domes Gulf Region, United States and Mexico: Houston, Texas, Gulf Publ. Co., 425 p.

Harbeck, G. E., 1955, The effect of salinity on evaporation: U. S. Geol. Survey, Prof. Paper 272A, 6 p.

Harris, L. D., 1973, Dolomitization model for upper Cambrian and lower Ordovician carbonate rocks in the eastern United States: Jour. Res. U. S. Geol. Survey, v. 1, no. 1, p. 63-78.

Holser, W. T. and I. R. Kaplan, 1966, Isotope geochemistry of sedimentary sulfates: Chemical Geology, v. 1, p. 93-135.

Hsü, K. J., 1972, Origin of saline giants: a critical review after discovery of the Mediterranean evaporite: Earth-Sci. Rev., v. 8, p. 371-396.

Hsü, K. J., 1983a, Lost secrets of the Mediterranean: The Sciences, v. 23, no. 5, p. 44-51.

Hsü, K. J., 1983b, The Mediterranean was a desert -- a voyage of the *Glomar Challenger*: Princeton, New Jersey, Princeton Univ. Press, p. 197.

Hsü, K. J., M. B. Cita, and W. B. F. Ryan, 1973, The origin of the Mediterranean evaporite, p. 1203-1231, *in* Ryan, W. B. F., K. J. Hsü, *et al*., 1973, Initial reports of the deep sea drilling project, v. XIII: Washington, U. S. Govt. Print. Office.

Hsü, K. J., W. B. F. Ryan, and B. C. Schreiber, 1973, Petrography of a halite sample from hole 134 -- Balearic Abyssal Plain, p. 708-711 *in* Ryan, W. B. F., K. J. Hsü, *et al*., 1973, Initial reports of the deep sea drilling project, v. XIII: Washington, U. S. Govt. Print. Office.

Jannasch, H. W. and C. O. Wirsen, 1979, Chemosynthetic primary production at east Pacific sea floor spreading centers, Biosci., v. 29, no. 10, p. 592-598.

Jensen, M. L. and A. M. Bateman, 1981, Economic mineral deposits, 3rd Ed.: New York, John Wiley and Sons, 593 p.

Kendall, A. C., 1978, Facies models in subaqueaous evaporites: Geosci. Canada, v. 5, no. 3, p. 124-139.

Kerr, S. D., Jr., and A. Thomson, 1963, Origin of nodular and bedded anhydrite in Permian shelf sediments, Texas and New Mexico: Amer. Assoc. Petr. Geol. Bull., v. 47, p. 1726-1732.

King, R. H., 1947, Sedimentation in Permian Castile Sea: Amer. Assoc. Petr. Geol. Bull., v. 31, no. 3, p. 470-477.

Kinsman, D. J. J., 1969, Modes of formation, sedimentary associations, and diagnostic features of shallow-water and supratidal evaporites: Amer. Assoc. Petr. Geol. Bull., v. 53, p. 830-840.

Kinsman, D. J. J., 1974, Evaporite deposits of continental margins, p. 255-259 in Fourth Symposium on Salt: Cleveland, Ohio, Northern Ohio Geol. Society, v. 1.

Kirkland, D. W. and R. Evans, 1973, Marine evaporites: origin, diagenesis, and geochemistry: Stroudsburg, Pennsylvania, Dowden, Hutchinson and Ross, Inc., 426 p.

Kozary, M. T., J. C. Dunlap, and W. E. Humphrey, 1968, Incidence of saline deposits in geologic time: The Geol. Soc. of Amer. Special Paper 88, p. 43-57.

Krauskopf, K. B., 1967, Introduction to geochemistry: New York, McGraw-Hill Book Co., 721 p.

Krumbein, W. C. and L. L. Sloss, 1963, Stratigraphy and sedimentation, 2nd Ed.: San Franscisco, W. H. Freeman and Co., 660 p.

Kudryavtsev, N. A., 1971, Evaporites and petroleum: discussion: Amer. Assoc. Petr.

Geol. Bull., v. 55, p. 2033-2061.

Longinelli, A. and M. B. Cita, 1973, Isotopic evidence of changes in oceanic circulation, p. 1400-1404 in Ryan, W. B. F., Hsü, K. J., et al., 1973, Initial reports of the deep sea drilling project, v. XIII: Washington, U. S. Govt. Print. Office.

Lonsdale, P. F., J. L. Bischoff, et al., 1980, A high-temperature hydrothermal deposit on the seabed at a Gulf of California spreading center: Earth and Planetary Letters, v. 49, no. 1, p. 2-19.

Marshall, W. L., R. Slusher, and E. V. Jones, 1964, Solubility and thermodynamic relationships for $CaSO_4$ in NaCl-H_2O solutions from 40° to 200° C., 0 to 4 molal NaCl: Jour. Chem. Eng. & Data, v. 9, no. 2, p. 187-188.

Mason, B., 1966, Principles of geochemistry, 3rd. Ed.: New York, John Wiley and Sons, Inc., 329 p.

Masson, P. H., 1955, An occurrence of gypsum in southwest Texas: Jour. Sed. Petr., v. 25, p. 72-77.

Meyerhoff, A. A., 1970, Continental drift, II: high-latitude evaporite deposits and geologic history of Arctic and North Atlantic Oceans: Jour. Geol., v. 78, p. 406-444.

Nesteroff, W. D., 1973, Minerology, petrography, distribution and origin of the Messinian Mediterranean evaporites, p. 673-694, in Ryan, W. B. F., Hsü, K. J., et al., 1973, Initial reports of the deep sea drilling project, v. XIII: Washington, U. S. Govt. Print. Office.

Nesteroff, W. D., F. C. Wezel, and G. Pautot, 1973, Summary of lithostratigraphic findings and problems, p. 1021-1040, in Ryan, W. B. F., Hsü, K. J., et al., 1973, Initial reports of the deep sea drilling project, v. XIII: Washington, U. S. Govt. Print. Office.

Nevins, S. E., 1974, Reply to critique by Daniel Wonderly: Creation Research Society Quarterly, v. 10, p. 241-244.

Ochsenius, C., 1888, On the formation of rock salt beds and mother liquor salts: Proc. Acad. Nat. Sci. Philadelphia, v. 40, p. 181-187.

Ohmoto, H. and R. Rye, 1974, Hydrogen and oxygen isotopic compositions of fluid inclusions in the Kuroko deposits, Japan: Econ. Geol., v. 69, p. 947-953.

Pautot, G., J. Auzende, and X. Pichon, 1970, Continuous deep sea salt layer along North Atlantic margins related to early phase of rifting: Nature, v. 227, p. 351-354.

Plummer, P. S. and V. A. Gostin, 1981, Shrinkage cracks: desiccation or synaeresis?: Jour. Sed. Petr., v. 51, p. 1147-1156.

Porfir'ev, V. B., 1974, Geology and genesis of salt formations: Amer. Assoc. Petr. Geol. Bull., v. 58, p. 2543-2544.

Rankama, K., 1954, Isotope geology: New York, McGraw-Hill Book Co., 535 p.

Raup, O. B., 1970, Brine mixing: an additional mechanism for formation of basin evaporites: Amer. Assoc. Petr. Geol. Bull., v. 54, no. 12, p. 2246-2259.

Renfro, A. R., 1974, Genesis of evaporite-associated stratiform metalliferous deposits -- a sabkha process: Econ. Geol., v. 69, p. 33-45.

Rode, K. P., 1944, On the submarine volcanic origin of rock-salt deposits: Indian Acad. Sci. Proc., v. 19, sec. B, p. 130-142.

Roehl, P. O., 1967, Stony Mountain (Ordovician) and Interlake (Silurian) facies analogs of recent low energy marine and subaerial carbonates, Bahamas: Amer. Assoc. Petr. Geol. Bull., v. 51, p. 1979-2032.

Schmalz, R. F., 1969, Deep water evaporite deposition: a genetic model: Amer. Assoc.

Petr. Geol. Bull., v. 53, p. 798-823.

Schreiber, B. C., 1978, Introduction -- Classification of marine evporites, p. 1-5, in Dean, W. E. and B. C. Schreiber, eds., Marine evaporites, SEPM short course no. 4.

Simoneit, B. and P. F. Lonsdale, 1982, Hydrothermal petroleum in mineralized mounds at the seabed of Guaymas Basin: Nature, v. 295, p. 198-202.

Sloss, L. L., 1969, Evaporite deposition from layered solutions: Amer. Assoc. Petr. Geol. Bull., v. 53, no. 4, p. 776-789.

Sloss, L. L., 1977, Reefs and evaporites: a summary, in Fisher, J. H., ed., Reefs and evaporites -- concepts and depositional models: Amer. Assoc. Petr. Geol., Studies in Geology #5.

Smithey, W., 1983, Personal Communication.

Sozansky, V. I., 1973, Origin of salt deposits in deep-water basins of Atlantic Ocean: Amer. Assoc. Petr. Geol. Bull., v. 57, no. 3, p. 589,590.

Steinhorn, I. and J. R. Gat, 1983, The Dead Sea: Sci. Amer., v. 249, no. 4, p. 102-109.

Stewart, F. H., 1963, Marine evaporites, 53 p., in Fleischer, M., ed., Data of geochemistry, 6th Ed., Geol. Survey Prof. Paper 440-Y.

Turner, J. S., 1969, A physical interpretation of the observations of hot brine layers in the Red Sea, p. 164-173 in Degens, E. T., and D. A. Ross, 1969, Hot brines and recent heavy metal deposits in the Red Sea: a geochemical and geophysical account: New York, Springer-Verlag New York Inc., 600 p.

von Knorring, O., 1962, Geochemical characteristics of carbonatites: Nature, v. 194, no. 4831, p. 860.

von Knorring, O. and C. G. B. Du Bois, 1961, Carbonatitic lava from Fort Portal area in western Uganda: Nature, v. 192, no. 4807,

p. 1064-1065.

Webster, G. 1957, Volcanoes: nature's blast furnaces: Sci. Dig., v. 42, p. 5

Wells, A. J., 1962, Recent dolomite in the Persian Gulf: Nature, v. 194, p. 274-275.

Whitcomb, J. C. and H. M. Morris, 1961, The genesis flood: Philadelphia, Presbyterian and Reformed Publishing Co., 518 p.

White, D. E., J. D. Hem, and G. A. Waring, 1963, Chemical composition of subsurface waters: U. S. Geol. Survey Prof. Paper #440-F, 67 p.

Wilcox, F. L. and S. T. Davidson, 1976, Experiments on precipitation brought about by mixing brines: Creation Research Society Quarterly, v. 13, no. 2, p. 87-89.

Woolnough, W. G., 1937, Sedimentation in barred basins and source rocks of oil: Amer. Assoc. Petr. Geol. Bull., v. 21, no. 9., p. 1101-1157.