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Primary Marine Evaporite Facies

Peter Sonnenfeld

University of Windsor, Windsor, Ontario N9B 3P4, Canada

ABSTRACT

Marine evaporites are derived from concentrating seawater; precipitation starts with aragonite followed by gypsum on sunlit shoals or shelves. Anaerobic bacteria consume incoming SO_4-ions while feeding on organic matter and cause an early sulfate deficiency. CO_2-solubility drops below 200 ppm, O_2-solubility below 4 ppm, and bicarbonate solubility to zero before the brine saturates for gypsum. While photosynthetic thiobacteria and cyanophyta reoxidize the H_2S generated by anaerobes and foster gypsum precipitation, dissolved proteins and alcohols delay it. NaCl-saturated or $MgCl_2$-containing brines are hygroscopic enough to turn gypsum into anhydrite even at ambient temperatures.

While gypsum continues to precipitate on sunlit shelves and shoals, the brine in deeps saturates for chlorides. Their solubility is reduced by dissolved cyanides and alcohols. Halites strip the brine of all Na^+ and no further primary Na-compounds precipitate; even though rates of halite precipitation exceed those of subsidence, periodic redissolutions keep halite accumulation in line with subsidence. Brines saturated for K- and K-Mg-chlorides decrease solubility and density when cooling; they rise and preferentially precipitate on basin slopes. Slowly nucleating sylvite crystallizes wherever dissolved protein derivatives, such as N-hydrides, increase $MgCl_2$-solubility. Carnallite precipitates in open waters or into a halite slush, if in contact with cooler pore waters; it contains abundant fluid inclusions of organic nitrogen and hydrocarbons, and red hematite platelets due to oxidation and dehydration of dissolved chlorophyll derivatives. Iron also substitutes for magnesium in distal parts of the basin if all organic matter has been removed; its oxidation contributes hematite needles to carnallite. Leaching of magnesium chloride from a red carnallite may then lead to a red sylvite. A small percentage of ammonia may be built into sylvite and carnallite lattices. Calcium and strontium eventually substitute for potassium in carnallites, wherever an absence of shoals or shelves has prevented a Ca- and Sr-depletion through gypsum precipitation. All other sulfates and chlorides found in evaporite sequences are of secondary origin.

Evidently not only bacteria and blue-green algae, but also various dissolved organic maceration products, control the primary evaporite precipitation sequence.

THE BRINE

Marine evaporites are rocks composed of minerals precipitated from seawater concentrating by evaporation. The difference in partial vapor pressure of air and brine declines, the surface tension increases as the brine concentrates; and the rates of evaporation decrease. Rates of precipitation accelerate in a gradually concentrating brine, but deposition need not be continuous.

The evaporation rate from NaCl-saturated and KCl-saturated solutions drops by about 30% and about 50% of that from a freshwater surface. To reach carnallite saturation, a brine requires an atmospheric humidity of 46%; a further concentration requires an even lower atmospheric humidity. The degree of aridity thus sets an effective limit to evaporation and concentration of residual brines.

Precipitation occurs in a density range of 1.1–1.4 g/cm^3, a salinity range of about 130 to 350–400 ppt and in a temperature range of about +32°C to −54°C. A cubic meter of seawater of a density of 1.0257 g/cm^3 contains 35.71 kg or about 21,360 cm^3 of potential precipitates.

Pseudomorphs after individual crystals or druses of evaporite minerals are known from rocks of nearly all ages. Bedded marine evaporite deposits (gypsum or anhydrite) occur only in mid- or late Proterozoic and Phanerozoic, bedded halites and K-Mg-salts in Infracambrian or younger sediments.

Marine evaporites are restricted to marginal seas and lagoons of the two belts of subtropical aridity. Such regions have a long dry summer, little surface or groundwater runoff, and only seasonal rains of considerable variability. A paucity of siliciclastics other than by episodic flash floods would create a 'starved' basin, were it not for a rapid filling with evaporite precipitation. The absence of coarse siliciclastics farther offshore and a uniform distribution of chloritic clay markers indicate a density stratified brine with high pH and low Eh in its bottom waters.

Continuous water supply

Subterranean seawater seepage into the basin alone cannot match evaporation losses and drain surplus solutes. The permeability of algal limestones is too small to allow seepage to maintain a water level over a broad entrance. At least a seasonal open flow must be maintained to prevent a very rapid drying out (Sonnenfeld and Al-Aasm, 1991).

The great thicknesses of marine evaporite accumulations mandate a continuous supply of seawater to prevent drying out. Even the deepest marginal sea, separated from the world ocean, would yield only a small fraction of the precipitates found in an average fossil marine evaporite basin. The absence of an isochemical distribution of precipitates and a progressive deficiency in salts of higher solubility mandate an inflow/outflow regime. Open marine shelves, no matter how wide, are unable to concentrate brines by more than about 10–12% before such brines slide into the open sea along an inclined seafloor. The quantities of dissolved salts in a normal marine inflow tend to become balanced by those in the concentrated outflow and no further concentration would occur, unless outflow is retarded by an entrance barrier.

The inflow and outflow of marine evaporite basins equilibrate in the gypsum saturation field even in the presence of a barrier, unless denser brines can accumulate in a depression. The depression develops and an equilibrium is averted by an accelerated differential subsidence. The interface between inflow and outflow, a pycnocline, impedes vertical fluid mixing, prevents convection, and dissipates storm energies. The depth of the interface is a function of the length of a strait to its total depth and the velocity of the inflow; the lower the interface, the less brine can escape.

Gypsum precipitation initially spreads over the whole basin floor, later retreats to shoals and shelves bathed in the gradually concentrating inflow, while the brine in deeps saturates for chlorides. Richter-Bernburg (1957) has aptly named these shelves "saturation shelves". In an analogous mode, modern salinas use condenser basins in series before allowing the brine to enter the crystallizer basin. As a result, anhydrite accumulations beneath a halite sequence are always much thinner than equivalent anhydrites on basin margins, giving the appearance of an inverse proportionality between anhydrite and halite thicknesses.

Metals and organics in the brine

Stiller and Sigg (1990) and Kostenko (1982) observed that the concentration of heavy metals decreased in surface waters and increased in hypersaline bottom brines in contact with precipitating salts. Several features of shallow stratified waters force the solute into concentrated bottom brines, which tend to heat up due to entrapped solar radiation. However, the average thickness of the brine layers decreases with increasing salinity gradients and appears to be independent of the applied heat flux (Huppert and Linden, 1979).

Downward ion migration due to thermal diffusion (the Soret effect) fortifies the salinity difference, as most of the major ions in seawater are thermophile (Sonnenfeld, 1984). The thermally driven salt diffusion decreases with increasing concentration, but increases more rapidly with temperature; in warm hypersaline brines, thermally driven diffusion can attenuate diffusion driven by concentration (Snowdon and Turner, 1960). The Soret coefficient is very small for dissolved $CaCl_2$ and $MgCl_2$, because the ionization factor compensates for the Soret effect (Porter, 1927).

The dynamic viscosity of a brine increases with its concentration. Complexed molecules and other particles larger than water molecules wander into the zone of maximum viscosity; water molecules in the brine depolymerize because of electrostriction of ions and move into zones of minimum viscosity (Tollert, 1950).

Surface runoff and discharging groundwater deliver products of chemical weathering mainly in the form of carbonates and bicarbonates. These anions are very poorly soluble in hot concentrated chloride brines; the carbon dioxide is expelled, leaving an excess of cations.

Anaerobic bacteria, feeding on organic matter, consume incoming SO_4-ions and cause an early sulfate deficiency (Borchert, 1969), as much of the developing H_2S can escape. CO_2-solubility drops below 200 ppm, O_2-solubility below 4 ppm, and bicarbonate solubility to zero well before the brine saturates for gypsum (Sonnenfeld, 1984). An increase in hydrogen ions and an excess of other cations resulting from hydrogen sulfide removal raise the pH and increase the stability of $CaCO_3$.

Finally, there is a voltage differential between the positive redox potential of oxygenated surface waters and a negative one in anoxic bottom brines of about 400–800 mV. Cations are thus attracted to bottom brines, whereas anions are driven toward the positive surface layer. This facilitates the expulsion of CO_3^-, HS^-, and possibly even Cl^-, and a concentration of metal hydroxides in the bottom waters.

THE INITIAL PRECIPITATES

Precipitation from seawater starts with aragonite [$CaCO_3$] at a density of about 1.100 g/cm^3, or threefold concentration, mainly due to the activity of blue-green algae and bacteria. The rapidly precipitating aragonite is the preferred form of $CaCO_3$ once the Mg-concentration exceeds 243 ppm, or about 18% of its concentration in seawater. Fewer Mg-ions are needed as the brine warms up, to foster aragonite and to subdue calcite precipitation; Na-ions somewhat counteract this effect. However, after deposition aragonite eventually converts to calcite; Mesozoic aragonite is very rare, pre-Permian aragonite is virtually unknown.

A prolific planktonic fauna and flora blooms in the inflow full of nutrients. Algal pinnacle reefs at the basin entrance feed on this surface inflow and produce more organic material than they consume; their oxygen consumption is high. This organic matter together with dead plankton sinks to the bay floor, generating organic films because it can neither be oxidized in the anaerobic environment nor be consumed by scavengers. The rising salinity and osmotic pressure in the bay has gradually killed resident burrowers and has terminated bioturbation and scavenging.

Dead reef trunks retard outflowing anaerobic bottom brines and fallen reef debris restricts the water exchange further. The closing of the Castile reef due to accumulating reef debris is said to have tilted the balance between inflow and outflow of the Delaware Basin of southeastern New Mexico and thus to have caused the concentration in the basin to increase to saturation first for gypsum, then halite and finally for potash deposits in the Castile Formation (Kroenlein, 1939).

Gypsum

Once saturation is achieved in subtropical lagoons, gypsum precipitates at 1.115 g/cm^3, or 4.5-fold concentration, generally at a rate of about 0.5–1.0 mm/year. Inorganic gypsum precipitation could utilize about a third of inflowing sulfate ions, but anaerobic bacteria, feeding on organic matter, consume not only incoming SO_4-ions that tie down Mg-ions, but also some attached to Ca-ions. Some calcium thus remains in the terminal brine. Bacterial sulfate reduction on a gypsum substrate leads to calcite precipitation, in some instances to magnesite (Sonnenfeld and Perthuisot, 1989). Fluid inclusions in halites, sylvites and carnallites frequently contain some CO_2.

Because oxygen dissolved in a saturated brine is insufficient for gypsum precipitation, it occurs only where additional oxygen is generated. Photosynthesizers, concentrated in a bacterial plate beneath the interface to inflowing waters, produce oxygen. Gypsum precipitation is thus restricted to water depths within the photic zone, to shelves and shoals. Gypsum crusts are transparent to UV-radiation and harbor several levels of cyanophyta and red photosynthetic thiobacteria that reoxidize the H_2S generated by anaerobes. Gypsified stromatolites are common.

While bacteria and algae foster gypsum precipitation, dissolved proteins and alcohols delay it (Sonnenfeld, 1984). Hydrogen sulfide would yield pyrite, that is not found in gypsum, very rarely in halites, never in K-Mg-salts. Once the brine concentrates further, NaCl- or K-$MgCl_2$-saturated brines are hygroscopic enough to turn gypsum even at ambient temperatures into anhydrite [$CaSO_4$].

The higher the pH during gypsum precipitation, the stubbier are gypsum crystals; alkanes, phenols, and fatty acids foster the formation of more tabular, equidimensional, or discoid-lenticular crystals, unless there is some dissolved silica. Gypsum crystals growing in low-pH environments produce elongate, prismatic shapes.

Nodular anhydrite, common in evaporite sequences, has at least four possible modes of origin. It is either (1) a supratidal alteration of a gypsum crust precipitated in the capillary zone of an ancient groundwater table, (2) an early diagenetic alteration of a semi-fluid gypsum/brine mush beneath the lagoonal floor, (3) a compaction texture of soft gypsum, or (4) a recrystallization of gypsum laminations in percolating halite-saturated hygroscopic brines. Current-deposited, cross-bedded gypsum sands (gypsarenites) or halite sands (haloarenites or halolites), turbidites, gravity flows, and submarine slides occur in a dense brine over very gentle slopes and have been reported from many localities.

Evidently not only bacteria and blue-green algae, but also various dissolved organic maceration products control the primary evaporite precipitation. Their importance cannot be overemphasized. Any dissolved cyanides and alcohols that raise the solubility of gypsum, reduce the solubility of all marine chlorides. Both halite [NaCl] and sylvite [KCl] crystallize normally as cubes, but form octaeders if some organic compounds are present. The slowly nucleating sylvite crystallizes wherever dissolved protein derivatives (N-hydrides) increase $MgCl_2$-solubility. They are preserved under any density stratification, but destroyed in open waters, where any dissolved Fe-organic compounds (from chlorophyll and hemoglobin) likewise decompose.

Rock salt

Following gypsum precipitation no other primary sulfates form on account of the sulfate deficiency.

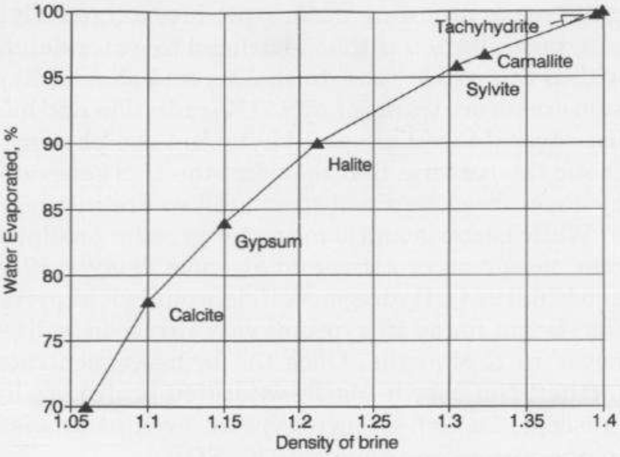

Fig. 1. Primary precipitation curve.

Further concentration leads to progressively greater hygroscopicity. The first chloride to precipitate is halite [NaCl] and depletes the brine of all its Na-ions and no further primary Na-compounds precipitate (Fig. 1). Halite saturation is reached at 1.2185 g/cm^3. Continuous precipitation of marine halite can occur at 36 mm/year (Tasch, 1970), but accelerates with progressive brine concentration; it varies between 3.6–14 cm/year. Rates of precipitation in preconcentrated and closed salinas can be significantly higher. The mean rate of halite accumulation is faster than even rapid rates of subsidence and yields a shallowing basin.

However, much of the salt is redissolved in the wet season or by episodic flash floods. In contrast to high precipitation rates, the preservation or accumulation rates may be as low as 0.1–4.0 mm/year (Barnett and Straw, 1983), thus keeping halite preservation in line with subsidence. Anhydrite crystals that form on halite crystal faces tend to inhibit halite crystal growth; enlarged halite crystals develop only in the absence of anhydrite.

Anhydritization

No external source of brines is required for the dehydration of gypsum to anhydrite. It is a very common early alteration, because it can be accomplished at ambient temperatures and pressures by exposure to any brines that are saturated at least for NaCl. Concentrating brines progressively increase their hygroscopicity and do not allow gypsum to be preserved. The conversion liberates strontium from the gypsum lattice and produces celestite [$SrSO_4$] nodules. Kalistrontite [$K_2SO_4 \cdot SrSO_4$] is a rare replacement mineral of celestite. Exposure to atmospheric humidity or to meteoric waters rehydrates anhydrite to gypsum.

Potash salts

The amount of water still to be extracted from a halite-saturated brine to reach potash saturation is very small (less than 5% of the original amount of water in the brine). Consequently, hardly any major primary salt deposit forms without having precipitated at least one horizon of potash salts, originally encased in halite. Potash salts are always shallow-water deposits in the decimeter-range of brine depths. Halite is followed by sylvite in brines covered by inflow, or carnallite in those exposed to the atmosphere.

Saturation for sylvite [KCl] occurs at a brine density of 1.290 g/cm^3, for carnallite [$KCl \cdot MgCl_2 \cdot 6H_2O$] at 1.344 g/cm^3 (Ivanov and Voronova, 1972). Almost all primary salt basins reach either sylvite or carnallite saturation before freshening sufficiently to revert to halite precipitation.

Brines saturated for K-Mg-chlorides are highly temperature-sensitive; upon cooling they decrease both their solubility and density; they precipitate on basin slopes and on shelf margins, preferably on those facing east. Shoreward they are limited by the effects of occasional rainwash. A separation develops: Gypsum is deposited on shoals and shelves, halite in deeps, and K-Mg- or Ca-Mg-chlorides preferentially on the western flank of a basin.

Primary carnallite [$KCl \cdot MgCl_2 \cdot 6H_2O$] precipitates into a halite slush, if in contact with cooler pore waters (Lowenstam and Spencer, 1990) and forms disseminated textures, or in distinct beds, where the open brine cools. It always contains abundant fluid inclusions of organic nitrogen and hydrocarbons, as well as needles or platelets of hematite. All potash deposits were originally encased in halite, indicating a gradual rise and eventual drop in the concentration of a continuous brine cover.

The terminal brine

Where steep coasts have prevented photosynthesizers to settle on sunlit shelves, Ca-ions are not consumed by gypsum precipitation and have a greater affinity to chlorine than magnesium. All primary tachyhydrite occurrences are in basins where little or no limestone or anhydrite is present, except as ultimate caprock. Even small amounts of $CaCl_2$ in the brine reduce the solubility of KCl but even more so of $MgCl_2$, thus forcing carnallite precipitation or a conversion of precipitated sylvite to carnallite.

The terminal brine-covered precipitate, once there is no more potassium left, is then tachyhydrite [$CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$]; it is in effect a Ca-carnallite (Table 1). In the Sergipe Basin of Brazil, the tachyhydrite contains about 10% antarcticite ($CaCl_2 \cdot 6H_2O$) (Kühn, 1992). Antarcticite loses two

TABLE 1

Mass balance of tachyhydrite formation from seawater completely depleted of sulfate ions. Tachyhydrite formation is prevented if first 1402 g (605 cm^3) of gypsum precipitate on shelves

Brine sp. grav.	Name	Formula	Precipitated (mol/m^3)	Weight (kg)	Volume (cm^3)
1.0257	1 m^3 Seawater	1.0257 t/m^3	526.9	35.675	18 013
1.100	Aragonite	$CaCO_3$	2.2	0.22	75
1.115	Gypsum	$CaSO_4.2H_2O$	0.0	0.00	0
1.212	Halite	NaCl	478.2	27.95	13 090
1.3235	Carnallite	$KMgCl_3.6H_2O$	10.1	2.80	1 745
1.395	Tachyhydrite	$CaMg_2Cl_6.12H_2O$	7.55	3.86	2 315
1.398	Antarcticite	$CaCl_2.6H_2O$	0.69	0.15	88
<1.3995	[Brucite]	$Mg(OH)_2$	28.4	1.65	700
Escaping	28.6 M SO_4, .22 M B_2O_5	<.2 M CO_3, .07 M F	trace elements	2.78	

molecules of water at 29.8°C and a further two molecules at 45.3°C (Gmelin, 1957). Since the rock temperature in the mine exceeds these temperatures, it is likely that only the dihydrate of calcium chloride is mixed into the tachyhydrite. Neither the tetrahydrate nor the dihydrate have hitherto been described as minerals, nor has the hexahydrate thus far been found in a primary marine sequence. It may be noted that Meyer and co-workers (1949) coprecipitated magnesium tetrahydrate with tachyhydrite in their laboratory at 35°C.

Saturation for tachyhydrite occurs at a brine density of 1.395 g/cm^3, which is only 4.5 kg/m^3 or 3.2 ppt less than the eutonic point of total loss of solvent. It represents a 310-fold concentration of seawater and requires atmospheric humidity to be below 35%, a figure reached only deep inland. For each unit of primary tachyhydrite [$CaCl_2{\cdot}2MgCl_2{\cdot}12H_2O$] more than half a unit of carnallite [$KCl{\cdot}MgCl_2{\cdot}6H_2O$] needs to be precipitated to deplete the brine of its potassium and so it always rests on an underlying carnallite bed.

Carnallite, tachyhydrite and antarcticite precipitation extracts water from the brine, speeding up the concentration of the residual liquor; they must form under brine cover, because they are so hygroscopic that they adsorb atmospheric moisture to dissolve in their adsorbed and crystal water. This constitutes evidence that the basin did not dry out, before halite salted out to cover the potash beds. With the consumption of the last remaining chloride ions it leaves 28.4 M Mg^{2+} to be either converted into 700 cm^3 of brucite pillars in mixed-layer clays or to be swept out.

Substitutions

The yellow color of primary tachyhydrite stems from a partial replacement of $MgCl_2$ by one part of $FeCl_2$ for every ten parts in solution (Kling, 1915). High Br/Cl and Sr/Ca values mark as source concentrating seawaters and not a soaking of carnallites in formation waters rich in $CaCl_2$ (Zharkov and Zharkova, 1989). In the distal parts of a basin, where both organic compounds and dissolved oxygen content reach a minimum, Fe^{2+} may also substitute for Mg^{2+} and NH_4+ for K^+ in the carnallite lattice. Both ammonium and iron are derived from the destruction of organic compounds. Some carnallite contains up to 6% kremersite [$(K,NH_4)Cl{\cdot}MgCl_2{\cdot}6H_2O$], in which ammonium replaces some of the potassium in carnallite. Iron may similarly replace the magnesium in a K-Fe-carnallite [$KCl{\cdot}FeCl_2{\cdot}6H_2O$]. Neither type is ever present in more than a few percentage points. Even a small rise in the partial pressure of O_2 would destroy Fe-chlorides and yield hematite needles.

Other chlorides are secondary: downward percolating brines can leach $MgCl_2$ from a carnallite, leaving a red sylvite; the reverse conversion of a pale sylvite into carnallite is rare and often confined to an outer rind, because of the more than fourfold volume increase required. Recrystallization of a red hematite-bearing sylvite displaces impurities to crystal boundaries; in carnallite it expels lattice substitutions. Hygroscopic brines may strip Fe-carnallite of 75% of its water volume, forming douglasite [$KCl{\cdot}FeCl_2{\cdot}2H_2O$], which may decompose to rokuehnite [$FeCl_2{\cdot}2H_2O$]. Rinneite [$3KCl{\cdot}FeCl_2{\cdot}NaCl$] occurs along joints in nests or small intercalations, juxtaposed to secondary sylvite, with carnallite or anhydrite inclusions. It appears to be secondary because of its low Br-content, its occasional pseudomorphs after carnallite and because it requires a low pH and a very high Fe/Mg ratio in the brine. Baeumlerite [$KCl{\cdot}CaCl_2$], at times intergrown with tachyhydrite, is likewise secondary.

Rubidium, cesium, thallium, and ammonium do not form independent evaporite minerals, but may substitute for potassium in the crystal lattice. Bromide substitutes for chloride and the amount varies with brine concentration, Mg-availability, distance from shore, brine depth and temperature, degree and frequency of recrystallization of any precipitate, sorption by clays, and scavenging by algae or bacteria. Fluorine, iodine, lithium, and many trace elements remain in the residual brine to be soaked up in interstitial spaces of the precipitates. Poorly soluble barite either occurs in nests in limestones or it replaces gypsum. Borates either form many hydrated minerals that precipitate together with gypsum, remain in the terminal brine or form occasionally authigenic tourmaline slivers. The boron comes from volcanic sources or from swept-in muscovite flakes. Phosphates are rare in evaporitic environments and are mutually exclusive with sulfates; nitrates, iodates, iodides and chlorates are unknown in marine evaporites.

Compounds of meteoric origin

Na-compounds other than halite, common in lacustrine evaporites, always occur only in nests and indicate a post-depositional introduction of meteoric waters of a continental source. K-Mg-sulfates or Na-Mg-sulfates are likewise the product of meteoric waters introducing additional sulfate supplies.

THE BASIN

Cyclicity of deposition is a key feature of all evaporite basins. Alternating gypsum/halite or halite/carnallite laminations on a mm–cm scale indicate seasonal variations in brine concentration. Laminations form only in perennially submerged parts of the basin, where they are not destroyed by bioturbation or a vertical brine discharge. They cannot occur in deep brines; annual, seasonal or daily fluctuations from supersaturation to undersaturation for the more soluble salt are only possible in shallow water. Commonly every eighth to tenth couplet is thicker, suggesting a record of major storms. Since each storm can remove up to 80% of the varve couplets deposited since the last storm, their count does not give a realistic estimate of elapsed time.

Cyclicity

Virtually all evaporite basins contain more than one evaporite cycle suggesting climatic cycles of greater amplitude. Major breaks within halite sequences (major freshenings) are common at intervals of 145 or 290 m, suggesting climatic influences (Sonnenfeld and Al-Aasm, 1991). A multiplicity of evaporite cycles suggests repeated renewal of subsidence along rejuvenated faults, sometimes delineating a graben. Punctuation of subsidence by stillstand periods is marked by a reversal of evaporite sequences and frequently a bank of uniformly thick biostromal limestone or dolomite. Its uniform thickness suggests a flat bay bottom in the photic zone. Marine anhydrites commonly grade abruptly into near-shore limestones or red beds with gypsum crusts in the soil. The thickness of shelf anhydrites varies inversely with the halite thickness offshore. Thickest halites mark subsidence centers, which do not necessarily mark basin centers.

Synsedimentary subsidence

When halite starts precipitating, the brine weight has increased by nearly one fifth over that of inflowing seawater, and the combined weight of brine and precipitate soon exceeds 170% of a corresponding seawater column. This must affect the isostatic equilibrium of the earth's crust. Finding several hundred meters of rock salt deposited on top of shallow-water gypsum beds mandates such synsedimentary subsidence.

Halite saturation requires the removal of 91% of the water, carnallite 96%; to remove it from brines descending to the bottom requires a basin configuration, where shelves represent 46.2% of the water surface to reach halite saturation, and 47.9% to reach sylvite or carnallite saturation. A sequential arrangement of interconnected basins encourages brine preconcentration, because the evaporation rate from concentrating brines drops by about 30% before halite saturation or 50% before potash saturation and expanded water surfaces are favored. In many instances the shelf areas of one cycle subside rapidly in a subsequent cycle and become additional sites of halite precipitation, while former shores become shelves. The subsidence is thus spreading from one cycle to the next. The final cycle is regressive, as subsidence is slowing down; this cycle is marked by anhydrite and open marine limestone beds, often followed by continental red beds with anhydrite nodules.

The shape of evaporite basins is controlled by tectonic forces that also are responsible for the intermittent rapid subsidence. Synsedimentary subsidence alters thickness ratios between shelf and basin and allows the brine to transgress over its former shoreline. Distension faults and slumping mark ancient hinge lines. In most evaporite basins, the depocenter migrated at least somewhat from one cycle to the next. Basic to intermediate volcanism is common both during and after evaporite deposition. It is so far only speculation to what extent the in-

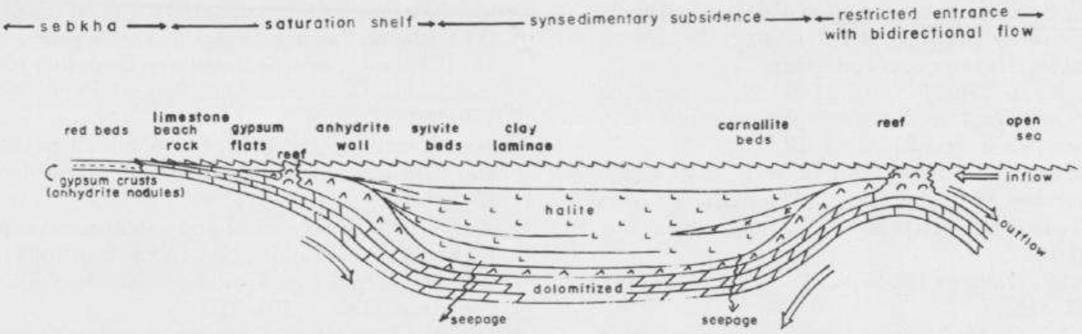

Fig. 2. Model of a marine evaporite basin.

creased contemporary volcanic activity might have contributed to the supply of sulfur or chlorine.

Basin configuration

The larger the brine volume in a basin, the longer it takes after a major freshened influx to reach saturation; the rate of salination is inversely proportional to the brine depth. It then becomes less probable that evaporation or subsidence rates remain constant; saturation of deep basins is thus difficult to achieve. The ratio between subsidence rates of gypsum-precipitating shelves and halite-precipitating deeps has commonly been 1:5 to 1:7 in ancient sediments. From Br/Cl studies (Tucker and Cann, 1986) and from rates of freshening to produce anhydrite intercalations in chloride sequences (Sonnenfeld, 1991), estimates of brine depth in evaporite basins yielded a maximum of about 100-150 m. Holser (1966) and Czapowski et al. (1990) arrived at similar values.

A model of a marine evaporite basin (Fig. 2) that takes these observations into consideration, contains broad saturation shelves covered with gypsum, a deeper area filled with halite. The flanks of the deep are the sites of sylvite or carnallite intercalations in the halite as well as of clay horizons that floated in along the interface to flash floods.

CONCLUSIONS

Marine evaporites are the product of concentrating seawater that first saturates for aragonite and gypsum, both precipitating on sunlit shoals or shelves under extensive involvement of bacteria and blue-green algae. Further concentration occurs only in portions of the basin subject to differential subsidence, as chlorides are apt to fill the basin. Halite follows in deeper parts, but sylvite and carnallite rise upon cooling and precipitate on basin flanks. Tachyhydrite occurs only where an absence of shoals or shelves has prevented Ca-depletion by gypsum precipitation. In small quantities iron may substitute for magnesium, ammonium for potassium. All other sulfates and chlorides found in evaporite sequences are of secondary origin.

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