THE EVOLUTION OF AN INLAND SEA OF MARINE ORIGIN TO A NON-MARINE SALINE LAKE: THE PENNSYLVANIAN PARADOX SALT

SHERLYN WILLIAMS-STROUD

United States Geological Survey, Branch of Sedimentary Processes, Denver, Colorado 80225

ABSTRACT: The Paradox Formation has long been identified as having a marine origin. However, the magnesium sulfate-poor potash assemblage in the salt cannot beexplained by simple equilibrium evaporation of seawater. Dismutation of associatedarbonate rocks was the key to the initial deposition of seawater sulfate in the form of additional gypsum and anhydrite deposition, which yielded to the non-deposition of magnesium sulfate minerals and the precipitation of halite and carnallite. The economic-grade potash ore in several of the evaporite cycles occurs as hydromagnesite, which is only minor carnallite. The deficiency of magnesium chloride minerals indicates that the water chemistry was not merely the result of evaporation of seawater. Replacement fabrics and depositional textures as well as sedimentary facies relationships indicate probable shallow water deposition of saline minerals in the basin, and subsequent exposure of the basin margins. The chemistry of the evaporite micromorphology can be explained by an altered seawater brine mixing with meteoric water in the form of stream runoff and flash floods in an arid basin.

INTRODUCTION

The episodic incursions of seawater into the rapidly subsiding Paradox Basin alternated with evaporitic periods which resulted in the deposition of a cyclic succession of salt beds separated by clastic interbeds (Raup and Hite, 1992). Hite (1960) identified 29 evaporite cycles in the salt, consisting of beds of halite, separated by interbeds of anhydrite, silty dolomite and black shale. Recent drilling data indicate that there are possibly 33 salt-bearing cycles in the sequence. Eighteen of the 33 cycles contain potash, mostly in the form of sylvite (KCl) and some carnallite (KCl MgCl2 6H2O) (Hite, 1961, 1965), and almost no magnesium sulfate minerals. Previous workers have identified the Paradox Formation as a marine evaporite deposit based on the proximity of the evaporites to carbonate rocks of marine origin (Sloss, 1933; Hite and Buckner, 1981) and on the bromine geochemistry of the halite (Raup and others, 1970; Raup and Hite, 1978; Hite, 1983). However, the chemical paragenesis of the saline minerals present is inconsistent with a seawater origin (Harvie and others, 1980; Harte, 1984). The paucity of magnesium sulfate minerals in potash deposits has raised questions about the role of magnesium sulfate in the basin, including incongruent dissolution of carnallite (Garrett, 1970; Britsch, 1971), dolomitization (Shearman, 1968; Hite, 1983), bacterial reduction of sulfate (Borden and Bowden, 1964), and alteration of seawater by mixing with hydrothermal brines rich in CaCl2 (Hite, 1975; Harte, 1990).

The recognition of primary, or syndepositional, textures in evaporites is critical because saline minerals are readily altered upon even shallow burial (Casas and Lowenstein, 1989; Lowenstein, 1982). Excellent preservation in the Paradox salt of primary textures, such as cumulate halite textures and sericite gypsium (pseudoephemerally replaced by halite and anhydrite), provides clues to deciphering the sedimentary environment. The textural and depositional relationships of the carnallite and sylvite zones of the salt probably resulted from syndepositional precipitation from original brines, rather than secondary dissolution and recrystallization. Geochemical models suggest that the majority of solutes entered the basin from two sources. The first, as seawater, flown into the basin during saline level stand or percolated through surrounding carbonates, and the second, as meteoric water from streams, storms, and flash floods. Lithostratigraphic and petrologic evidence indicates that the sources of the two major water types were from opposite sides of the basin. A considerable amount of detrital carbonate was brought into the basin from the western and southern margins during the marine incursions. The periods of high sea stands more or less correlate with pluvial climatic phases when evaporite deposition ceased. The deeper water shales show an increased clastic input toward the southeast basin margin (Feinzer, 1960), and the apparent source area was the San Luis uplift (Hite and others, 1984). During most of the history of the salt depositing phase of the basin, the drops in sea level below the marginal topographic highs caused complete disconnection of the oceans from the brine in the basin, after which brine salinities increased by evaporative drawdowns, in a scenario similar to that proposed for the Silurian Michigan basin (Cercone, 1988). The environment of deposition of the evaporites can be characterized as a perennial saline lake.

LOCATION AND GENERAL GEOLOGY

The Paradox Basin is located in southeastern Utah and southwestern Colorado and contains extensive evaporite deposits of Middle Pennsylvanian age. The boundaries of the evaporite basin are usually determined by the extent of Paradox salt (Fig. 1). The basin is in the Colorado Plateau province, bounded on the northeast by the Uncompahgre uplift, on the east by the San Luis uplift, on the southwest by the Monument upwarp and Defiance Uplift, and on the northwest by the San Rafael Swell. The salt basin itself is an elongate asymmetrical trough, with the deepest part adjacent to the Uncompahgre fault line on the northeast basin margin. Wengard (1958) identified the uplifts and swells to the southwest and west as the basin shelf. The Uncompahgre uplift was a high to moderately high positive feature. Subsurface data along the Uncompahgre front indicate that the Uncompahgre fault was a Pennsylvanian-Pерmian low-angle thrust fault (Frahme and Vaughan, 1983). The asymmetrical deepening of the basin near the northeast border is interpreted to be the result of a basin foredeep related to the thrusting (Johnson and others, 1991).
The distribution of Pennsylvanian sedimentary facies and structural elements in the Paradox Basin is shown in Figure 2. The Uncompaghre Uplift is postulated to have been a structure of moderately high to high relief (Mallory, 1975; Johnson and others, 1991). Seawater access into the deeper basin is inferred to have been through the moderate to low relief platform to the southeast, west and northwest (Hite, 1970).

The Paradox Formation overlies the Pinkerton Trail Formation, and is in turn overlain by the Honaker Trail Formation. The three formations constitute the Hermosa Group (Fig. 3). The Honaker Trail Formation is similar in lithology to the Pinkerton Trail Formation, consisting of gray to reddish-gray finely-grained to coarse-grained limestone with black and red chert, and reddish-gray to buff-gray carbonaceous sandy siltstones. More detailed descriptions of the lithology and stratigraphy of the carbonate rocks can be found in Clair (1952), Wengerd and Strickland (1954), and Wengerd (1958).

**LITHOLOGIES AND SEDIMENTARY FACES OF THE PARADOX FORMATION**

**Basinal Evaporite Facies**

Wengerd and Strickland (1954) and Wengerd (1958) divided the Paradox Formation into three members. The lower member is a complex of arkosic granulite, sandy and gypsiferous siltstones in the southeastern part of the basin. To the southwest, it consists of dark gray shales, gray porous dolomite, and gray cherty limestones that grade into interbedded black shale, siltstone, gypsum and dolomite toward the central part of the basin. The upper member is similar in lithology to the lower member with penesaline depositus in the central basin and biotromal-biothermal dolomite and limestone, gray shale, and silty dolomite on the southwest shelf area. The middle, or "salt member" (Wengerd, 1958) contains interbedded silty dolomite, anhydrite, black shale and halite, with or without potash. The limestone facies on the shelf is considered to be contemporaneous with the salt (Wengerd and Strickland, 1954; Hite 1970; Hite and Buckner, 1981). The original maximum depositional thickness of the salt facies is estimated to be ~1,000 m, pinch- ing out to zero on the margins of the basin.

Textures in the halite beds of the evaporite facies range from euhedral cumulates with grain sizes of a few tenths of a millimeter, bottom growth halite crusts with crystal sizes up to one half centimeter in diameter, draped by fine grained anhydrite, to mosaic fabrics found in the tops of the potash-bearing halite where the rock is more than 50 percent pyrite. Potash is present in the salt over a large extent of the salt deposit (Fig. 1). The sylvite zones occur in the tops of the halite beds, and are commonly red due to hematite inclinations (Raup and Hite, 1991a, 1991b). The thicknesses of the individual salt beds range from 7 to 270 m in the center of the basin to zero on the basin flanks. Because of flowage of salt in the basin center, salt in the anticlines has increased in total thickness to as much as 4,700 m.

The use of each evaporite cycle is interpreted to represent the beginning of a period of influx of seawater, or a freshening of the brine in the basin due to sea-level rise and climatic changes that resulted in increased precipitation.
The presence of silt in the dolomite is attributed to reworking of sediments from the basin margins and the transport of fine grained detritus via low-density inflow over the high salinity brines in the basin (Hite, 1970). Hite (1965) suggested that the dolomite, which is mostly microcrystalline but also occurs as rhombs that appear to be detrital, was a primary precipitate. Erosional surfaces and evidence of subaerial exposure found in the marginal carbonates are found in outcrops of the marginal carbonates along the Flomaton Trail, and in cores through the carbonate mounds facies of the basin (Peterson and Hite, 1969, Goldhammer and others, 1991). I suggest that the silty dolomite beds are a diagenetic deposit which is gradational in member to terrigenous clastics in the southeastern part of the basin.

The average thickness of the shale beds is about 10 m. Most of the interbed sequences in the 32 cycles contain some black shale beds, but they cannot always be correlated. There are exceptionally thick black shale units which are present throughout the basin that have high organic carbon content, nearly 13 percent in some beds (Hite and other, 1994). They have a distinctive signature on gamma-ray logs and have been given specific names by the petroleum industry (Fig. 4). The shales, together with the lithologic sequence of the interbeds of each cycle, serve as marker beds for identification of stratigraphic units within the sequence.

**Shelf Carbonate Facies**

Where they are not separated by the evaporite facies, the Pinerton Trail and Flomaton Trail Facies are not distinguished from each other and form the Hermosa Formation. On the lower shoals to the southwest, the Hermosa Formation consists of interbedded black shale, dark-gray (Hite and Buckner, 1981). After sea level fell again, evaporite concentration resulted in precipitation of evaporite minerals. The base of an "idealized" cycle (Peterson and Hite, 1969) is an erosion or dissolution contact between authigenic and an underlying flint bed. The authigenic grades upward into silty dolomite, shale (which ranges from black to tan or gray in various cycles), dolomite, anhydrite then halite.

Anhydrite occurs in beds that are fine grained and laminated, nodular, or pseudomorphous after sedimentary gypsum. Pseudomorphs of sedimentary gypsum are also replaced by halite. Anhydrite is also present in beds with millimeter-scale laminae defined by carbonate mud, or in beds with wave to laminae-parallel laminae containing large amounts of silty material.

The fine-grained dolomite usually shows little to no visible texture, though some beds are faintly laminated, are interlaminated with shaley or anhydritic layers, or show laminations disrupted by bioturbation. Some silica fossil detritus, such as diatoms and sponge spicules are found in the black shales, but except for polytomorphs which are well preserved in the salt and the black shale (B. F. Bueker, 1991), the other lithologies in the evaporite facies are anhydrosilicious.
Halite

The most distinctive texture found in the halite beds is the halite/anhydrite couplets composed of layers of euhedral halite crystals draped by fined grained anhydrite (Fig. 5A). The anhydrite drapes also contain clays and carbonates. The largest halite crystals are about 0.5 cm across, with slight vertical elongation indicating their formation as bottom growth crusts (Fig. 5B). In some places there is a sharp boundary between the top of a layer of halite crest fabric containing anhydrite drapes and the bottom of a layer of nearly pure halite. This indicates that some dissolution preceded precipitation of the halite cubes of the next crust layer. The euhedral texture of halite cubes is not preserved where there is no anhydrite drapes over the halite grains. In the potash-bearing salt of cycle 5, sylvite layers alternate with layers of fine grained anhydrite plus clay and carbonate (Fig. 6). In cycle 13 sylvite, halite crystals are found as poikilitic inclusions floating in larger anhydral syl- vite crystals (Figs. 7A, 7B). The texture of the sylvite in potash ore from cycle 5 is an anhedral mosaic (Fig. 7C). The layers of halite sandwiched between the sylvite zones and the anhydrite laminates consist of smal (0.1 mm), fluid inclusion-rich halite crystals (Fig. 8). In the halite of cycle 10, the crystal sizes are much larger than the crystals in the other cycles, on the order of 1 to 2 cm (Fig. 9A). Fluid inclusion banding of chevon halite is found in some places, but the texture appears to be largely recrystallized (Figs. 9B, 9C). Patches of clear halite with black muddy inclusions are found adjacent to cloudy halite.

Anhydrite

Anhydrite and halite pseudomorphs after swallow-tail septane gypsum crystals are common in anhydrite layers di-

Marginal Clastic Facies

The northeastern margin of the evaporite basin consists mainly of a thick wedge of arkosic sediments derived from the Uncompahgre Uplift. Although the foredeepening of the basin along the Uncompahgre front trapped most of the sediments in the trough adjacent to the northeast margin (Johnson and others, 1991), arkosic debris was carried westward almost completely across the basin at the end of Pennsylvanian time and during Permian time (Peterson and Hite, 1969).

The clastic facies of the Paradox Formation on the south- east basin margin was interpreted by Fettzer (1960) to be part of a large fan-delta complex, which he named the Silver- ton fan delta. Spoerh (1970) defined 19 depositional cycles in the complex, and suggested that their cyclic nature was related to eustatic sea-level changes. The source area for the Silverton fan delta was probably the San Luis Uplift, which, as indicated by their thickening toward the southeast, is also the source area for the black shale facies.

MINERALOGY AND PETROGRAPHY OF THE EVAPORITE FACIES

Petrographic examination of the rocks from drill cores in the evaporite facies of the Paradox Formation reveals a wide variety of textures. Cores drilled in Utah through Cany Creek Anticline (S25, T26S, R20E), Staefer Dome (S15 T27S, R20E) and Gibson Dome (S21, T30S, R21E) were studied, and the clastic interbed relationships in cycles 4 and 5 were compared. The locations of the drill cores are shown in Figure 1.
nated anhydrite show a horizontal preferred orientation. In some beds, the fine-grained, laminated anhydrite grades upward into nodular anhydrite, then to silty dolomite or black shale.

Figure 11A shows an example from the Shaler No. 1 core of selenite replaced by fine-grained anhydrite in which the gypsum crystal morphology is well-preserved. Nodular anhydrite commonly occurs in the silty dolomite of each cycle (Fig. 11B). Nodules can form discrete layers comprised of feint tufts of anhydrite crystals with small amounts of included silty or dolomitic material.

The nodular anhydrite that occurs in shale beds (Fig. 11C) usually shows a more developed "chicken wire" texture, with some horizontal relict bedding traces. More detailed descriptions of the stratigraphy and lithology of the Cane Creek and Shaler Dome cores can be found in Rupp and Hirt (1991a, b, 1992).

**Dolomite**

The dolomite is fine-grained and faintly laminated in some places, but generally is structureless. There are some casts of what appear to be recrystallized fossil debris. Bioturbation and possible microbial laminae are present in some silty dolomite beds. The interbed sequence of cycle 4, of the D.O.E. Gibson Dome No. 1 core contains a silty, anhydritic dolomite bed with laminations showing evidence of extensive bioturbation (Fig. 12). The color in the silty, anhydritic dolomite ranges from gray near the top to brown and dark gray at the bottom, where it grades into a black shale. Grains of quartz silt are dispersed throughout. The dolomite is usually gradational to laminated anhydrite and/or black shale.

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**Fig. 7.** Photomicrographs of halite/sylvite rock. Photomicrographs of cycle 13 potash shown of (A) euhedral halite grains (b) in sylvite (C). (B) halite grain enclosed by sylvite; and (C) mosaic sylvite texture from cycle 5 potash mine ore sample. Scale bar = 1 mm for all photographs.
Shale

The shale beds that occur as marker beds are brownish-black to black, slightly lititic, calcareous, and highly argillaceous. In places the black shale shows millimeter-scale lamination. The sparse fossils found in the beds include trachichopi, calcareous bivalves, conodonts, and a few fish remains. Palynoforms are found in the black shale, as well as in the biotite and silty dolomite. The lower part of each black shale unit has a substantial amount of terean quartz and siliceous, and contains inorganic amounts of dolomite toward the top where, in most cycles, it grades into a silty dolomite (Hite and Backer, 1981; Rupp and Hite, 1992).

Some shale beds are above or below nodular ashy shale with a black shale matrix. Figure 13 shows a portion of core from cycle 21 in the GD-I hole. The shale bed shown is just above the nodular ashy shale in Figure 13C. The layering is disturbed, with possible rip-up clasts (Fig. 13A), and mud cracks new filled with halite (fig. 13B).

Exposures of gypsum and black shale on the southeast shelf of the Paradox Basin at Homest Mountain near Ourang, Colorado, show alternating centimeter-scale gypsum and silty layers (Fig. 14). The gypsum occurs in beds which are nodular to fine-grained massive to laminated. The exact cycle in which this particular gypsum occurs cannot be determined from the outcrop, but it probably correlates to the upper middle part of the Paradox Formation (K. J. van der Wagt, pers. commun., 1991). The cratic contacts between the different lithologies are usually abrupt. The texture of the gypsum is recrystallized and nodular, and there are no saline crystals or pseudomorphs. Reflect laminations can be seen in the nodular beds. The gypsum here has probably rehydrated from secondary anhydrite after exposure to meteoric water.

Environments of deposition

The origin of the Paradox Formation has been attributed to evaporite deposition in a restricted marine environment (Hite, 1970, 1983) and to playa salt deposition in a deep, closed basin (Kendall, 1987, 1988). There is evidence for the existence of both of these depositional end members in the Paradox basin (Fig. 15). The high content of clastics in the dolomite or carbonates in the shales and siltstones suggests deposition in a marine environment, but where the meteoric water that flowed into the basin as rain-runoff from the major uplift greatly influenced the character and composition of the basin waters. Wengard and Strickland (1954) first suggested that the biorthms which are visible in the San Juan Canyon at the Homaker Trail locality acted as the principal barrier that caused the Paradox Basin to be cut off cyclically from normal seawater Harde and others (1981) define a perennial saline lake as a surface body of brine that persists for many years (e.g., hundred or thousands) without drying up. In the Paradox Basin, the halite beds alone represent a depositional period on the order of thousands of years, because the majority of evaporite deposition probably occurred in an environment that is most accurately described as a perennial saline lake.

The sedimentary structures observed in the Paradox basin cores are both primary and diagenetic. The halite cumulative textures, sub-brittle siltstone crystals on a horizontal substrate, and tine laminated ashy shale and shale are all indicators of subaqueous deposition. Absent brine depth cannot be determined from the textures alone, but many of the textures, such as the bottom growth halite crust fabrics, and the swallow-tail siltstone gypsium, in the evaporite bed indicate that the environment of deposition was probably relatively shallow water.

The position of the laminated anhydrite at the erosional contact with the underlying saline beds indicates a sudden lowering of salinity of the basin brines, due to marine transgression and perch the beginning of a parval climatic phase (Hite and Backer, 1981). Only a small fraction of the halite is dissolved, because in the beginning of the rise of sea level, the seawater supplied to the basin contained an intermittent outflow, possibly from storm surges over the barrier. A relatively thin layer of seawater covered the brine after each influx, which then evaporated and precipitated a layer of gypsum. The first one or two centimeters of fine laminated anhydrite that mark the sharp
contact at the base of a cycle could be a residue formed by dissolution of halite in the halite/anhydrite couplets, as was suggested for the Palo Duro Basin evaporite cycrns (Fraccasso and Huyorka, 1986). The residues formed when the brine became undersaturated with respect to halite after repeated seawater influxes, followed by dissolution of halite until the bottom brine became saturated and prevented fur-

![Image of halite dissolution](image)

then halite dissolution. R. J. Yee (pers. comm., 1991) estimates that as much as 1 m of halite dissolves at the top of each bed.

Gypsum and anhydrite structures in the Paradox basin provide the best record of environmental indicators of the rock types present. The nodular anhydrite texture found in some cores usually occurs above and/or within a silty dolomite. The silty dolomites, which were probably brought into the basin by periodic floods of seawater from the west and southwest, were deposited on top of gypsum crystals growing on the bottom of the water body. Discrete layers
of nodules could have formed from dehydration of bottom-growth selenite crystals when lake salinities increased periodically to the anhydrite stability field. The very well preserved pseudomorphic textures of bottom growth selenite in silty dolomite in the Gibson Dome 1 core is a possible precursor texture for the layered nodular anhydrite (Fig. 12B). This one-centimeter layer of anhydrite after gypsum is only a few centimeters below a halite bed, and it is possible that in this example, the heine did not stay in the stability field of anhydrite long enough to precipitate additional calcium sulfate and the intrasediment growth texture of anhydrite nodules did not develop. Dehydration of selenite to anhydrite probably occurred after lithification of the silty dolomite, thereby accounting for the preservation of the selenite crystal morphology.

In the selenite beds that are gradational to halite, replacement of selenite gypsum is by both anhydrite and halite. Selenite occurs as layers of millimeter to centimeter-sized vertically oriented gypsum crystals (now replaced by anhydrite and halite) growing from a common substrate of fine-grained anhydrite in the upper anhydrite bed in the cycle 4 interbed of the Shafer No. 1 core. The grain size of the selenite pseudomorphs gradually increases to centimeter size toward the top of the anhydrite bed. Primary bedded selenite of this type is found throughout the Upper Miocene Sediments in Sicily (Hardie and Eugster, 1971; Schreiber, 1988), and in the Holocene gypsum salina deposits in south Australia (Warren and Kendall, 1985). The environment of deposition was probably shallow, such that wind-induced mixing could contribute to continued bottom growth of the selenite with progressive evaporation. Selenite bottom growth is observed in shallow water environments such as Lake Assal in the Danakil Depression, Djibouti (Schreiber, 1988), in the shallow lagoon deposits of Marion Lake in South Australia (Dickinson and King, 1951; Crawford, 1965), and in the modern Persian Gulf (Jilling and others, 1965). The replacement of the larger selenite crystals near the tops of the gypsum beds by halite was probably syndepositional to
HIGH SEASTAND

\[ \text{carbonate mud} \rightarrow \text{silty mud} \rightarrow \text{silty carbonate mud} \]

BEGIN REGRESSIVE PHASE

\[ \text{bioherms} \rightarrow \text{carbonate mud} \rightarrow \text{silty mud} \]

BEGIN EVaporative DRAWnDOWN

\[ \text{subaerial exposure with periodic wetting by seawater overflows} \]

\[ \text{subaqueous saline precip.} \rightarrow \text{seawater seepage as groundwater overflows} \rightarrow \text{groundwater seepage of water of marine origin} \]

CLOSED BASIN SALINE LAKE STAGE

\[ \text{to alluvial fans} \rightarrow \text{groundwater seepage of water of meteoric origin} \]

BEGIN TRANSgressive PHASE

\[ \text{sedimentation of carbonate sheet} \rightarrow \text{Ca-sulfate precip. by brine mixing and evap. concentration} \rightarrow \text{fine-grained laminated Ca-sulfate} \]

TRANSgressive PHASE / HIGH SEASTAND

\[ \text{ooiIes} \rightarrow \text{carbonate mud} \rightarrow \text{black shale} \]

FIG. 15.—Stages in the depositional environment of the Paradox basin, starting with high sea-stand and open communication with the ocean (A), through regressive phase (B), and subsequent evaporative drawdown (C) in the basin to closed-basin, saline lake stage (D). Marine transgression during saline lake stage gradually fills basin with lower salinity water (E) until open communication with ocean is again established with the next high sea-stand (F).
very early diagenetic, and occurred when halite saturated brines that were undersaturated with respect to calcium sulfate reacted with the previously precipitated gypsum.

The halite/anhydrite couplets in the halite beds vary in thickness throughout the halite bed, with thicknesses between anhydrite partings ranging from 20 cm to 1 or 2 cm. The fine-grained anhydrite drapes appear to contribute to the excellent preservation of the bottom-growth crust fabric of vertically elongated halite crystals. Halite crusts have been observed in many other ancient evaporite deposits (e.g., Lowerstein, 1982; Hardie and others, 1983; Lowenstein and Spencer, 1990). The crust texture does not imply any maximum or minimum depth, but their position in the sequence above the zeolite bottom growth textures, and the fact that a mixed brome column is required in order to promote bottom growth, suggests that they too were deposited in a shallow brine.

In individual halite beds, the texture commonly grades upward from the primary sedimentary texture of the mud to a more texturally uniform millimeter-sized sylvite and halite crystals. In the potash ore zone of cycle 5 in the Paradox Basin, the sylvite is sandwiched between two halite layers, which in turn are sandwiched by anhydrite laminite. In the Oligocene potash deposits in the Rhine Graben, primary, cemented-size chevron halite is found undisturbed by millimeter-sized crystals of sylvite with an equigranular mosaic texture (Lowenstein and Spencer, 1990). Millimeter-sized cubes of halite with primary fluid-inclusion bands occur in the sylvite layers, indicating that this texture is either primary, or that the sylvite was precipitated as a very early cement.

In cycle 13 in the Shafer No. 1 core, a fine-grained halite cumulate layer that overlies the anhydrite laminite (Figs. 6A, 8) thin over a large sylvite crystal (Fig. 7B). The cumulates were formed when the evaporation of a peritidal brine body resulted in the precipitation of small cubes of halite at the air-brine interface. As the crystals grew and the surface tension of the brine could no longer support them, they would founder and fall to the bottom of the water body. The gradation of textures from mostly halite to sylvite, with individual halite grains floating poikilitically in sylvite suggests an original precipitate of halite crust where void space was filled with sylvite cement. Precipitation of halite on top of the sylvite layer resulted from reduction in brine salinity at the surface of the brine body with maintenance of a sylvite-saturated brine at the brine-sediment interface. This is consistent with subaqueous precipitation of salts within a periodically stratified perennial brine body, similar to the interpretation given by Lowenstein and Spencer (1990) for the Rhine Graben. The lack of a well-defined crystal-cumulate texture in some of the sylvite layers near the top of the cycles in the Paradox Basin may have resulted from dissolution and reworking near the beginning of the next marine transgression.

Figure 15 shows the sequence of events that could have lead to cyclic deposition of evaporites in the Paradox basin. After a sea-level drop, the water in the basin no longer has open circulation with the ocean (Fig. 15B). Meteotropic water, which was also supplied to the basin during high sea level, would have a more important influence on the brine chemistry during the closed-basin phases. Evaporative drawdown lowers the water level and reduces the areal extent of the brine (Fig. 15D). Precipitation of halite from the air-brine interface results in the accumulation of halite cubes on the sediment-brine interface. Intermittent influxes of seawater into the basin increase in volume and frequency during the transgressive phase, gradually raising the basin brine level until it is the same as sea level, and open communication with the ocean is re-established (Figs. 15E, F).

PERENNIAL SALINE LAKE ENVIRONMENT

Halite and anhydrite are important minerals in both marine and non-marine evaporite deposits, and their presence does not preclude a non-marine origin (see Hardie, 1984, p. 195). Likewise, the thickness of a halite deposit is not necessarily an indicator of marine origin, as shown, for example, by the several thousand meters of halite and anhydrite found in the Dead Sea (Zak and Bentor, 1972). The Paradox basin was probably open to seawater for part of its depositional history. However, it may not be possible to establish a horizontal salinity gradient in an open basin into which seawater flows over a shallow sill, which would result in concentration to halite saturation at the distal end of the basin. It is more likely that complete disconnection from the ocean may be required to reach not only halite, but perhaps also gypsum saturation (Lucia, 1972; Shaw, 1977).

In the closed basin phase of deposition in the Paradox Basin, surface inflow of seawater is cut off, but solutes would be supplied to the basin via meteoric precipitation, river flow and floods, and groundwater. A large portion of the saline brines in the basin could have been marine derived, but seawater percolating through permeable carbonate rocks would have reacted with the rock until it entered the basin as ground water with a composition which was no longer that of seawater. After sea level dropped below the level of the carbonate shelf forming marginal highs, the rate of inflow into the basin was less than the rate of evaporative and evaporative drawdown resulted. The resulting salination of the basin from the ocean created a perennial saline lake which persisted until the next rise in sea level. If evaporite deposition occurred during a closed-basin stage accompanied by exposure of the marginal carbonates, then the halite and the carbonate deposition is no longer contemporaneous. Figure 16 is a reinterpretation of the cycle boundaries shown in Hite and Bowker (1981), which counts for non-deposition of carbonates while evaporites were being precipitated in the basin.

The black shales, which probably represent the extent of the Paradox Sea at the highest level and lowest salinities, grade into red and greenish-black arkosic siltstones and coarse-grained clastics toward the major uplift areas (Wendt and Stickland, 1954; Peterson and Hie, 1969). The presence of pyrite and the high-organic content of the shales suggest surface reduction by microorganisms, which resulted in the development of anoxic environment in the clays within the evaporite facies. Though the presence of anoxic bottom waters is usually attributed to deep-water environments, black sulfurous muds are found in many modern examples of shallow perennial saline lakes, such as the
Fig. 16.—Correlation of measured section from Hite and Buckner (1981) and interbed sequences in cycle 4 of Delhi-Taylor Cane Creek No. 1, Shafer No. 1 and D.O.E. Gibson Dome No. 1 cores.
Great Salt Lake in Utah (Eardley, 1938; Hardie and others, 1981), indicating that deep water is not required for their development.

The coarser sediments along the northwestern margin of the Paradox basin are alluvial fan deposits from the Uncompahgre uplift, a region that represents a major source of meteoric water inflow to the basin. Hise and Buckner (1981) described cores in Salt Lake northwest (Paradox Basin) contain some of the coarsest deposits and suggest that their source could be storms or floods from the Uncompahgre Uplift. The sandstones have graded bedding, poor sorting, small-scale cross laminations, and mole mounds, with cross laminae, accented by concentrations of clay. Also found in the sandstones are mafic nodules of volcanic origin and thin clasts of gray shale. Hise and Buckner (1981) interpreted these sandstones as turbidites. However, studies of modern saline lakes and their subenvironments (Hardie and others, 1981) describe the clastic deposits from the deep mudflat subenvironment of saline lake basins with many of the same features found in the Salt Lake core.

The effect of the meteoric water input on the brine chemistry was more pronounced during the drawdown phases when salts were precipitated. Estimates for rates of deposition of various lithologies within the evaporite facies (Hise and Buckner, 1981) suggest that the salt precipitating phase occupied the shortest interval of geologic time, on the order of thousands of years for each halite bed. Limiting the analogy to the Paradox Formation only, the depositional environments found in the Great Salt Lake correlate very closely with the Paradox depositional environments. The Wasatch Mountains in Utah serve as the catchment for a plentiful supply of meteoric water into the Great Salt Lake via the Bear, Jordan, and Weber Rivers. When the lake level is low, precipitation of halite occurs. Thermobromic carbonate halite beds are formed on the east side of the Great Salt Lake, and surrounding the lake are dry mudflats that originated as bottom sediments when the lake level was high. When the lake level is low, the carbonate biomonos and oolitic shells become subaerially exposed. Periodic flooding into the lake from meteoric water and evaporative concentration produce brine layers, and these contribute more solutes to the lake. The lake, itself is shallow, (maximum depth ~10 m), perennial and stratified. The Paradox basin was bounded on the northeast by the high relief of the Uncompaghré highlands, and its catchment supplied meteoric water into the basin via the river route that passed through the Silverton fan delta. Carbonate biomonos formed on the shelf margins when the water level was high, and after evaporative drawdown, the biomonos were exposed and dry mudflats formed from former lake bottom sediments. Silty detritus indicates a high clastic input into the Paradox Basin, and the depositions features in the halite and gypsum indicate shallow water.

Although the Great Salt Lake contains many environmental features that make it a good process analog for the depositional environment of the Paradox Formation, the Great Salt Lake is more than 1000 km from the sea and the solute composition of the waters would lead to precipitation of minerals that are generally recognized as characteristic of continental evaporite deposits, such as the sodium sulfates, nitrates (NaNO₃, KNO₃) and natrium (Na₂SO₄). The potassium-rich composition of the Paradox Formation, the presence of carnallite, and a small amount of magnesium sulfate minerals in at least one cycle, indicate that the Paradox Basin may have been a saline lake/sea with marine influence.

The sediments of the Danakil Depression in Ethiopia are a modern example of an evaporite deposit that originated from seawater, but which now precipitate minerals which suggest that the depression is under strong influence from hydothermal and meteoric waters (Holwerda and Hutchinson, 1968). Potash-bearing evaporites are found in a depression more than 100 m below sea level, formed by an extensional triple junction between tectonic plates. The depression is separated from the Red Sea by carbonate highlands formed by fault-block tilting from extensional tectonic. Seawater percolating through the coastal carbonates to the east and meteoric water runoff from the Balasa Mountains to the west are, at present, the main sources of solutes for the sylvite-precipitating brines found in the basin. Of the three potash-bearing members of the Houston Formation in the Danakil depression, only the intermediate member contains a near normal seawater sequence that includes magnesium sulfate minerals. The syrivate content increases toward the top of the potash interval, and the characteristic marine evaporite minerals are no longer present, indicating an evolution of salt-precipitating brines away from seawater composition. The composition of the hot brine pools in the basin could not have resulted from simple evaporation of seawater, and is probably the result of increasing influence of both meteoric and hydrothermal water inflow over time.

The salt pan of the Danakil Depression only is 45 km from the coast of the Red Sea, and it is very likely that seawater percolating through the rocks as groundwater has a strong influence on the chemistry of the brine pools. The fact that sylvite precipitates from the brines indicates the presence of a magnesium sink, such as is required for the Paradox Basin. In both the Paradox Basin and the Danakil Depression, the occurrence of carbonate rocks reacting with groundwater flow of seawater origin. In addition to the magnesium sink provided by dolomitization in the Danakil Depression, the inflow from hydrothermal brines strongly affects the brine composition. Such brines are high in Na⁺, K⁺, Ca⁴⁺ and Cl⁻, but low in Mg²⁺ and SO₄²⁻, and the influence of these brines lead to the precipitation of magnesium sulfate-poor potash evaporites. There is no indication of hydrothermal activity in the Paradox basin during Pennsylvanian time, but mass balance calculations indicate that the volume of carbonate rocks that could have been dolomitized as seawater percolated into the basin as groundwater is more than enough to change the Mg/Ca ratio to the point where magnesium sulfate minerals would not precipitate. The predominance of sylvite over carnallite suggests an additional magnesium sink, probably related to refluxing of these brines that reacted with clays interbedded with the evaporites.

During the perennial saline lake stage of the Paradox Basin, the edge of the brine, or the maximum extent of salt, was a minimum of 150 km from the ocean. The carbonate shelves to the southwest contain numerous exposure horizons in the form of caliche crusts, gypsum sediments, and
mobilization, solution-tailed porosity (Golddammer and others, 1991). The exposure horizons represent periods of non-deposition of carbonates that correlate with the accumulation of silts in the basin. The Pennsylvanian aged sediments in the basin are overlain by tuffaceous siltstone and alluvial plain deposits. The distance of the salt-encrusted brine body in the Paradox Basin from downriver seawafer inflow in all directions indicates that the basin was probably more strongly influenced by the input of non-marine inflow waters. Both inflow volumes based on rates of river flow in the Great Salt Lake and the volume of halite in the Paradox Basin, estimates were made of the relative volumes of seawater, seawater-derived brines and meteoric water that entered the Paradox Basin during the peretial saline lake stage. Calculations indicate that inflow of nearly twice as much meteoric water as seawater is required to produce the mineral assemblage found in the Paradox Formation. In addition, the presence of rare-earth element minerals in the Paradox Formation indicate the presence of arsinean springs that can provide relatively high salinity input (relative to meteoric water) that is not seawater-derived (Rasch, 1972).

**CONCLUSIONS**

Comparison of two possible modern analogs to the Paradox, the Great Salt Lake in Utah, and the Danakil Depression in Ethiopia, suggests that the Paradox salt was deposited in an environment that contained elements present in both. Chemical and hydrological constraints in the Paradox basin were similar to those found in the Danakil Depression. At present the Danakil depression is disconnected from the ocean, but a substantial sea-level rise would flood the basin again, and a sequence of marine to brine-marine evaporite deposition would recommence. Geomorphic similarities between the Great Salt Lake basin and the Paradox Basin are indicated by comparing depositional environments to the facies present in the Paradox Formation. The cyclic evaporite deposition in the Paradox probably resulted both from climatic cycles associated with sea-level fluctuations and pluvial phases, and from tectonic pulses related to thrumming on the Uintaathedral fault (Hite and others, 1944; Johnson and others, 1991). Between the time when the basin water level was high, evaporative drawdown resulted in a reduction of the brine body, and eventual precipitation of evaporite minerals. Though the duration of salt deposition probably represents the smallest amount of time, the rapid rates of precipitation of halite resulted in that lithology having the largest proportion of thickness. After the basin was isolated, the influence of altered seepage, which percolated through carbonate barriers, and meteoric water, which entered the basin via rivers and springs, became more important than the seawater that initially filled the basin. It was not necessary for the basin to be deep, as continued subsidence of the basin floor provided enough space to accommodate this halite body. Although there were periods when the Paradox Basin was best described as a normal marine environment, the deposition of the evaporite minerals, beginning possibly with calcium sulfate, occurred during a time when the water body was isolated, shallow, and had brine characteristics which were predominately non-marine, with the sedimentation controlled by morphologic features similar to those found in the Great Salt Lake and the Danakil Depression today. The Paradox Formation is the result of deposition in a closed evaporite basin where the volume of continental-derived inflow waters exceeds marine-derived inflow waters by nearly two to one. The record is one of a marine-influenced, neomarine interglacial saline lake which existed for millions of years at a time.

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