

# Shelf Carbonate Sedimentation Controlled by Salinity in the Paradox Basin, Southeast Utah<sup>1</sup>

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## ABSTRACT

*Deposition of shelf carbonates, adjacent to and contemporaneous with a basin evaporite facies, is closely controlled by salinities originating in the evaporite basin. Changes in depositional environment due to rising sea level in these basins is often misinterpreted, especially when the resultant transgression is linked to freshening and expansion of normal marine conditions. Rising sea level may terminate evaporite deposition in the basin, but anaerobic hypersaline conditions are displaced onto the basin shelf and margins during this transgressive period.*

*Circulation in marine evaporite basins includes some return flow or reflux. Reflux is controlled by change in sea level, evaporation rates, and size of accessways.*

*Middle Pennsylvanian evaporite cycles in the Paradox basin of southeast Utah and southwest Colorado probably were due to periodic fluctuations in sea level. Each complete evaporite cycle consists of a transgressive and a regressive hemicycle bounded by disconformities. Beds comprising these cycles grade shelfward into predominantly carbonate facies. Salinities of the evaporite basin controlled carbonate sedimentation on the adjacent shelf to the southwest. High sea level and related maximum reflux carried toxic brines onto the shelf and created unfavorable conditions for life and deposition of biogenic carbonates. During maximum reflux, reducing conditions initiated deposition of black sapropelic shale where normal marine life previously thrived. Only during low sea level, with little or no reflux, were shelf conditions optimum for growth of algal bank carbonates.*

*Using bromine distribution in halite units of evaporite cycles as an index of basin reflux, cycle favorable for the development of algal carbonate facies can be predicted. Because algal carbonate facies in many marine evaporite basins are major sources of petroleum, bromine geochemistry gains still another use in exploration.*

## INTRODUCTION

All marine evaporites, unless the deposit is the result of solution and redeposition of preexisting evaporites, have an adjacent and contemporaneous carbonate facies. The rock types and distribution of this facies often reflect radical but rhythmic changes in the depositional environment. Similar depositional rhythms are found in the facies of the neighboring evaporite basin where the deposition response has been clearly shown to be controlled by salinity. In the evaporite basin the specific response of the chemical facies to salinity change can be easily demonstrated by the solubility order of the various salts involved. In contrast the effect of salinity changes on the carbonate facies of the adjacent shelf is not well understood, primarily because it involves changes in the biologic community, and our methods of interpreting the ecology of a biofacies are unprecise. In addition the deeper, more stable environment of the evaporite basin probably preserves a more complete depositional record than the shallower shelf. In the latter the depositional record may be complicated

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by erosion, nondeposition and onlap and offlap relationships. On a shallow, gentle-sloping shelf even minor changes in sea level can cause significant shifts in facies. Thus, the vertical sequence of units in a depositional cycle of shelf rocks may be incomplete or seemingly without order.

Salinity changes in the evaporite basin can be brought about by runoff, differential rates of evaporation, breaching of circulation barriers, and the like; however, most probably are due to variations in sea level. Because evaporite deposition is such a sensitive record of salinity, it is only logical that these chemical sediments are also our best record of sea level change. Therefore, where evaporites are associated with shelf carbonates it may be possible to use the evaporites as the key to deciphering the complex depositional history of the carbonates.

This paper includes a review of certain principles of evaporite deposition and, through model studies, shows how these principles were involved in deposition of evaporites and contemporaneous carbonates in the Paradox basin of southeast Utah and southwest Colorado. Some of the basic principles on which this paper is based, and conclusions drawn from application of these principles, are as follows:

- (1) All evaporite basins undergo some degree of reflux.
- (2) Rate of reflux is primarily controlled by sea level. If sea level is high, then the rate of reflux will be great; if, however, the sea level is low, reflux is absent or minimal.
- (3) Every marine evaporite facies must have a contemporaneous carbonate facies unless the evaporites are the result of solution and redeposition of preexisting deposits.
- (4) The contemporaneous carbonate facies will be deposited in the area of seawater ingress, and thus will also be in the path of refluxing brines from the basin.
- (5) Contrary to popular opinion, biogenic carbonates should develop during a low sea level or regressive phase when reflux is minimal.
- (6) Studies of bromine distribution in the chloride facies of evaporite cycles can establish the relative rate of basin reflux. The reflux index for individual cycles can be used as a tool in evaluating the cycle's favorability of having a biogenic carbonate facies. Because buildups of these carbonates (usually algal) commonly form petroleum reservoirs, bromine geochemistry may serve as a new tool for petroleum exploration.
- (7) In undrilled sedimentary basins the presence of algal carbonate buildups in depositional cycles,

around the margins of the basin, might indicate a potential target zone for salt and potash exploration deeper in the basin.

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## SOME PRINCIPLES OF EVAPORITE DEPOSITION

In order to understand better how the evaporite environment can influence the deposition of an adjacent carbonate facies, it is first necessary to review some of the principles governing evaporite deposition. Although there are other equally important principles involved in evaporite deposition, there are three that have special significance to the deposition of contemporaneous carbonates. The principles reviewed here are known to most evaporite geologists but have seldom been applied in studies of carbonates associated with evaporites.

### *Principle 1.*

The deposition of each individual mineral facies of an evaporite deposit must first be preceded by the deposition of the other less soluble facies. For a unit volume of halite to be deposited, calcium carbonate and calcium sulfate must first be deposited, and the unit volumes of these salts must at least equal (they usually exceed) the theoretical seawater ratio. A more soluble salt cannot be deposited in excess of the seawater ratio of the less soluble salts. This simple principle is commonly overlooked.

Seawater is a complex system of many ions but the sequence of salts deposited by its evaporation follows a definite order, at least until the bitter stage of concentration is reached. After that the sequence of salts deposited varies according to changes in physicochemical and even biologic factors. The depositional sequence of rock-forming minerals, which was established by Usiglio (1849), starting with the least soluble mineral is (1) calcite, (2) gypsum or anhydrite, and (3) halite. Thus a marine evaporite deposit containing a halite facies must have an associated sulfate and carbonate facies. Possible exceptions would include removal of the sulfate facies by dissolution or bacterial reduction. Where it is assumed that these facies are missing they are either yet to be drilled or their contemporaneity with the halite has not been recognized. One reason that geologists sometimes

conclude that a facies is missing is that they have only examined a vertical sequence and have not considered lateral facies changes. In addition salt, due to its greater mobility, may be displaced from its former associate facies in areas affected by salt tectonism.

### *Principle II.*

All marine basins containing thick evaporite deposits have undergone reflux. Without reflux the evaporite deposits of all basins would include the full spectrum of evaporite minerals, and the relative amounts of one mineral to another would be directly proportional to the ratio of the parent elements in seawater.

During the embryonic stage of evaporite geology it was noted that most natural sequences of evaporites do not conform to the sequence of salts produced in the laboratory by evaporation of seawater. In particular, it was observed that the volumetric ratios of various minerals in the deposits differ sharply from laboratory results. An often cited example is the Castile Formation of the Delaware basin which has an anhydrite/halite ratio of about 1:1 whereas the theoretical seawater ratio is about 1:30. Other deposits containing thick halite layers are totally lacking in salts of potassium and magnesium. The solution to the problem came when King (1947) utilized the reflux theory of Ochsenius (1877) to explain the various mineral imbalances observed in evaporite deposits of the Delaware basin. Mineral imbalance, or the complete absence of some of the more soluble salts, was explained by loss of salts back to the sea during reflux.

### *Principle III.*

Reflux is controlled by rise or fall in sea level, change in carrying capacity of the accessway, or change in evaporation rates.

Of these three controls, change in sea level is probably the most significant. When sea level is high the basin will experience a large amount of reflux. Conversely when sea level is low there will be little or no reflux. This last principle is the key to the proper interpretation of carbonate deposition on shelves bordering evaporite basins.

## **BARRED BASIN EVAPORITE MODEL**

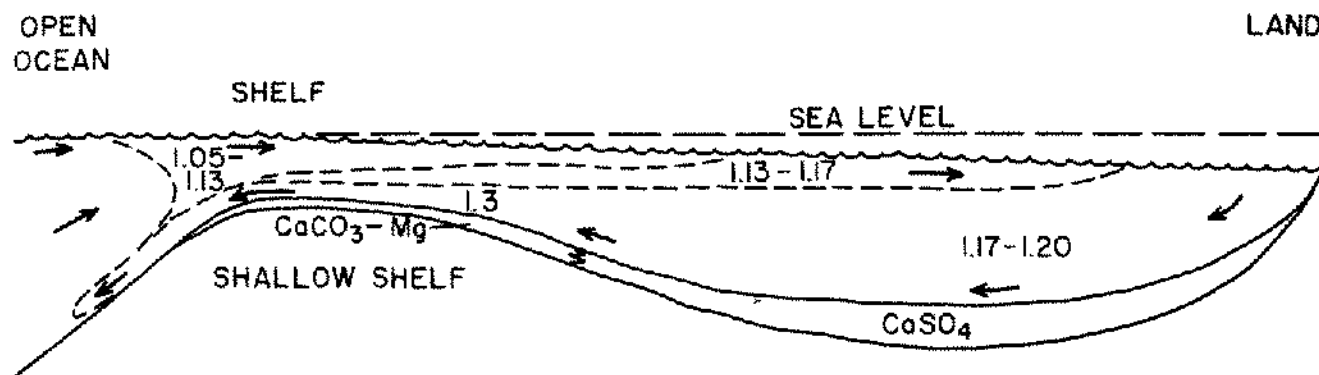
The principles of evaporite deposition, outlined in the preceding section, and the strong influence of the evaporite basin on carbonate deposition in the surrounding environs, can be illustrated best with models. Following the barred basin model of

Ochsenius (1877), models of various other evaporite depositional sites, involving both physical and dynamic barriers to oceanic circulation, have been proposed; however, in this paper only the barred basin model is discussed because it fits best with the Paradox basin deposits.

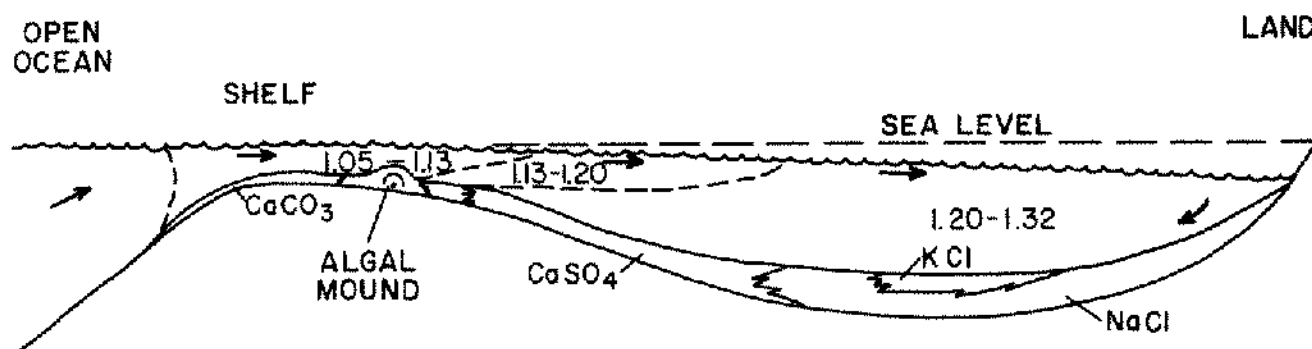
In the barred basin evaporite model, circulation with the open ocean is restricted by topographic barriers. Marine access to the basin may consist of a narrow strait or channel analogous to the Strait of Gibraltar and the Mediterranean Sea. In the geologic past most oceanic accessways probably extended across broad gently sloping shelves. Seawater moving slowly across such shelves, which might be several hundred miles in width, can become highly concentrated through evaporation even before it reaches the evaporite basins (Fig. 1). Such features have been aptly named "saturation shelves" by Richter-Bernburg (1955, p. 600). These conditions create strong horizontal salinity gradients which extend across the saturation shelves into the evaporite basins. In response to these gradients chemical sedimentation develops an orderly pattern of facies with the most soluble salts, such as potash, located in the most distal reaches of the basins (Scruton, 1953, p. 2510). In addition to controlling the position of each chemical facies, the salinity gradients exert considerable influence on the deposition of biogenic carbonates. Each biofacies is positioned in relation to the salinity tolerance, or preference, of the organism involved.

The mechanics of basin evaporite deposition can be more clearly understood if stated in terms of salt load carried into the basin and salt load carried back to the ocean. At a high sea level stage (Fig. 1a) the evaporite basin will undergo a large amount of reflux. If sea level is high enough the reflux salt load will equal influx salt, preventing a salinity increase and deposition of evaporites. The Mediterranean Sea is a perfect example of a basin in which the incoming salt load is balanced by reflux so that the salinity of the sea remains well below saturation (Peterson and Hite, 1969, p. 893).

The circulatory system of the evaporite basin model is a dynamic system and, therefore, its salt budget is in a continuous state of change. The rate of influx, and therefore the influx salt load, is controlled by evaporation rates in the basin. If these evaporation rates remain the same, the influx salt load can be considered a constant. The greatest variable in the system is the reflux salt load. If we begin to lower sea level in our model the influx salt load will remain constant and for a while so will



A. BASIN-TYPE EVAPORITE MODEL  
TRANSGRESSIVE PHASE



B. BASIN-TYPE EVAPORITE MODEL  
REGRESSIVE PHASE

Figure 1. Models of a barred evaporite basin during (A) the transgressive phase (high sea level) and (B) the regressive phase (low sea level). Numbers (representing water densities) are approximate.

the reflux load. However, the velocity of the influx current always dominates the accessway so that any reduction in flow, by constriction of the channel, must take place at the expense of the reflux current. Eventually lowering of sea level will reduce the carrying capacity of the accessway to a point that reflux is inhibited. This creates an imbalance between influx and reflux salt, and the surplus salt retained in the basin raises the salinity. Continued lowering of sea level will increase this imbalance and eventually bring about the deposition of evaporites. Extremely low sea level may so restrict circulation between open ocean and basin

that only enough water to replace evaporation losses can enter the basin. At times this inflow may have been completely shut off. Under these conditions very high salinities will build up in the basin and potash salts will be deposited (Fig. 1b).

The models discussed here help to demonstrate the dynamic nature of the evaporite environment which creates conditions that cannot be duplicated by simple evaporation in a laboratory beaker. For example, the salt budget of the evaporite basin must always show a balance between the amount of influx salt and the amount of salt lost to the depositional layer and reflux. If the salt budget of

an evaporite basin has reached equilibrium at a point when the brine is saturated for calcium sulfate, only this salt and the less soluble carbonates will be deposited (Fig. 1a). The horizontal salinity gradient will sufficiently separate the solubility fields of these minerals so that an infinite thickness of each facies will result unless there is a sea level change or some other event that alters the basin's salt budget (Zen, 1960). The dynamic system of the evaporite basin also creates another important condition which I refer to as the "funnel effect." Although a basin evaporite deposit may cover a few thousand square miles, the evaporative surface, which affects the salinities in the basin, may cover several hundred thousand square miles. When the nearly saturated brine, generated in this much larger area, is funneled into a relatively small depression very rapid deposition of evaporites can occur.

The principle of a refluxing evaporite basin has received wide acceptance, but the strong influence of reflux brines on sedimentation outside the basin has rarely been considered. Evaporite brines, compared with other natural waters, are strongly active chemical agents. These brines can have a salt content 10 times that of seawater. Compared with seawater, which is weakly alkaline, brines may have pH values of 4.0 and lower. Brines are usually anoxic because of the depletion of oxygen by decay of organic material and the depressed solubility of oxygen in concentrated salt solutions (Fig. 2). Toxic concentrations of hydrogen sulfide are also characteristic of these waters. In addition, high brine temperatures are common owing to the "green house" effect caused by solar radiation passing through the influx layer of fresher seawater into the dense reflux layer where the energy is absorbed. The "green house" effect is being studied as a possible energy source by Israeli scientists who have recorded temperatures of 90°C in dark-bottomed solar brine ponds. Considering all these factors it seems reasonable to assume that an evaporite brine and normal seawater are in chemical disequilibrium. Mixing of these waters should play a prominent role in chemical sedimentation and diagenetic processes on the shelf of the evaporite basin and perhaps on the floor of the open ocean as well.

The concept of the mixing of natural waters as an important process of diagenesis and chemical sedimentation has been proposed and factually supported by Runnells (1969). He showed how the mixing of waters, which differ by one or any combination of the following: (1) salt content,

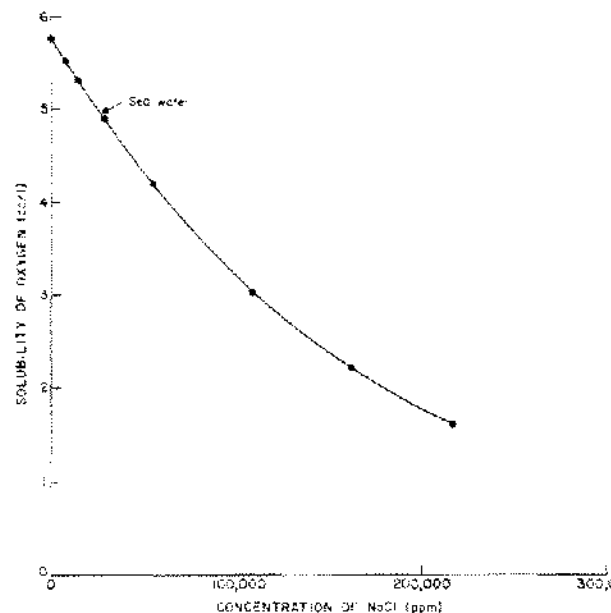


Figure 2. Solubility of oxygen in sodium chloride solutions at 25°C. Data from MacArthur (1916) and Geffcken (1904).

(2) temperature, (3) pressure, (4) pH, (5) content of dissolved organics, and (6) partial pressures of gases, can cause precipitation or dissolution of common minerals such as calcite, gypsum, dolomite, anhydrite, and barite. Direct precipitation of dolomite, calcite, or magnesite might be effected by mixing of the warm hypersaline Mg-Ca-Na brines of the reflux current with colder carbonate-bearing seawater of the overlying influx current. Briggs (1958, p. 50) also proposed the mixing of evaporite brines, of contrasting composition, as a means of precipitating sulfates and carbonates. A similar mechanism has been suggested by Pettijohn (1949, p. 301) who stated "Observations on the formation of calcareous oolites that are forming at the present time indicate that sodium or ammonium carbonate-bearing waters may be the precipitating agent. Upon introduction of waters containing these ions into waters containing calcium in solution, an exchange takes place, and the less soluble calcium carbonate is thrown down. Under suitable current conditions, the calcium carbonate takes the oolitic form." A solubility differential for silica between the influx and reflux waters, might also be responsible for the deposition of chert layers which are commonly associated with shelf dolomites.

Refluxing brines may also be responsible for large-scale diagenesis of shelf sediments due to chemical disequilibrium between the brine and the

sediment layer. Dolomitization by seepage refluxion has been proposed by Adams and Rhodes (1960); however, dolomitization by magnesium-rich brines moving *over* preexisting carbonates may be an equally important mechanism. Solubilities of calcite, dolomite, anhydrite, and gypsum increase with increasing concentrations of NaCl according to Hem (1959, p. 74, 82) and Runnells (1969). Therefore, dissolution of previously deposited carbonates and sulfates by chloride brines might be expected during periods of substantial reflux.

Added to the important role that refluxing evaporite brines may play in chemical sedimentation and diagenesis is the pronounced influence on the biologic community of the shelf. During reflux the shelf waters are divided into two strongly contrasting environments. The overlying inflow layer of seawater could support the normal nektonic-planktonic biota, but the refluxing layer would bring the anoxic highly reducing environment of the evaporite basin onto the shelf. The survival of benthos under these conditions is doubtful except in areas where a topographic rise might project into the life-supporting inflow layer.

Summarizing, it seems probable that evaporite basins can exert a powerful influence on the chemical and biological sedimentation of the adjacent shelf. Because variations in sea level control basin reflux, and therefore control basin salinities, any given time-rock layer in the chemical facies can be used as a guide to predict the rock type in the contemporaneous shelf facies.

#### APPLICATION TO A NATURAL SEQUENCE (PARADOX BASIN)

The principles of evaporite deposition described in the preceding section can be applied to problems of contemporaneous carbonate and evaporite sedimentation in the Paradox basin. This basin contains a thick sequence of evaporites of Middle Pennsylvanian age and a thinner complementary facies of shelf carbonates. The evaporite facies, which is predominantly halite, extends over 11,000 square miles in southeastern Utah and southwest Colorado (Fig. 3). The greatest thickness of evaporites occurs in a troughlike depression bordering the ancestral Uncompahgre uplift along the northeast margin of the basin (Fig. 3). This elongate structural depression has been referred to as the Uncompahgre trough (Hite, 1968). The original thickness of evaporites deposited in the trough area is difficult to estimate because of the widespread effects of salt flowage in the numerous diapiric salt

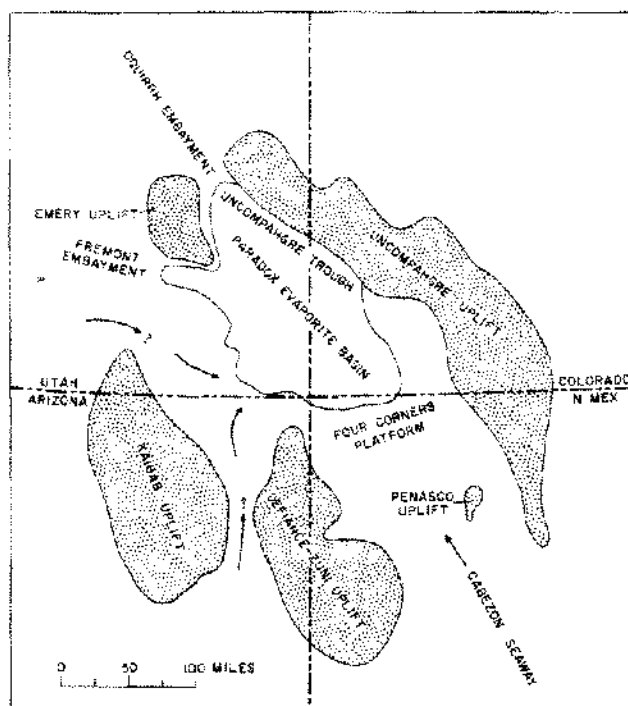


Figure 3. Index and paleogeographic map of Paradox basin during Middle Pennsylvanian time showing land areas (stippled) and possible marine accessways (shown by arrows).

anticlines associated with this region. From observations made in areas where the salt is not so severely disturbed, it is estimated that the original thickness of the evaporite sequence may have been between 5,000 and 6,000 feet.

The evaporite or halite facies forms the middle unit or Paradox Member of the Hermosa Formation. Where the halite facies is present the Hermosa Formation can be divided into an upper member above the halite and a lower member below (Fig. 4). Both of these members are predominantly a carbonate facies, although a few thin anhydrite, black shale, and sandstone layers are present locally. The upper and lower members are respectively the Honaker Trail and Pinkerton Trail Formations of Wengerd and Matheny (1958) and Wengerd and Strickland (1954). The Paradox Member exhibits a remarkable cyclic pattern of chemical and clastic sedimentation. The member can be subdivided into 29 evaporite cycles in the deeper part of the basin and for convenience of correlation each cycle has been given a numerical designation (Hite, 1960). Each evaporite cycle can be correlated across the salt basin into an equivalent cycle within the carbonate facies on the southwest shelf of the basin. Many of the

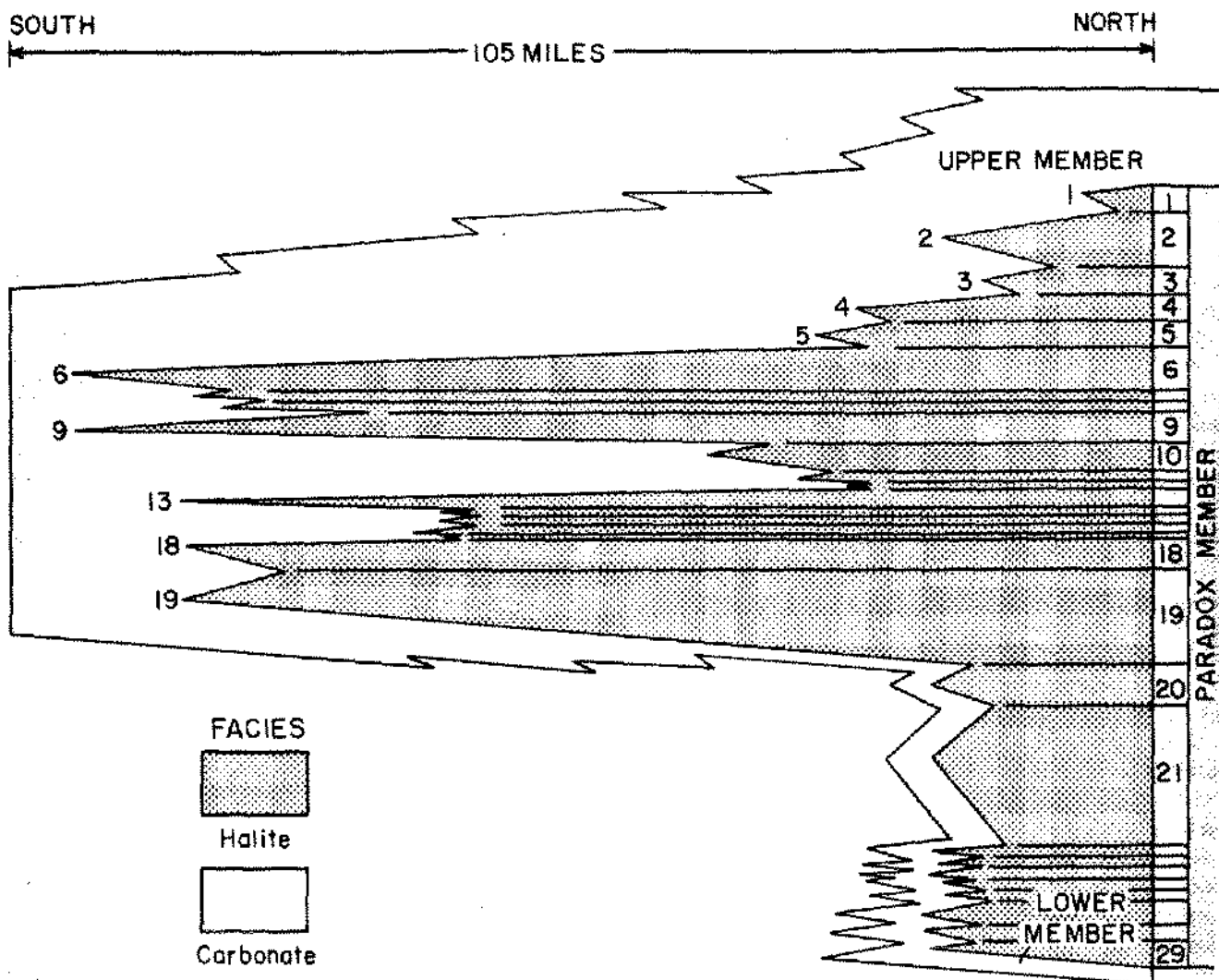


Figure 4. Diagrammatic north-south stratigraphic section across the Paradox basin showing stratigraphy of the Hermosa Formation of Middle Pennsylvanian age. Numbered units are evaporite cycles of the Paradox Member which consist primarily of halite.

carbonate cycles contain petroleum reservoirs, and these producing intervals, which usually span several depositional cycles, have been lumped by petroleum geologists into units known as the Ismay, Desert Creek, Akah, Barker Creek, and Alkali Gulch zones. For a detailed discussion of stratigraphic nomenclature of the shelf carbonates see Baars and others (1967).

The initial deposition of evaporites in the Paradox basin began in the Uncompahgre trough and was restricted to this depression through cycles 29 to 20. It was not until the deposition of cycle 19 that the halite facies began to spread out of the trough toward the western and southern margins of

the basin (Fig. 4). This spread of the evaporite probably was due more to filling of the Uncompahgre trough by rapid deposition than to an intensification of the evaporite regimen. During the deposition of cycles 10, 11, and 12 the evaporite facies was again restricted to the trough area suggesting a period of mild downwarpen. Maximum expansion of the evaporite environment came during cycles 6 and 9 when halite was deposited far out on the shelf. After the deposition of cycle 6 the evaporite facies retreated rather suddenly back to the trough area and remained there until the basin was finally flushed out by an incision of normal marine waters.

### The evaporite cycles.

The evaporite cycles of the Paradox Member are unequaled in number and completeness by those of other evaporite deposits of the world. The Paradox cycles are also unique in that they afford an excellent opportunity to study the relationship of contemporaneous deposition of carbonates and evaporites. The Paradox evaporite cycles were first described by Herman and Sharps (1956), and later in greater detail, by Herman and Barkell, (1957), Hite and Gere (1958), Hite (1960, 1961, 1968), and Peterson and Hite (1969).

A typical Paradox evaporite cycle consists primarily of chemical rocks; however, a small amount of detrital and organic material forms an integral part of the cycle. The lithofacies of the cycle include halite with or without potash salts, anhydrite, silty dolomite, and black shale (Fig. 5). The halite and anhydrite units of each cycle are entirely a chemical facies; however, the dolomite

and black shale are both chemical and clastic, and contain organic material. The dolomite is extremely fine grained and contains abundant uniformly sorted quartz silt. The black shale is the most complex of the facies. About 20 to 30 weight-percent of this rock is carbonate which is divided about equally between dolomite and calcite. The remainder of the black shale is clay-size detritus consisting of quartz, feldspars, various clay minerals, and locally as much as 15 percent organic matter.

The sequential order of units in a typical Paradox cycle is determined by the degree of solubility of the rock-forming mineral in seawater. If a cycle is defined on the basis of the chemical sequence of rocks deposited, as seawater undergoes a gradual increase and then a decrease in salinity, the sequence is (A) silty, calcareous, dolomitic, argillaceous, organic-rich black shale, (B) silty dolomite, (C) nodular and laminated anhydrite, (D) halite with or without potash salts, (C) anhydrite as before, (B) dolomite as before, and (A) black shale as before. In this sense the cycle can be termed a chemical cycle and, on the basis of the position of lithologic units, shows mirror-image symmetry as A, B, C, D, C, B, A. However, the Paradox chemical cycle is not symmetrical. At the base of the cycle, units A, B, C, and D are deposited as the result of gradually increasing salinity and each unit shows a gradual transition with the overlying unit. The halite (unit D), however, neither shows a gradual decrease in salinity nor grades into the overlying anhydrite unit. Studies by Raup (1966, p. 245) of the bromine content of halite in the Paradox Member have shown that salinities gradually increased all the way to the top, or near the top, of each salt bed. Further evidence of asymmetry can be seen in those cycles that are potash bearing. The potash deposits, which represent the period of highest salinity in the cycle, usually occur at the top of the halite instead of in the normal middle position (Hite, 1968, p. 323). A strongly asymmetrical distribution of detrital quartz through the cycle can also be noted (Fig. 5). The lower dolomite unit (transgressive phase) contains nearly twice as much quartz as the upper dolomite unit (regressive phase). Later it will be shown how this pattern of quartz distribution can be an important factor in correlating facies between evaporite cycles and the carbonate cycles on the shelf.

Boundaries of Paradox cycles have been defined on the basis of rock units, generally the black shales but recently it was recognized that a more workable system of cycle boundaries can be made

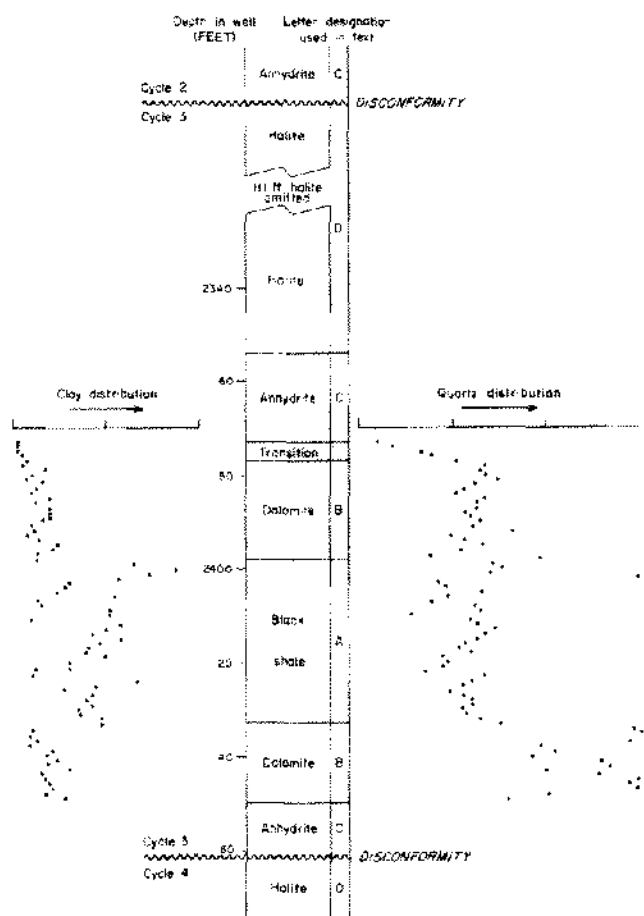


Figure 5. Typical evaporite cycle (cycle 3) of the Paradox Member. Relative distribution of clay and quartz, through the cycle, determined by X-ray diffraction analysis. Data from core hole located in sec. 25, T. 26 S., R. 20 E., Grand County, Utah.



if disconformities are used (Peterson and Hite, 1969). In the evaporite cycle the base of each halite unit forms a transitional contact with the underlying anhydrite (Fig. 7); however, the upper contact is very abrupt (Fig. 6). This sharp contact, at the top of the halite unit, is a dissolution surface or disconformity along which several feet of halite has been removed. These disconformities, which interrupt the chemical sequence, are the results of major rises in sea level and subsequent freshening in the evaporite basin. Using the disconformities as cycle boundaries, the order of units would be C, B, A, B, C, D. The change from transgressive to regressive conditions occurs somewhere near the midpoint of unit A so that the transgressive hemicycle is C, B, A, and the regressive hemicycle is A, B, C, D. Comparison of the transgressive and regressive hemicycles shows considerable condensation of the sedimentary sequence in the transgressive phase. According to Duff and others (1967, p. 178) this is a normal aspect of sedimentary cycles. A similar observation has been made by Sheldon (1963, p. 147), who concluded that in cycles of the Phosphoria Formation transgression was more rapid than regression.



Figure 6. Photograph of drill core showing sharp dissolution contact between coarsely crystalline halite and finely laminated anhydrite. This is typical of the upper contact of salt beds in the Paradox Member.

The presence of disconformities at the tops of halite units in the Paradox cycles was first suggested by Welsh (1963, p. 489), and has been documented since by drill hole data and by observations from mine exposures. The amount of halite removed along these disconformities is generally unknown; however, it is likely that at least 5 to 10

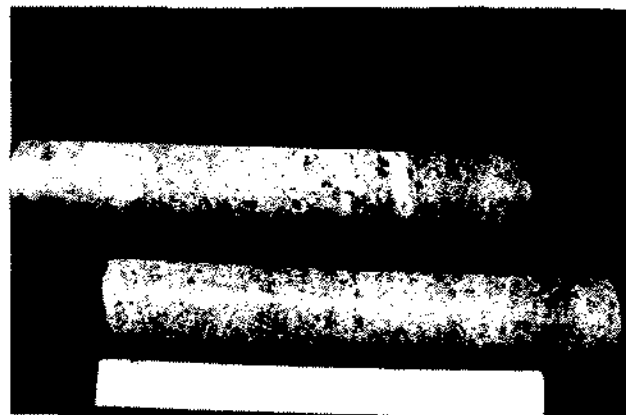


Figure 7. Photograph of a typical basal contact between a halite bed and underlying anhydrite of a Paradox evaporite cycle. The right-hand end of the upper drill core fits together with the left-hand end of the lower core. Note the gradual transition from massive light-gray anhydrite at the top left of the core into dark-gray halite on the right.

feet is missing. The disconformity at the top of cycle 5 is readily visible at various locations in the Texas Gulf Sulphur Co. Cane Creek potash mine near Moab, Utah (Fig. 8). Immediately overlying this disconformity is a thin zone of glassy anhydrite (Fig. 9) which probably represents the residuum formed when the underlying halite was taken into solution. Based on the average anhydrite content of the halite immediately underlying the



Figure 8. Underground view of abrupt contact (dissolution surface) between light-gray halite and overlying glassy dark-gray anhydrite (Fig. 9); pocket knife is positioned at contact. Contact forms the top of Paradox evaporite cycle no. 5. Photographed in Texas Gulf Sulphur Co. Cane Creek potash mine near Moab, Utah. (Photograph by O.B. Raup.)

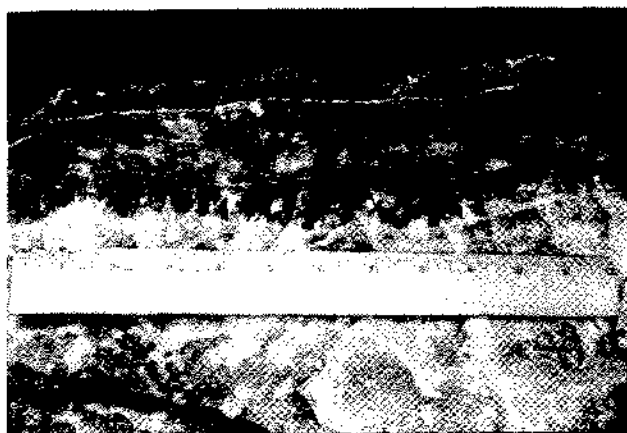


Figure 9. Closeup view of same contact shown in Figure 8. Note 1-inch-thick layer of glassy dark-gray anhydrite immediately above contact with light-gray halite.

disconformity, determined from insoluble residues, the glassy anhydrite layer represents the dissolution of about 10 feet of halite. This thickness compares favorably with local truncation of microstratigraphic units in the upper part of the halite and sylvite of cycle 5 as observed in the mine.

Disconformities at the top of cycles 3 and 4 can also be observed in the Cane Creek mine. In exposures along the incline, connecting the bottom of the mine shaft with the mine workings in the potash deposit in cycle 5, small folds in the halite units of each cycle are truncated by the overlying anhydrite layer of the next cycle (Fig. 10).

In the preceding description of the Paradox evaporite cycles, much emphasis was placed on the disconformity boundaries of the cycles. The importance of the disconformity in the facies relationships between basin evaporites and shelf carbonates is shown in the next section of this paper. The significance of unconformities, or disconformities, in relation to facies has been ably stated by Momper (1966, p. 90d) as follows: "Advocating a search for unconformities does not imply a denial of the existence of facies changes or an attempt to minimize the significance of facies concepts. Quite the contrary is true because correct identification of unconformities is essential to accurate interpretation of facies as well as rock units in general."

#### *The carbonate cycles.*

On the southwest shelf of the Paradox basin the carbonate cycles of the Hermosa Formation have been studied in great detail by numerous petroleum geologists. The discovery of petroleum in



Figure 10. Underground view in Texas Gulf Sulphur Company Cane Creek potash mine of a fold in light-gray halite truncated at dissolution surface by overlying dark-gray anhydrite; end of hammer at contact. Note truncation of thin crenulated anhydrite laminac in the halite underlying the dissolution surface.

several of these cycles has resulted in a relatively high concentration of drill holes and therefore detailed subsurface studies of lithofacies have been possible. In addition to subsurface control, excellent exposures of many of the carbonate cycles occur along the San Juan River near Mexican Hat, Utah, (Figs. 11, 12). Most investigations have been concentrated on the two most important zones of petroleum production, the Ismay and Desert Creek.



Figure 11. Photograph of carbonate cycles in the Hermosa Formation in the canyon of the San Juan River near Mexican Hat, Utah. (Photograph by M.O. Glenap.)

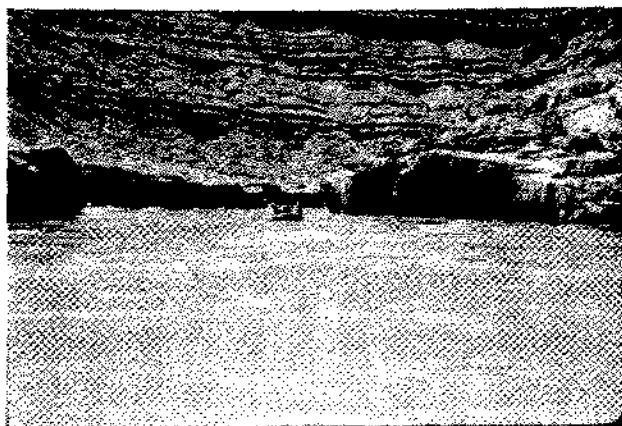


Figure 12. Photograph showing algal carbonate buildup facies of Ismay zone along the San Juan River. The algal beds are the dark undulating strata at river level. (Photograph by M.O. Gierup.)

The lithofacies of the shelf carbonate cycles is very diverse, and reflects combinations of chemical, clastic, and biogenic sedimentation. This complex pattern of sedimentation was primarily due to the relatively shallow-water environment of the shelf. Under these conditions only a minor change in sea level might drastically alter the environment at the depositional interface. If local topographic irregularities were present on the sea floor then the depositional environment of a rise could be markedly different from that of an adjacent depression. All of this could lead to abrupt lateral facies changes and dissimilarities in the vertical sequence between contemporaneous rock units. Because of the great variety of lithofacies, described by different authors at different localities for the same cycles, an attempt was made to roughly group the facies of each author into four categories (Table 1). Each facies from the shelf was grouped on the basis of similar lithic character and shown in approximate correlative relationship to the lithofacies of the evaporite cycles. From this comparison it can be noted that the black shale, silty dolomite, and anhydrite of the evaporite cycle have similar facies counterparts in the shelf carbonate cycles. The halite and potash of the evaporite cycle are represented by a totally different facies on the shelf consisting of an algal limestone formed primarily from the leaflike remains of the alga *Ivanovia*. Thus, as shown on Table 1, the boundaries of the facies groups represent time lines; however, several facies probably span these time surfaces. The contemporaneity of the various facies is

explained in greater detail in a later section of the report.

All the authors cited in Table 1 have proposed one or more idealized cycles involving the various lithofacies of the shelf. For example, Choquette and Traut (1963, p. 169) recognized (1) an evaporite cycle containing anhydrite and dolomite, (2) a normal-marine cycle with an algal buildup, and (3) a normal-marine cycle without algal buildup. They acknowledged that lateral transition from one type of cycle to another could take place in a few thousand feet. The descriptions of cycles differ also because some are based on intervals in the Ismay and others on intervals in the Desert Creek. In addition, Pray and Wray (1963) made their observations on the basis of surface exposures whereas all the others used subsurface data. Thus it is difficult to diagram the vertical sequence of facies in a "typical" cycle. Much of the emphasis of this paper is placed on explaining why certain carbonate cycles favored the development of an algal carbonate facies. For that reason the idealized cycle described here includes an algal buildup. The following sequence of lithofacies represents a synthesis of descriptions by other authors, and although this version is probably an oversimplification of the problem, it does include elements common to all the cycles.

#### IDEALIZED SHELF CARBONATE CYCLE

	Next cycle
Cap facies	disconformity
Buildup facies (algal limestone)	
Intermediate facies (silty dolomite and limestone)	
Euxinic facies (black, argillaceous, calcareous shale)	
Intermediate facies (siltstone and sandstone or very silty dolomite)	
Cap facies (pelletal-foraminiferal limestone)	disconformity
Buildup facies	Next cycle

As shown above, the carbonate cycle is bounded by disconformities. Disconformities in the shelf carbonate facies have been recognized and described in the subsurface and in measured sections along the San Juan River by Wengard and Matheny (1958), Welsh (1958, 1963), Elias (1963), and Pray and Wray (1963) but it is probable that some disconformities have been

Table 1. Lithofacies of the Hermosa Formation on the Southwest Shelf of the Paradox Basin, as Described by Various Authors, and the Approximately Contemporaneous Facies of the Inner Evaporite Basin

Reference	Shelf Area					Evaporite Basin
	Choquette and Traut (1963)	Elias (1963)	Gray (1967)	Peterson (1966)	Pray and Wray (1963)	Hite (this paper)
Lithofacies	Laminated carbonate boundstone	Black shale	Shelly mudstone	Black shale	Muddy algal	Black shale
	Shelly calcilutite		Laminated boundstone		Intermediate	
	Black shale		Black shale			
	Dark carbonate mudstone	Sponge	Crinoidal limestone	Sponge		
	Sponge-bearing calcilutite		Carbonate mudstone			
	Earthy dolomite	Quartz sandstone and siltstone	Earthy dolomite	Very silty	Quartz sandstone and siltstone	Silty dolomite
	Calcareous sandstone and siltstone		Evaporitic dolomite	Chalky to dense dolomite		
	Foraminiferal-pelletal limestone	Fusulinid	Foraminiferal-pelletal limestone	Foraminiferal-pelletal limestone	Cap	Anhydrite
	Buildup	Pelletal mud	Algal	Mound carbonate	Sparry algal (Ivanovia)	Halite and potash
	Anhydrite	Ivanovia	calcirudite breccia	Anhydrite	Anhydrite	

overlooked. In fact, all the carbonate cycles probably are bounded by disconformities. These disconformities may separate facies which are only slightly dissimilar, and the breaks in sedimentation can easily be overlooked. Recognition of some disconformities may come only after detailed mineralogic and geochemical analysis of the vertical sequence. The positions of the disconformities in the idealized cycle described here are different from those as interpreted by Elias (1963, p. 188) who places them at the top of the pelletal-foraminiferal limestones. The same eustatic control, effecting deposition in the evaporite basin, is

also in operation on the shelf. Previously it was shown how the initiation of a transgression creates an asymmetrical break in the depositional sequence of the evaporite cycle. If a similar depositional pattern exists on the shelf, as seems reasonable to expect, the disconformity should separate the initial transgressive phase from the underlying regressive phase. Using this concept the logical position of the disconformity would be between the pelletal-foraminiferal limestone (cap facies), which is interpreted here as representing the initial transgressive phase, and the underlying regressive phase of algal limestone (buildup facies).

### THE PARADOX BASIN MODEL

The facies relationships in the depositional cycles of the Paradox basin can best be explained through the use of models. However, to model the basin the paleogeographic setting of the region must first be established. Numerous authors, notably Wengerd and Matheny (1958), Fetzner (1960), Ohlen and McIntyre (1965), and Peterson (1966), have shown that the Paradox basin is bordered on the northeast by highlands of the Uncompahgre uplift and on the northwest (Emery), south (Defiance-Zuni), and southwest (Kaibab) by low-lying land masses (Fig. 3). Wengerd and Matheny postulated marine accessways at the northwest (Oquirrh) and southeast (Cabezon) ends and along the west flank (Fremont) of the basin. Elias (1963) suggested that the basin may have been completely enclosed except for two narrow straits which coincide with the Fremont and Oquirrh accessways of Wengerd and Matheny. Facies relationships within the Paradox basin suggest that none of these features, with the possible exception of the Cabezon accessway, were responsible for any significant ingress of seawater. There is some evidence of marine access to the basin through the Cabezon seaway during deposition of Paradox evaporites. However, Fetzner (1960, p. 1408) suggested that a clastic delta from the Uncompahgre uplift provided a sedimentary barrier across the southeast margin of the basin. Additional evidence of circulation barriers between the basin and the Cabezon seaway were found by Peterson and others (1965, p. 2087), who stated that "The Four Corners platform apparently underwent minor growth as a southwest-northeast positive-trending feature during Pennsylvanian time causing shallow-water conditions and shelf carbonate development to extend northeastward along the platform. The combination of the southwest-northeast projection of the shelf carbonate buildup on one side and rapid accumulation of deltaic deposits on the other caused the Paradox basin to be cut off effectively from the main seaway at the southeast." Along the southwest edge of the basin the facies belts within individual cycles tend to broaden, and extend convexly into the basin much like a chemical delta. Facies are distributed in order of solubility, with the least soluble facies in the outer belt and progressively more soluble facies basinward. If seawater were moving into the basin from the postulated Oquirrh seaway, then it is difficult to explain how relatively insoluble calcium carbonate could be carried across 200 miles of

saturated chloride brine and finally precipitated at the opposite end of the basin. On the southwest shelf of the basin stratigraphic markers retain their identity in a southwesterly direction through a carbonate facies for greater distances than in any other part of the basin. These relations suggest that the principal marine access was across this broad southwest shelf. Connections between the shelf and the open ocean may have been between the Kaibab and Defiance-Zuni uplifts or around the north end of the Kaibab uplift (Fig. 3).

The barred basin evaporite model, discussed in the first part of this paper, fits well with the lithofacies pattern and geochemical relationships observed in the Paradox depositional cycle. The operation of the Paradox model during a regressive and a transgressive phase of deposition (Fig. 13) can be described as follows:

A. Regressive phase (Fig. 13a). Sea level begins to fall sometime during the deposition of the black shale facies. Lowering of sea level brings about a proportionate decrease in reflux, and salinities begin to increase in the basin. The ratio of calcium ions in the influx layer to magnesium ions in the refluxing brine layer is less, and mixing at the brine interface, combined with mass action effects, causes precipitation of more dolomite than calcite. The increasing salinity within the basin depresses evaporation rates causing a reduction in volume of influx. With less water moving into the basin, there is a proportionate decrease in the amount of organic matter swept in, and the color of the sediment layer deposited is gray rather than black. As the regressive sea retreats across previously winnowed source areas the supply of detritus is reduced, and silt and sand-size particles predominate over clay minerals. Further lowering of sea level and increase in salinities brings about deposition of calcium sulfate and, finally, sodium chloride in the evaporite basin. Extreme lowering of sea level finally restricts the carrying capacity of the accessway to a point where reflux is halted, maximum salinities are achieved, and potash deposits form in the deepest part of the basin. Lack of reflux allows contemporaneous development of algal mounds or banks in the shallows on the shelf. The horizontal salinity gradient from open ocean to the distal end of the basin is strongly developed during this phase. Seawater, moving slowly into the basin across the long and somewhat circuitous accessway, is highly concentrated by the time it reaches the shelf. This warm,

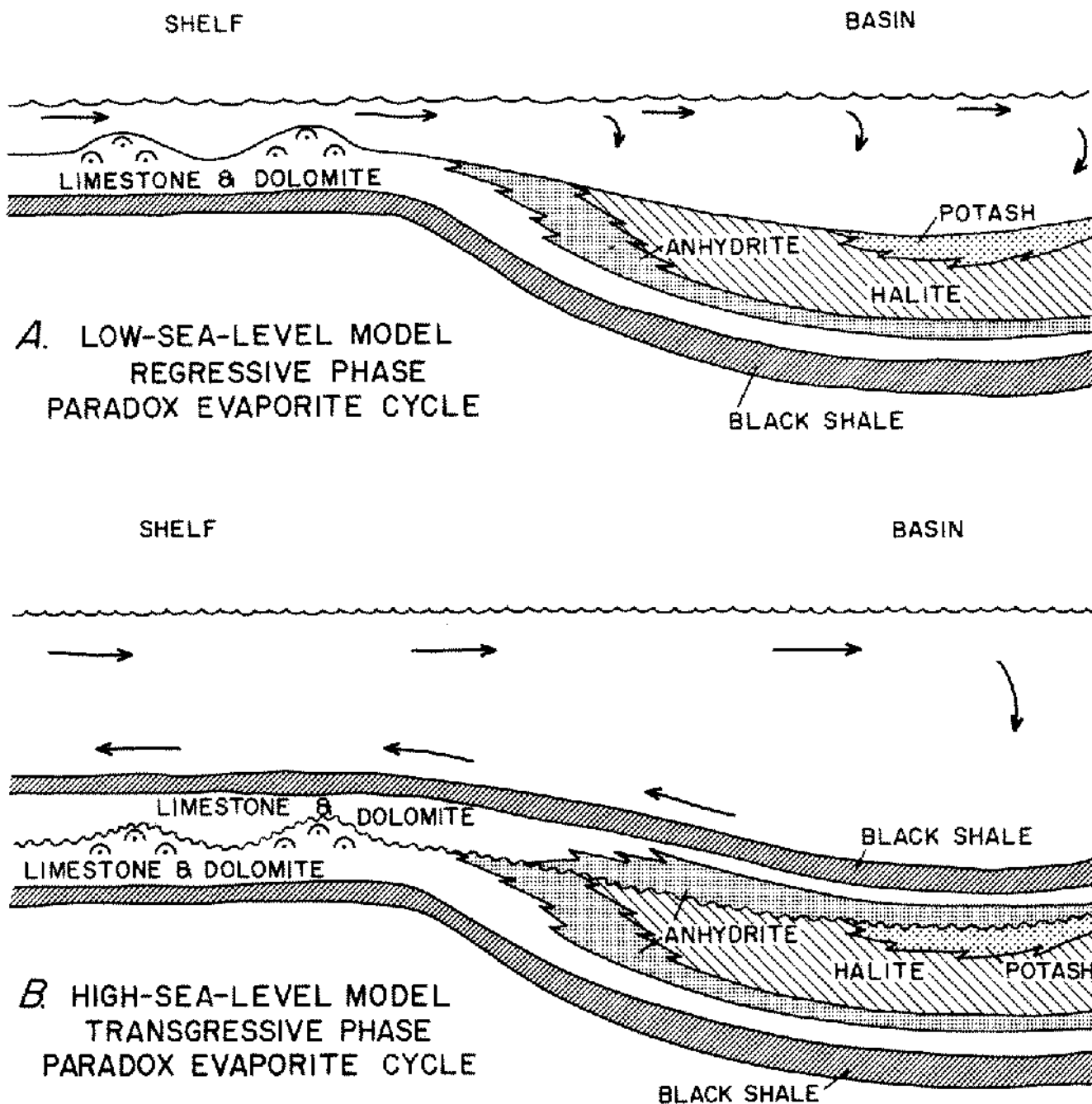


Figure 13. Depositional model of the Paradox basin during (a) the regressive phase and (b) the transgressive phase showing relationships of various basin and shelf facies. Wavy line represents disconformity. Symbol in the shelf limestone and dolomite represents algal mound development.

clear, briny water, carrying a constant supply of nutrients, provides the ideal environment for algal growth while the high salinities eliminate most other competitive forms. Because this current is also vertically stratified, calcium sulfate may

deposit in low areas surrounding the algal mounds. In summary, synchronous facies at the close of the regressive phase are (1) algal limestone, (2) dolomite, (3) anhydrite, (4) halite, and (5) potash.

B. Transgressive phase (Fig. 13b). The regressive phase of deposition is terminated by a relatively abrupt rise in sea level. With higher sea level the basin begins to reflux. The reflux layer of toxic brine moves out across the shelf area killing the algal growths. This interruption of sedimentation is represented by a disconformity in shelf area. Reflux creates a deficit in the basin salt budget which reduces salinities. Continued loss of salt by reflux undersaturates bottom brine layers, and corrosion of the previously deposited salt layer begins. The dissolution surface in the basin develops synchronously with the disconformity on the shelf. The first sediments of the transgressive phase on the shelf are foraminiferal-pelletal limestones which grade basinward into "earthy" dolomite, and anhydrite. Limestone pellets form as the result of mixing of the colder carbonate-charged influx layer and the warmer refluxing brine. With further rise in sea level, the corresponding increase in reflux of magnesium-rich brine from the basin results in deposition of most carbonate as dolomite. The strongly transgressing sea begins to churn up sand and silt from formerly emergent source areas. Silt-laden influx water rides across the heavier basin brine depositing extremely well sorted detritus throughout the basin. At maximum high sea level large quantities of marine plankton are swept into the basin along with clays and silts from the higher reaches of the source areas. The accompanying increase in reflux completely covers the shelf with a brine which is anoxic and rich in hydrogen sulfide. At this stage, reflux has extended the euxinic environment of the basin onto the shelf, and only extremely hardy organisms such as sponges survive. A layer of black, organic-rich mud blankets both the basin and the shelf at the culmination of the transgressive phase of deposition.

The model described here is very similar in construction to that of Welsh (1963, Fig. 148); however, it differs greatly in operation. In Welsh's concept of deposition during a Paradox cycle there is no lateral facies change, and the sequence of limestone, dolomite, anhydrite, and salt exist only in a vertical dimension (op. cit., p. 489). Welsh stated, "The writer's interpretation of the salt basin is one of shallow water in which the concentration reached and remained at saturation for the particular salt until the observed thickness of the individual evaporite unit was deposited (op. cit., p. 487)." Apparently, Welsh believed that each evaporite cycle was the result of filling up the evaporite basin, cutting off influx, and allowing complete desiccation of basin water so that first a layer of

carbonate, then sulfate, and finally chloride was deposited. Such a static system cannot explain beds of pure halite, several hundred feet in thickness, which are commonplace in the Paradox cycles. Under static conditions it would require a basin nearly 200,000 feet deep to deposit a halite layer 100 feet thick. Accordingly a static evaporite model is untenable with observed relationships in the Paradox basin.

Certain concepts of the Paradox model, as used in this paper, represent a radical departure from previous interpretations by Peterson and Ohler (1963), Peterson (1966), Peterson and Hite (1969) and Elias (1963). The black shale facies is interpreted here as representing deposition during culmination of the high sea level or transgressive phase of the cycles when basin reflux was greatest. A similar interpretation was made by Pray and Wray (1963, p. 216) for their sponge facies which is probably the shelf equivalent of the black shale facies of the evaporite basin. These authors stated "We suggest that these rocks were deposited in an anaerobic environment of but slight bottom turbulence. \*\*\* We suggest that this facies represent deposition below sill depth at times when the more saline stagnant waters of the Paradox basin to the east and north transgressed highest onto the shallower depositional province represented by the bulk of the Honaker Trail sequence." They also believed that this facies was deposited when water was deepest in the shelf area. The interpretation of depositional conditions during the development of the algal carbonates, as presented here, also differs from that of some of the previously mentioned authors. Evidence suggests that this facies represents conditions of low sea level and high salinities, and that it was deposited contemporaneously with halite and/or potash.

#### APPLICATION OF BROMINE GEOCHEMISTRY TO SEARCH FOR ALGAL BUILDUPS

Moundlike buildups of algal limestone constitute the major reservoir rock in the petroleum fields of the Paradox basin. Although nearly 30 depositional cycles are known in the area, each of which might be considered a potential host of an algal facies, only a few are known to contain buildups of this facies. Thus, it seems that certain cycles are favorable for the development of this facies and others are not. The models described in preceding sections of this paper suggest that the algal facies developed during the regressive phase of a cycle when morereflux was cut off. The key to exploring for a



algal facies, then, might be the determination of which cycles were characterized by a high rate of reflux and which had minimum or no reflux. One simple way of evaluating the favorability of cycles, such as those in the Paradox basin, is on the basis of presence or absence of potash deposits. If a cycle contains a potash deposit then it should have experienced relatively little reflux during that phase of deposition. In the Paradox basin, potash deposits occur in evaporite cycles 5, 6, 7, 9, 13, 16, 18, 19, 20, 21, 24, and 27 (Hite, 1961). Therefore, all these cycles might somewhere contain an algal limestone facies. At present a productive algal facies is known in cycle 5 (lower Desert Creek zone), and possibly in cycles 9 and 19. Production of petroleum has also been established in an algal facies for cycles 2 and 3 (upper and lower Ismay zone) which do not contain potash deposits. The cycles containing the Ismay mounds and perhaps others may have experienced periods of little or no reflux even though potash deposits were not deposited. A more precise means of determining the amount of reflux during the regressive phase of a cycle involves the use of bromine geochemistry. Without going into a detailed discussion of theory it is sufficient to say that normally the bromine content of chloride minerals increases in proportion to concentration of the parent brine. If the distribution of bromine in a salt bed shows no increase from base to top, then it can be assumed that bromine was being lost from the basin by reflux. If the bromine profile shows a rapid increase from base to top of the salt bed then reflux was minimal or absent. One of the best developments of an algal facies in the Paradox basin depositional cycle occurs in the lower Desert Creek zone which is equivalent to evaporite cycle 5. The halite of this cycle, which contains a potash deposit of economic importance, has a flat sloping bromine profile suggesting little or no reflux during the regressive phase of deposition (Fig. 14). In contrast the upper Desert Creek zone (cycle 4) carbonate facies contains a thick buildup of oolitic-pelletal-foraminiferal limestone, much like the initial transgressive facies of other cycles. The bromine profile of cycle 4 halite is almost vertical (Fig. 14). This probably means that the basin was refluxing and there was a close balance between inflow salt and outflow salt plus depositional salt. The refluxing brine during this period created unfavorable conditions on the shelf for algal growth, but did favor chemical precipitation of carbonates by interaction between the refluxing brine and inflowing seawater. At the same time agitation

by the overflowing and underflowing currents caused oolitic and pelletal structures to form.

The rate of reflux during the deposition of a halite bed is not always constant. The detailed bromine profile of cycle 2 halite (upper Ismay zone) by Raup (1966, Fig. 3) shows five periods of rapid bromine increase. Each one of these periods represents a low rate of reflux and a favorable time for algal carbonate development. Perhaps this helps explain why at least three separate intervals of algal carbonate have been identified in the upper Ismay zone (Gray, 1967, Fig. 7). Other cycles which show irregular bromine profiles may also contain more than one interval of algal carbonate.

Using the data of Raup (1966); Raup and others (1970), I rated the Paradox evaporite cycles for favorability of algal carbonate development. Each cycle, where data were available, was assigned a reflux index on the basis of the slope angle of the bromine profile for the halite unit of the cycle (Fig. 15). The slope angle was measured from vertical, and a large angle (flat slope) means a low reflux index. Conversely a small slope angle (steep or vertical slope) means a high reflux index. On the basis of reflux index, 14 Paradox cycles may be favorable for development of algal carbonates.

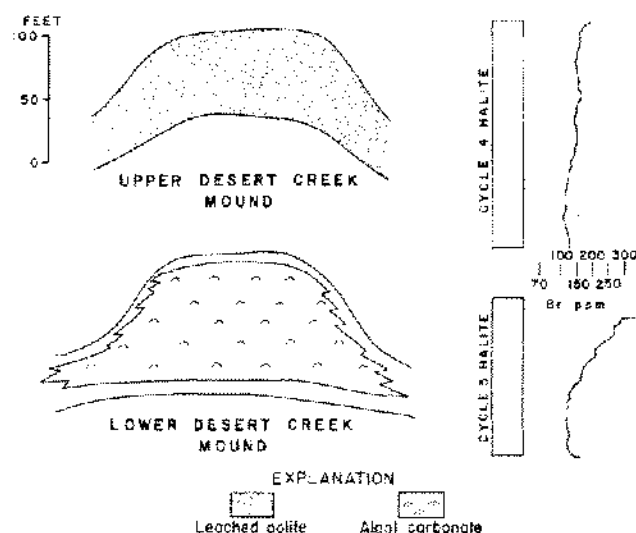


Figure 14. Comparison of bromine profiles of the halite facies of evaporite cycles 4 (upper mound, Desert Creek zone) and cycle 5 (lower mound, Desert Creek zone) to their contemporaneous carbonate facies on the shelf.



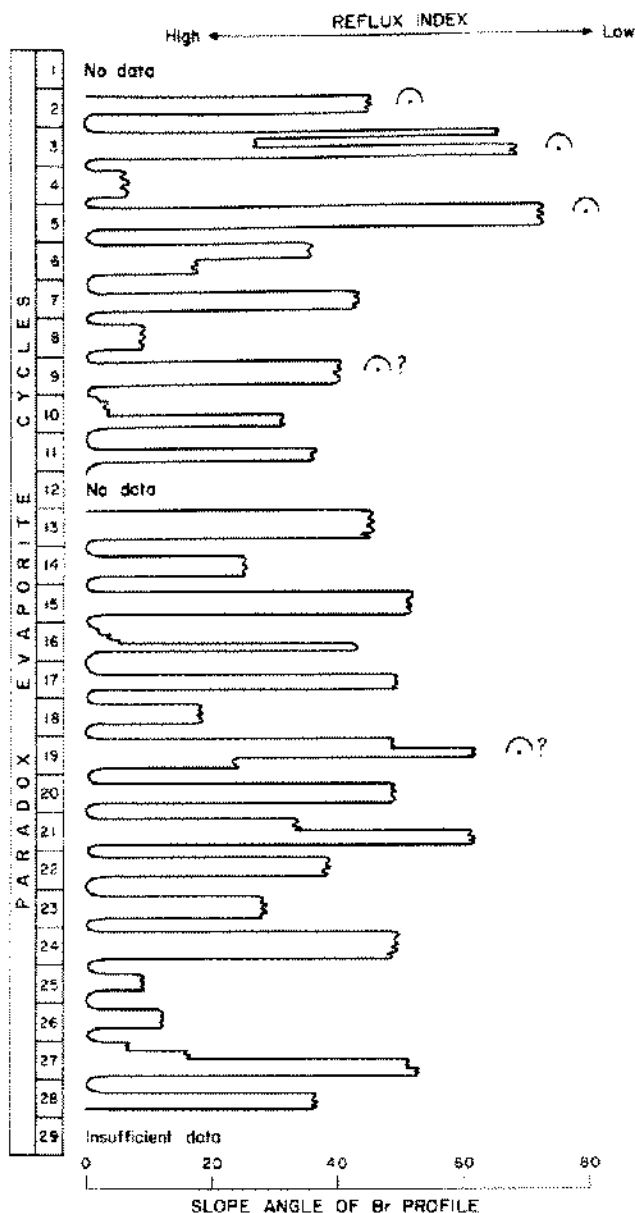


Figure 15. Index or degree of basin reflux during the deposition of the chloride facies of each Paradox evaporite cycle. Reflux index determined by slope angle of the bromine profile for each cycle. Symbol indicates cycles in which the presence of an algal buildup facies has been confirmed; queried where identification is uncertain.

These cycles, ranked in order of favorability starting with the most favorable, are 5, 3, 19, 21, 27, 15, 24, 20, 17, 2, 13, 7, 16, and 9. Cycles 17 and 16 had favorable indexes for a relatively brief period of deposition and if an algal facies is present in these cycles it probably will be thin. At present major developments of algal facies are known in

cycle 5 (lower Desert Creek zone) and cycle 1 (lower Ismay zone). A lesser development is known in cycle 2 (upper Ismay zone). Other possible algal developments occur in cycles 9 (upper Akah zone) and 19 (lower Barker Creek zone). The halite unit of cycles 19 and 21 are very thick and have very low reflux indexes; therefore, it is suggested that the carbonate facies of these cycles offer potentially important exploration targets for the petroleum industry in the Paradox basin.

The same relationships of an algal carbonate facies to evaporites might also be useful in another sense of exploration. In undrilled sedimentary basins algal carbonate buildups in exposure around the margins of the basin might indicate the presence of halite and potash deposits in the subsurface of the basin.

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