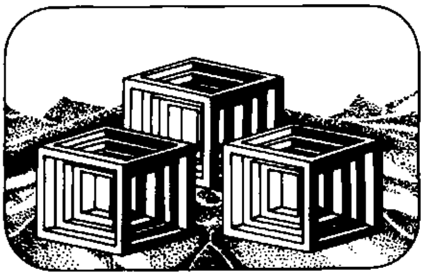

Brines and Evaporites

Peter Sonnenfeld
Department of Geology
University of Windsor
Windsor, Ontario N9B 3P4

Abstract

Evaporites are precipitated in marginal bays from hypersaline brines generated in an arid climatic regime and replenished by a sustained surface influx of waters. The resulting density stratification leads to an entrapment of solar energy in the brine, a depletion of oxygen and an enrichment in organic matter. A continuous bottom outflow flushes those compounds not found adequately represented in the sedimentary record of the evaporite basin. The vertical sequence of precipitates is reversed either in cooler years or by tectonic causes, and is always a function of inflow velocities dictated by the need to maintain a common sea level with the open ocean.

Resumé

Les évaporites sont précipitées en baies marginales par des saumures hypersalines, qui sont engendrées par un régime climatique aride et qui sont remplies d'une influxion des eaux soutenues à la surface. La stratification par densité prend au piège d'énergie solaire dans la saumure, épuise l'oxygène et enriche la matière organique. Ces sels sont nettoyés avec une chasse d'un effluve continu au fonde, qui ne se trouve pas proportionellement dans la colonne sédimentaire du bassin évaporitique. La séquence verticale des précipités est intervertée dans les années plus fraîches ou par des causes tectoniques. Elle est toujours une fonction des velocités de l'influxion commandées par la necessité de conservir un niveau commun avec l'océan.

Introduction

Hypersaline brines form only in bodies of water where rates of evaporation exceed or balance the rates of replenishment of the water supply. Evaporite deposition is a function of available suitable brines reaching saturation. A few saline lakes located on exposed salt domes or in abandoned open pit salt mines seem to contradict this rule, but they merely lead to leaching and local redeposition of already precipitated halite, not to the formation of an essentially new evaporite body.

Continental evaporite deposits are lacustrine sediments commonly rich in sodium and magnesium carbonates and sulphates, with relatively subordinate sodium chloride. Calcium compounds are rare. Marine evaporites are usually much larger in volume and comprise an initial calcium carbonate and calcium sulphate precipitation which is then augmented by dolomitization of precipitated aragonite and calcite and by precipitation of sodium chloride. Eventually further concentration of the brine can produce hydrous potassium and even magnesium sulphates and chlorides. It is the physics and chemistry of the hypersaline brines which dictates the nature of the precipitate. Therefore, it is desirable to review the characteristics of natural brines as they affect sediment genesis.

The Characteristics of Natural Brines

An arid or semi-arid climate is required. In order to generate saturated hypersaline brines in a bay or gulf, the evaporation losses must be greater than can be compensated for by runoff and rainfall. The higher the rate of evaporation in an area, the smaller is the rainfall and the fewer are the rivers, reinforcing the aridity of the area. Most present and fossil evaporites, however, were not generated in the heart of the desert regions but on their margins, in areas of a long dry summer season and a brief winter rainy season.

There must be a sustained influx of waters. A water-filled depression proceeds to dry up if the evaporation losses are greater than can be compensated for by runoff and rainfall. This is the case in many continental hypersaline lakes, which are ephemeral, existing for a while, dry up and then revive only seasonally. The volume of evaporite deposition in them is relatively small.

The new influx of water entering into a completely dried up pan immediately redissolves some if not all of the precipitated salts, leaching out first the most soluble ones, i.e., the ones precipitated last. Only where a sustained inflow from outside balances evaporation losses and maintains a free water level, can a hypersaline brine exist perennially and continue to precipitate salts. Thick evaporite deposits are thus invariably the result of a sustained influx of water, such as ocean waters flowing into a bay..

Bay circulation is climate dependent. If the embayment is situated in a humid climate, i.e., a climate where runoff and rainfall produce a water surplus, the outflow of excess water is of lower salinity than the main body of water and floats out on the surface. At depth a compensating inflow maintains equilibrium. This is today the case in Hudson Bay, the Baltic Sea, the Black Sea, the Sea of Okhotsk, as well as in all fjords.

On the other hand, if the embayment is situated in a semi-arid or arid climate, i.e., a climate where runoff and rainfall are insufficient to match evaporation losses, the resulting water deficit lowers the water level and ocean waters enter in order to maintain a common sea level. These ocean waters then override the heavier brine.

The inflow sets up an outflow. Inflowing and gradually evaporating surface waters set up an interface with bay waters inclined towards the entrance. The bottom waters then flow "downhill" along this inclined interface. Inflowing waters thus set up a compensating outflow at depth. Present-day examples include the Persian Gulf and the Mediterranean Sea. Interestingly, the latter reverted from a water surplus type of circulation during cooler Pleistocene times to a water deficit type in Holocene times when evaporation rates again increased (Mars, 1963, Vergnaud-Grazzini and Bartolini, 1970; Valette, 1972; Huang and Stanley, 1973; Huang *et al.*, 1972, Sonnenfeld, 1975a). *Incoming waters set up a density stratification (pycnocline).* Whenever a free water level can be maintained throughout the year, the incoming new waters do not mix to create a homogeneous body of hypersaline brine, but float on top of the denser waters, provided that the density difference is at least 15 g/l (Sonnenfeld and Hudec, 1978a). This holds whether we are dealing with river inflow or with saltwater influx from adjacent open seas. Such a density stratification persists until the new layer has evaporated for the most part. Laboratory experiments by the author showed that a mixing zone establishes itself almost instantly, but the downward advance of the interface between mixing zone and uncontaminated hypersaline brine (the pycnocline) is slower than the downward displacement of the air-water interface by evaporation losses, even at a very moderate (400 mm per annum) water deficit. Even strong winds cannot induce an overturn (Maxim, 1936; Dzens-Litovskii, 1968; Hudec and Sonnenfeld, 1978).

Density stratification prevents oxygenation. The hypersaline brine, separated from the air-water interface by surface waters, quickly depletes its oxygen supply. However, the well oxygenated upper layer teems with life where an annual generation of up to 50 g of biomass per litre of water has been observed. Brine shrimp, diatoms, schools of minnows, zoo- and phytoplankton abound in addition to varieties of algae and bacteria. In a fossil setting, Sturani (1973) found a desiccated eel in Messinian evaporites in northern Italy, a great distance from the nearest shore. The eel did not voluntarily enter the concentrated brine, but presumably was enticed into the upper layer by the ample food supply, was then killed or died by accidentally dropping below the interface into the anaerobic, highly hygroscopic hypersaline brine.

The concentrating brine becomes progressively more inimical to life causing the death of salinity-sensitive (stenohaline) forms. Such mass extinction has, indeed, been observed beneath Messinian evaporite deposits in the western Balearic Sea (cf. Sonnenfeld, 1977). Benthonic and nektonic biota are reduced to a very few endemic forms hampering correlation to areas outside the basin. Only surface waters remain full of planktonic life.

Any organic compound falling through the chemocline can no longer be oxidized. It can be entrapped in the bituminous shales and limestones that are so often found interfingering with evaporites on the basin margins. Not all organic compounds are caught on the bay floor in impervious beds, some fraction probably can advance with the brines into aquifers.

The frequent occurrence of pinnacle reefs growing in an evaporite basin, particularly near the basin entrance (Sonnenfeld, 1973), can only be explained by active growth above the interface between anaerobic hypersaline brine and oxygenated surface waters. Lower levels of the pinnacle reef consist of dead reef growth, at times even infilled with evaporite minerals (such as the salt-filled vugs in Silurian reefs of Ontario). Whether in a given instance the reefs died before evaporite precipitation or were still concurrently growing with it, can only be decided by a study of the uppermost layers of a pinnacle reef.

Incoming waters can set up a thermal stratification (a thermocline). The surface layer absorbs sun light and returns this energy to the atmosphere through evaporation and back radiation. Solar radiation penetrating the interface into the hypersaline brine (the chemocline) is trapped up to 89 per cent (Hudec and Sonnenfeld, 1974) and is converted into thermal energy. This gives rise to hot hypersaline brines in all latitudes between 80°N and 80°S, even under ice cover on the lower salinity surface layer (Sonnenfeld and Hudec, 1978a). Temperature differences across the interface (thermocline) of 30-40°C have been measured by the author in Caribbean and British Columbia localities (Hudec and Sonnenfeld, 1978). Others have measured the absolute temperature of the hypersaline brine to be as high as 105°C, induced entirely by solar radiation (Z. Weinberger, 1977, pers. commun.).

The more concentrated the brine, the slower is its rate of evaporation and thus the lower are the evaporative heat losses of absorbed solar radiation. Precipitation also releases thermal energy; per unit volume, the crystallization of halite releases five times more heat than gypsum, sylvite three times more than halite. Hydrous magnesium and potassium sulphates and chloride-sulphates release even higher amounts of stored thermal energy. Precipitating salines always contain warmer waters than undersaturated ones.

The heating of the mixing zone from below reinforces the permanence of the density stratification (Stern, 1978). It is this stratification which prevents large scale convection currents, overturning and homogenization of the brine, or the mixing in of atmospheric oxygen. The consequence is reducing conditions within the precipitating layers of the brine (Hudec and Sonnenfeld, 1978). The current sapropel deposition in the Gulf of Cariacou in Venezuela and the eastern Mediterranean Sea are examples of how the surface circulation prevents oxygenation of bottom waters.

The bay must have an entrance sill to restrict passage of waters. A high rate of evaporation is not enough to produce saturation of brines in a marine bay. Despite rates of evaporation in excess of 5,000 mm/year, neither the Persian Gulf (apart from restricted marginal lagoons) nor the Red Sea currently precipitate salts from solution. Even slightly concentrated brines in these embayments simply slide out into the open ocean and spread at the level of their density equilibrium. The submarine delta of Mediterranean waters extends at a depth of about 1,200 m to Brazil and southern Ireland and prevents the upwelling Canary Current reaching the surface within the environs of the Straits of Gibraltar. However, monthly observations at Gibraltar show that the inflow is considerably larger than the outflow in June - November, when evaporation losses are high. The outflow only manages to catch up again in winter and spring when less inflow is required to maintain a common sea level (Ovchinnikov, 1975).

A sill is required to restrict the in- and outflow; this was recognized by Ochsenius (1878, 1888) a century ago. Since an evaporating basin tries to maintain a common sea level with the ocean, the rate of inflow is controlled by the cross sectional area of the entrance passage and by the evaporation losses. The latter are the product of the rate of evaporation and the surface area of open waters in the basin. The larger the basin or the higher the rates of evaporation, the greater the influx velocity. If the entrance constriction maintains a constant profile, then only inflow drag will inhibit and can ultimately prevent the outflow.

The Kara Bogaz Gol is fed by brackish waters of the Caspian Sea, a remnant of the much larger Late Tertiary Paratethys Sea (Sonnenfeld, 1978). Its sediments contain about three times as much sulphate as normal marine evaporites do, depicting the substantial contribution of river waters in Holocene times to the chemistry of the Caspian Sea. The Kara Bogaz Gol had a bottom outflow at the beginning of this century. Earthquakes reduced the entrance profile and increased rates of evaporation accelerated the rates of inflow; by the early thirties no more outflow was measured, although a bottom counter current still flows inside the Kara Bogaz Gol. Progressively more soluble salts started to be deposited year by year as saturation in the trapped waters increased. At the same time the surface area of open waters shrank substantially around the edges (for discussion cf. Sonnenfeld, 1974). However, the worldwide cooling trend in mid-century reduced the rates of evaporation and thus the water losses. Eventually the precipitation of highly soluble salts ceased and gypsum again spread out over much of the gulf bottom along with sodium sulphates (Kolisov *et al.*, 1974) just as had been the case around the turn of the century. No reduction in area occurred since 1958.

The waters in a bay are subject to Coriolis effects. The horizontal component of the Coriolis effect forces the inflowing current to hug the basin rim before sinking and flowing out from the centre. Thus precipitates of low solubility are normally found nearer to the rim of the basin and are coeval with precipitation of other salts in the centre.

The vertical component of the Coriolis effect tilts the brine interfaces, so that in the northern hemisphere they dip east- and southward. Consequently, embayments on the northern and western shores can entrap bottom brines with lower sills; embayments with evaporite deposits are more frequent along these shores. In the northern hemisphere this effect partially counteracts the tilt induced by surface waters flowing in over an entrance passage located on the western or southern shore of the embayment and thus slows down any bottom outflow in that direction. It enhances the tilt for outflow to the north and east.

Based on these and other oceanographic considerations a model of brine circulation was evolved (Sonnenfeld, 1974, 1975a, c, d) that is not too different from Ochsenius' (1878, 1888) ideas. More prominence is merely given to the continuing outflow and to the effects of the Coriolis force (Fig. 1).

The onset of saturation for different evaporite minerals is a function of time. We can reduce the parameters involved in evaporite generation in a basin into a simple material balance equation,

$$I.s_I + R.s_R + P.s_P = A.e + O.s_O \quad (1)$$

whereby I and O are volumes of inflowing and outflowing waters per unit of time, R and P are the volumes per unit of time of runoff and atmospheric precipitation respectively, s_I, s_R, s_P and s_O are the appropriate densities of the different waters, A the surface area of the embayment and e the prevailing rate of evaporation (volume per unit area and time), which slightly decreases with decreasing vapour pressure of a concentrating brine.

As the inflow increases, it carries in more salts; as the outflow is depressed, less salts are allowed to exit. Eventually the solute balance tilts in favour of the inflow, producing the following inequality (the density of evaporating water approximated at 1),

$$[I(s_I - 1) + R(s_R - 1) + P(s_P - 1)]_t > [O(s_O - 1)] \quad (2)$$

where $[\ldots.]_t$ indicates average values over time t. If for a unit of time t, the incoming volume of salt (albeit in weak concentration) is greater than the volume of salt flushed out, the concentration of the brine keeps increasing. Thereafter it is merely a question of time until saturation is achieved.

Since the salt content of runoff and rainfall is small in comparison to the salt content of inflow and outflow, the inequality (2) can be reduced to

$$[I(s_I - 1)]_t > [O(s_O - 1)]_t \quad (3)$$

without incurring a great error. From this we can calculate that, for example, by the time the basin reaches halite saturation the volume of inflow must be almost 5.2 times the volume of outflow per unit of time.

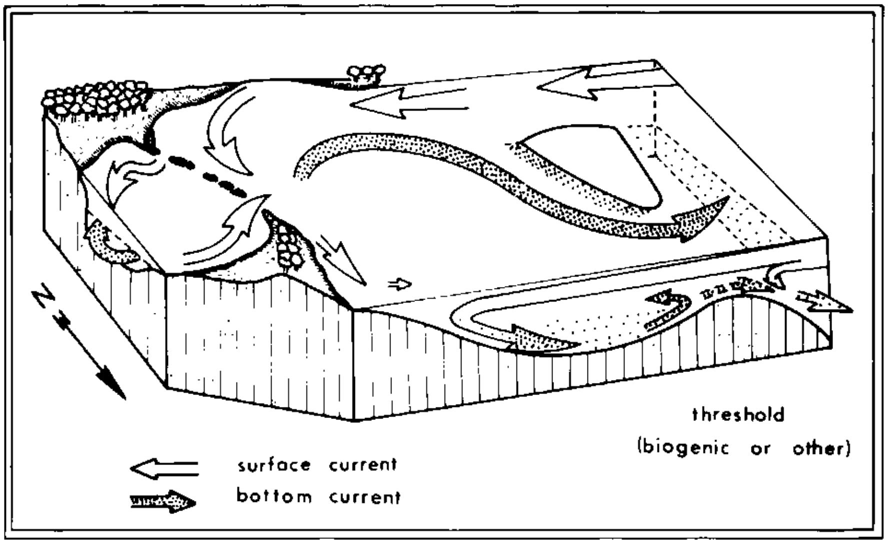

Figure 1
Model of evaporite genesis by inadequate water exchange. A low-density surface current carries more salinity per unit of time into the basin than is discharged by the outflowing bottom current. The current interface is depressed in the south, while the current direction is controlled by the Coriolis effect. Concentration is controlled by increments in water loss (rate of evaporation x surface area) per unit of time and by the reduction of cross sectional area over entrance swell. Rising inflow velocity increases drag and reduces outflow. Both flow directions persist as long as there is a common sea level. (Sonnenfeld, 1974, 1975)

To saturate a brine takes longer, the greater the volume of water to be saturated. The more time required, the more likely it is that climatic conditions will change. For the volume of the present Mediterranean Sea with a maximum depth of 5 km, it was calculated (Sonnenfeld, 1974) that 650,000 years would be required to allow the present annual water deficit to produce a gypsum precipitating brine. A body of water of the same area, but with only 500 m maximum depth would require a mere 65,000 years. The end-Miocene (Messinian) Mediterranean Sea was larger than the present one by embayments in Lombardy, Provence, Roussillon and Catalonia, as well as encroachments onto coastal Yugoslavia, Albania and the Suez area. According to Ogniben (1957) it took 90,000 years to accumulate the several Messinian evaporite cycles which include gypsum, halite and even potash salts now outcropping in Sicily. Judging from the Quaternary history of the same area, it becomes a matter of probabilities, how long climatic conditions can remain constant. A basin of any size can theoretically reach saturation, but the bigger the initial volume of water, the less probable it becomes that saturation can be reached before climatic conditions undergo a change. That inhibits the formation of salt bodies in very deep waters. Schmalz (1969) visualized a deep water model with hopper crystals forming at the air-water interface. This would require the whole brine body to have reached saturation. It is most unlikely that climatic conditions could remain constant for the required amount of time. *The initial salinity of the inflow need not be great.* The Kara Bogaz Gol is fed by brackish Caspian waters. With an influx of lower salinity more time is required to reach saturation than with an inflow of normal salinity. However, the time requirement can be significantly reduced if the waters are first pre-concentrated. Such may have been the case with Silurian waters that entered the Michigan Basin from the Ohio Basin through the Chatham Sag. Artificial brine ponds use pre-concentration to precipitate gypsum separately from halite.

When the brine becomes saturated for gypsum, precipitation starts over nearly the whole basin. Denser brines then begin to accumulate in the deeper depressions within the basin, that is, the parts subject to highest rates of subsidence. When saturation for halite is reached, additional incoming waters have to go first through a stage of gypsum saturation, continuing to precipitate gypsum along the path of the longshore current. This sets up lateral, shoreward facies changes from halite to gypsum. When saturation for potash salts is reached, the same shoreward facies changes are set up so that halite and gypsum become lateral equivalents.

The deepest parts of the basin are the sites of potash accumulation. The deepest part of the basin is that portion which experiences the highest rate of subsidence. Densest brines slide by gravity into these depressions. The removal of a given quantity of water from progressively more concentrated brines, whether by evaporation or by hygroscopic desiccation precipitates progressively larger volumes of salt (Sonnenfeld, 1974). When concentration has reached the stage that potash beds form, they are generally thicker than halite beds and these are thicker than gypsum laminae. Furthermore halite and potash beds are never found near the rims of the basin, but in the deeper parts and are laterally and vertically in contact only with evaporite minerals of lower solubility.

Since the solubility of potash compounds is very temperature-sensitive, most of the potash precipitation would occur in that period of the year when the hypersaline brine cools down. That is not necessarily the winter time when the rainy season reinforces the surface layers of low salinity. It may well be the time of maximum evaporation losses, when density differences between the hypersaline brine and surface waters get minimized and the brine returns to ambient temperatures because the thermocline has been destroyed. The appropriate season depends on the thickness of the inflowing current.

Throughout the period of increasing concentration of the brine, some outflow is maintained, to flush out excess magnesium salts and to reduce the amount of potash compounds present in solution, when compared to halite. No evaporite basin contains the evaporite minerals in isochemical proportions as calculated from seawater. If the volume of potash deposits is computed for any fossil evaporite basin, it shows a gross deficiency if compared to the volume of precipitated halite. In turn, there is disporportionately less halite than gypsum or anhydrite. All basins are very grossly deficient in magnesium salts. This can only be explained if we allow for some outflow to continue flushing the basin after precipitation of evaporite minerals has commenced. This denser outflow depletes the brine of heavier compounds of higher solubility. Magnesium chlorides and sulphates accumulate only when the outflow is practically stopped and this is a rare occurrence in evaporite basins.

Wetter years, cooler years, i.e., years with lesser water deficit in the embayment, allow the continuing inflow to reduce the salinity of the brine. A reverse order of precipitates sets in. The brine is still saturated for halite and precipitates any further incoming sodium chloride in solution, when it no longer precipitates potash salts. It still continues to precipitate incoming gypsum when it is no longer saturated for halite. Inflow and outflow rates are thereby dictated by the size of the entrance profile and the magnitude of the water deficit.

Catastrophic dilution of the brine is only possible by tectonic events, such as substantial widening of the entrance strait. Even then a simple calculation shows that it would take millennia to drop the salinity of a body of water of the size of the Elk Point Basin or the Mediterranean Sea from maximum concentration to normal salinity. There is then ample time to have potash deposits covered by halite and for halite in turn to be covered by newly precipitated gypsum and this by carbonate. Once a gypsum cover is established, even exposure to rain and runoff does not readily redissolve the salts, as shown by the presence of Triassic anhydrite boulders in Messinian gypsiferous sandstones of Zante (Zakynthos Island, Greece; Dermitsakis, 1978, pers. commun) or the several Paleozoic gypsum occurrences in Alberta, on Cape Breton Island or in NE Ohio, all of which are either exposed or locally covered by 1-2 m of Late Wisconsin glacial drift.

The frequently observed reverse order of precipitation towards the roof of an evaporite deposit and the frequently observed basin-wide intercalations of lower-solubility salts (such as anhydrite layers separating lower from upper halite beds, or dolomite layers lined by anhydrite and sandwiched between salt members) are thus the sedimentary record of the oscillating climatic conditions and of the oscillating rates of evaporation over the millennia. Once a brine is saturated, precipitation produces very large quantities of evaporites. Unless the rates of subsidence are rapid, the basin fills up and no thick evaporite sequences can form. When the basin fills up, the final gypsum layers bear the marks of at least intermittent subaerial exposure.

When rates of subsidence within the basin increase, the brine is diluted by the increasing inflow trying to maintain a common sea level between embayment and open sea. Rates of rapid subsidence in turn mark tectonically active areas, those where an unsupported crust is foundering along high angle normal faults such as the Neogene Mediterranean Sea (Sonnenfeld, 1978). If rates of subsidence exceed rates of precipitation, the water depth in the basin is increasing, its salinity decreasing. This results in a reverse order of precipitates similar to the one produced by lowered rates of evaporation, ending not in an erosional surface but in open marine sediments deposited in waters of normal salinity. Only detailed stratigraphic cross sections across an evaporite basin can differentiate between the basinward thickening of individual units due to excessive sag as opposed to the thickening of salt beds covered by a nearly uniform thickness of gypsum and dolomite in a basin of moderate or constant subsidence but oscillating climate.

Groundwater does not enter the hypersaline brine, but may surface as spring water near the shores of the basin. Groundwater is normally of lower density than a hypersaline brine and thus will be displaced by the brine in subsurface aquifers in analogy to saltwater encroachment in coastal freshwater aquifers. In the Danakil depression of Eritrea, the drainage of all residual brines, after seasonal seawater flooding and halite precipitation, occurs through groundwater aquifers back to the sea, but below Red Sea level, exiting there as hot brines. Similarly, perennially added sea water to a closed, gypsum precipitating lagoon in the Venezuelan Antilles does not lead to even halite saturation because of a continuous subterranean transudation through porous beds into the nearby sea (Sonnenfeld *et al.*, 1977; Sonnenfeld and Hudec, 1978b).

The Masada fortification, built by King Herod high on the cliffs overlooking the Dead Sea depression, had to gather the very meagre rain waters for its people, since no water table of potable groundwater could be reached by drilling, either then or now. Between Mediterranean seawater encroachment at depth beneath a Ghyben-Herzberg lens of freshwater inside the Judaean Hills, and Dead Sea brine encroachment from the east, potable drinking water pinches out at Masada (Fig. 2). Sulphurated salt springs emerge at the foot of the mountain some distance north of Masada.

Evaporite basins cannot be considered as groundwater sinks; subsurface drainage with high piezometric head may exit as surface springs, only to desiccate in one of the wadis of the coastal plain. Even then it must be counted as runoff entering the basin area. On the other hand, the advancing encroachment of magnesium enriched bitterns from the evaporite basin sets up a mixing front with the formation waters in the aquifer (Fig. 3). This advancing mixing front can react with the wall rock of the aquifer. Such mixing fronts between magnesium-rich bitterns and lower salinity formation waters could be considered as agents of secondary dolomitization (Sonnenfeld, 1964; Folk and Land, 1975). The higher the concentration of the brine, the greater is the pressure it exerts on interstitial fluids in adjacent subsurface aquifers and the lower is the need for surface outflow. The heavier hypersaline brines probably lose all their magnesium and most of their potash bitterns through subsurface drainage into aquifers, rather than through surface outflow over a sill. High-salinity fronts are very common in the subsurface aquifers (for an Alberta example see Fig. 12 in Sonnenfeld, 1964).

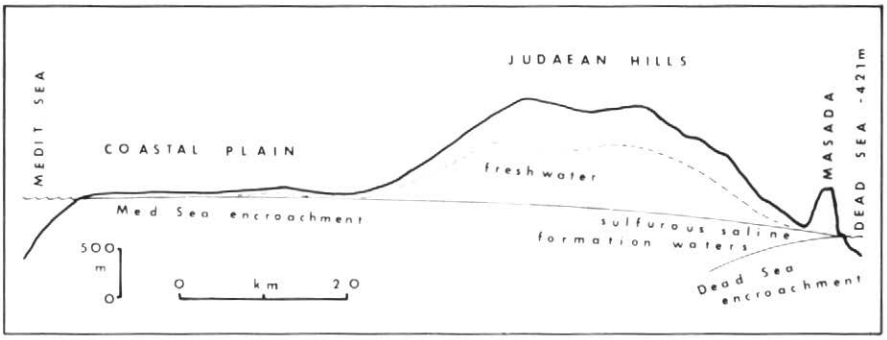

Figure 2
Groundwater shut out from a depression below sea level: Dead Sea area.

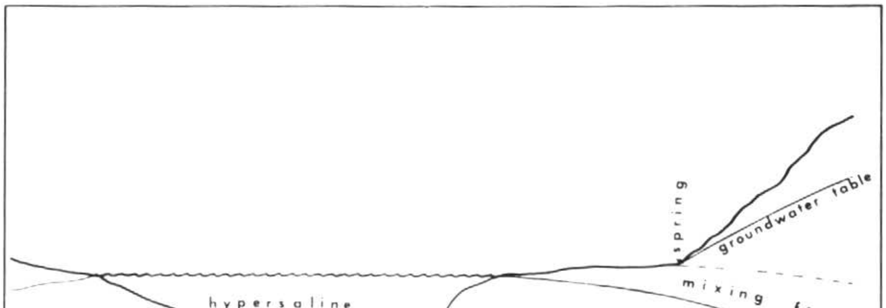

Figure 3
Groundwater regime near brine pond.

Gypsum precipitates only if there is an outside oxygen supply. Gypsum precipitation requires four oxygen atoms for each molecule. Since hypersaline brines separated by a low-salinity layer from the air-water interface are anaerobic, they cannot supply the required oxygen. Algae growing within the photic zone of the anaerobic brine could be a probable source of the required oxygen, but then gypsum would be (in a way) an organic deposit, restricted to the photic zone. This has not been sufficiently investigated in view of the very low solubility of oxygen in hypersaline brines.

The Meteor cruise recovered gypsum from anaerobic sapropel cores of the eastern Mediterranean Sea only when the cores were not immediately washed upon recovery. Similarly, hypersaline brines from a gypsum precipitating lagoon in Los Roques, Venezuela, promptly precipitated gypsum upon addition of sulphuric acid or even of hydrogen peroxide. In both cases evidently, the sulphur and calcium were present in solution, the oxygen lacking. Originally the Dead Sea yielded only shallow-water gypsum in the photic zone (Neev and Emery, 1967). However, deep-water gypsum commenced to form after the nearby potash works started to dump very dense residual magnesium bitterns well aerated in a set of drainage canals. As heavy brines they sank, carrying the dissolved oxygen with them to the bottom of the Dead Sea. Conversely, gypsum replacement of oxygen producing algal stromatolites has been observed in recent sediments of Caribbean islands (Sonnenfeld *et al.*, 1976), in the Suez - Red Sea area (Grabau, 1920) or in Messinian evaporites (Nesteroff, 1973) in the Mediterranean region.

Chloride based brines are concentrating base metals whereas continental sulphate brines do not (Sonnenfeld *et al.*, 1976, 1977; Hudec and Sonnenfeld, 1978). Some of these base metals enter the crystal lattice of gypsum, others are distributed through the gypsum laminae in point form. Upon conversion of gypsum to anhydrite the base metal content is lost, presumably leaving with the bound crystal waters (Sonnenfeld and Hudec, 1975).

The model of a deep dry basin for evaporite genesis is now seriously questioned even in its type area, the Mediterranean region. This model was first evolved to explain the unexpected encounter of end-Miocene (Messinian) evaporites in drilling through the bottom of the Mediterranean Sea. Hsu *et al.* (1973) assumed that the evaporites now found at the bottom had been deposited there thousands of metres below present sea level. They did not consider that the evaporites had been dropped there by later tectonic events which would have been also responsible for elevating them above sea level in Sicily, Albania, Greece and elsewhere. There are undisturbed sedimentary contacts between underlying normal marine, reasonably shallow-water Tortonian sediments and the hypersaline environment of Messinian evaporites; in turn there are in many places, undisturbed sedimentary contacts between Messinian evaporite horizons and overlying normal marine Pliocene sediments, leaving no room for a desiccated deep basin or related catastrophic events (Fabricius *et al.*, 1978).

The model of a deep dry basin in the Mediterranean Sea at first glance appears to be supported by the occurrence of Plio-Quaternary canyons and related turbidites (Hsu *et al.*, 1973). However, canyons of equivalent age occur on both sides of the Atlantic Ocean, as well as in other oceans (Sonnenfeld, 1975a). Mediterranean canyons have been rejuvenated in Plio-Quaternary times (Nesteroff, 1973). Today, turbidites occur in waters of 40 to 100 m depth in Lake Mead and Lake Geneva, both freshwater lakes. Increasing density of the water lowers the requirement of minimum depth, since the buoyancy of incoming materials is increased. Thus turbidite deposits are feasible in hypersaline brines of much shallower depth than in freshwaters and are affected by the density stratification, but are not by themselves indicators of any great depth. Moreover, in hypersaline brines the terrestrial clays flocculate, float for a while on the pycnocline and spread out basinward, while coarse silts and sands sink to the floor much more slowly than in lower salinity waters.

Messinian (end-Miocene) evaporites occur today in the Mediterranean region 1,500 to 3,000 m above sea level in central Italy, southeastern Turkey and Tunisia, but are found 3,000 to 4,000 m below sea level under the Mediterranean Sea. However, the configuration of the Mediterranean Sea is a modern phenomenon. Various investigators have found that the Alboran Sea (Pfannenstiel, 1975), the Tyrrhenian Sea (Selli and Fabbri, 1971), the Ionian Sea (Fabricius and Hieke, 1977; Mueller *et al.*, 1978), the Aegean Sea (Neumayr, 1886) and the Nile Abyssal Plain in the southern Levantine Sea (Hsu *et al.*, 1973) are Plio-Quaternary collapse features, some as young as mid-Pleistocene. Such drops translate into rates of subsidence of 2-5 mm/year (Sonnenfeld, 1975a, b), probably composed of periods of rapid subsidence and periods of relative stagnation.

The Mediterranean region has remained a tectonically very unstable area. The current rate of burial of Miocene evaporites under the lower Po River sediments is in excess of 130 mm/year, yet the Po delta advanced 7 m/year to 1700 A.D. and 12 m/year since then (Colantoni *et al.*, 1978, and pers. commun.); the city of Ravenna, the main naval base of the Roman emperors, is now many km inland. Conversely, both Alps and Caucasus are rising 15 to 30 mm per annum and western Crete 4 mm per annum (Fleming, 1978). The uplift of Messinian rocks in Tunisia or southeastern Turkey from a putative sea level position would have had the same rate but a higher rate if we assume an initial position below current sea level.

If changes in elevation have affected Messinian evaporites in post-Miocene time in the order of 3,000 to 5,000 m down or 2,000 to 3,000 m up, there is then no need to assume that they were originally deposited several thousand metres below present sea level and that only upward displacements have taken place. A model of evaporite genesis that cannot be unequivocally proven to have generated the evaporites in its "type area", can then not be transplanted to other evaporite basins.

The Elk Point Basin has not been a deep dry basin, later filled with evaporites, as first suggested by Hsu *et al.* (1973). There is no abrupt facies boundary evident between an older set of basin-flank sediments and the younger evaporites. The former were not at one time standing as steep walls during an interval of non-deposition and desiccation preceding the infill of this depression by the younger sediments. It is not too difficult to draw very detailed gamma-ray-log cross sections across the Elk Point Basin, showing the interfingering facies changes of individual bed sequences towards the axis of the basin. Each sequence of evaporites ends with evidence of a filled basin capped by open marine carbonates. These were then sometimes subaerially exposed and partially eroded before further subsidence renewed the cycle.

Conclusion

Evaporite deposits depict the properties of hypersaline brines from which they had been precipitated. Hypersaline brines, in turn, are the product of an arid climatic regime over an embayment, and a restricted entrance passage to it. The Coriolis force affects the inflow as does the necessity to maintain a common sea level with adjacent open seas in the face of different rates of subsidence. A continuous outflow flushed those compounds not found adequately represented in the sedimentary record of the evaporite basin.

Acknowledgements

Research into the properties of evaporite precipitating hypersaline brines is supported by grant No. A8713 from the National Science and Engineering Research Council. I thank Dr. P.P. Hudec for critically reading the manuscript and for evaluating the formulae.

References

Colantoni, P *et al.*, 1978, The sediments of the Po River Delta and the adjacent continental shelf: Rapp. Comm. Int. Mer Médit., v. 25, in press.

Dzens-Litovskii, A.I., 1968, Saline Lakes of the USSR and Their Mineral Resources (in Russian): Leningrad, Nedra, 119 p.

Fabricius, F.H., and W. Hieke, 1977, Neogene to Quaternary development of the Ionian Basin (Mediterranean): Considerations based on a "dynamic shallow basin model" of the Messinian salinity event: *in* B Biju-Duval and L. Montadert, eds., Structural History of the Mediterranean Basins: Paris, Editions Technip, p. 391-400.

Fabricius, F.H., K.O. Heimann, and K Braune, 1978, Comparisons of Site 374 with circum-Ionian land sections: Implications for the Messinian "salinity crisis" on the basis of a "dynamic model": *in* K.J. Hsu, L. Montadert *et al.*, Initial Reports of the Deep Sea Drilling Project: Wasington, U S. Govt. Printing Office., v. 42 (Pt. 1): 927-942.

Flemming, N.C., 1978, Holocene eustatic changes and coastal tectonics in the North-east Mediterranean: implications for models of crustal consumption: Phil Trans. Royal Soc., Ser. A, v. 289 (1362), p. 405-458.

Folk, R.L., and L.S. Land, 1975, Mg/Ca ratio and salinity: Two controls over crystallization of dolomite: Amer. Assoc. Petrol. Geol., Bull., v. 59, p. 60-68.

Grabau, A.W., 1920, Geology of the Non-Metallic Mineral Deposits Other Than Silicates, Vol. 1. Principles of Salt Deposition: New York, McGraw-Hill, 435p

Huang, T C , and D.J. Stanley, 1973, Western Albroan Sea. sediment dispersal, ponding and reversal of currents. *in* D J Stanley, ed , The Mediterranean Sea: A Natural Sedimentation Laboratory Stroudsburg, Pa . Dowden, Hutchinson and Ross, p. 521-560

Huang, T.C., D.J. Stanley, and R. Stuckenrath, 1972, Sedimentological evidence for current reversal at the Straits of Gibraltar: Jour. Marine Technol Soc., v. 6, p. 25-33

Hsu, K J , W B F Ryan, and M B. Cita, 1973, Late Miocene desiccation in the Mediterranean Nature, v 242 (5395), p. 240-244.

Hudec, P P and P Sonnenfeld, 1974, Hot brines on Los Roques, Venezuela. Science, v. 185 (4149), p. 440-42 and v. 186 (4169) p 1074-1075

Hudec, P P , and P. Sonnenfeld, 1978, Comparison of Caribbean solar ponds with inland solar lakes of British Columia *in* A. Nissenbaum, editor, Saline Lakes and Natural Brines Amsterdam, Elsevier, in press

Kolisov, A.S., A.M. Pustyl'nikov, and V.P. Fedin, 1974, Precipitation of glauberite and conditions of glauberite-bearing sediments in the Kara Bogaz Gol Doklady Akad. Nauk SSSR, Earth Sci. Sec., v 219 no. 6, p. 1456-1460, Trans Amer. Geol. Instit., v. 219, p. 184-186.

Mars, P., 1963, Les faunes et la stratigraphie du Quaternaire Mediterraneen: Recueil Trav. St. Marit. Endoume, Bull., v. 24, no. 43, p. 61-97.

Maxim, I A., 1936, Contributions to the explanation of the heating process of water in saline ponds of Transylvania (in Romanian) Univ. Cluj, Rev. Muz. Geol. Mineral., v. 3, no. 1, p. 49-86 (1929; v. 4, no. 1, p. 47-111 (1930); v. 6, no 1-2, p. 209-320 (1936)

Mueller, J., W Hieke, and F. Fabricius, 1978, Turbidites at Site 374: Their composition, provenance and paleobathymetric significance: *in* K.J Hsu, L. Montadert *et al.*, Initial Reports of the Deep Sea Drilling Project: Wasington, Govt. Printing Office, v. 42, no. 1, p. 397-400.

Neev, D., and K.O. Emery, 1967, The Dead Sea, depositional processes and environments of evaporites: Israel Geol. Survey, Bull , v. 41, p. 1-147.

Nesteroff, W.D., 1973, Mineralogy, petrography, distribution and origin of the Messinian Mediterranean evaporites: *in* W.B.F. Ryan, K.J. Hsu *et al.*, eds., Initial Reports of the Deep Sea Drilling Project Washington, Govt. Printing Office, v. 13, no. 2, p. 673-694.

Neumayr, M., 1886-1887, Erdgeschichte: Leipzig, Bibliogr Inst , 2 vols.

Ochsenius, K , 1878, Beitraege zur Erklaerung der Bildung von Steinsalzlagern und ihrer Mutterlaugensalze: Nova Acta der kaiserlich Leopoldisch-Carolinischen deutschen Akademie der Naturforscher, v. 40, no 4, p. 121-166

Ochenius, K., 1888, On the formation of rock salt beds and mother liquor salts. Philadelphia Acad. Sci , Proc. Pt 2, p 181-187.

Ogniben, L., 1957, Petrografia della Serie Solfifera siciliana e condizioni geologische relative, Memorie descritt Carta Geol. D'Italia, v 23, p 1-275.

Ovchinnikov, I M , 1975, Water exchange through the Straits of Gibraltar Doklady Akad Nauk SSSR, Earth Sci. Sec., v 220, no. 303, p. 703-706, transl Amer. Geol Instit , v 220, p. 218-220

Pfannenstiel, M., 1975, Die Entstehung des Alboranmeeres aus dem alten Alboranland. Ein Beitrag zur Geotektonik des westlichen Mittelmeeres Mémoires de l'Institut Océanographique, v 8, p. 1-70

Schmalz, R.F., 1969, Deep-water evaporite deposition: a genetic model: Amer. Assoc. Petrol. Geol., Bull., v. 53, no. 4, p. 798-823.

Selli, R., and A. Fabbri, 1971, Tyrrhenian: A Pliocene deep sea: Acad. Naz. Lincei, Cl. Sci. Fis. Mat. Nat. Rend., Ser. 8, v. 50, no. 5, p. 580-592.

Sonnenfeld, P., 1964, Dolomites and dolomitization – a review: Can. Petrol. Geol. Bull., v. 12, no. 1, p. 101-132.

Sonnenfeld, P., 1973, Hydrocarbons in the southern Aegean Sea?: Ann. Géol. Pays Hellén., v. 25, p. 215-224.

Sonnenfeld, P., 1974, The Upper Miocene evaporite basins in the Mediterranean Region – a study in paleo-oceanography: Geol. Rundschau, v. 63, no. 3, p. 1133-1172.

Sonnenfeld, P., 1975a, The significance of Upper Miocene (Messinian) evaporites in the Mediterranean Sea: Jour. Geol., v. 83, p. 287-311.

Sonnenfeld, P., 1975b, Post-Miocene geodynamic trends in the Mediterranean Sea: Rapp. Comm. Int. Mer Médit., v. 23, no. 4a, p. 117.

Sonnenfeld, P., 1975c, A model of evaporite genesis: Rapp. Comm. Int. Mer Médit., v. 23, no. 4a, p. 229.

Sonnenfeld, P., 1975d, The Upper Miocene evaporites of the Mediterranean regiona: IXth Intern. Congr. Sedimentology, Proc., v. 2, p. 141-147.

Sonnenfeld, P., 1977, Origins of Messinian sediments in the Mediterranean Region – some constraints on their interpretation: Ann. Geol. Pays Hellen., v. 27, p. 160-189.

Sonnenfeld, P., 1978, Eurasian ophiolites and the Phanerozioc Tethys Sea: Geotekton. Forsch. (E. Schweizerbart, Stuttgart), v. 56, p. 1-88.

Sonnenfeld, P., and P.P. Hudec, 1975, Sedimentation by heliothermal brines on Los Roques, Venezuela: IXth Intern. Congr. Sedimentology, Proc., v. 9, p. 201-297.

Sonnenfeld, P., and P.P. Hudec, 1978a, Heliothermal lakes: *in* A. Nissenbaum, ed., Saline Lakes and Natural Brines, Ch. 2, Amsterdam, Elsevier, in press.

Sonnenfeld, P., and P.P. Hudec, 1978b, Geochemistry of a meromictic brine lake: Geologie en Mijnbouw, v. 57, no. 2, p. 333-337.

Sonnenfeld, P., P.P. Hudec, and A. Turek, 1976, Stratified heliothermal brines as metal concentrators: Acta Cientifica Venezolana, v. 27, p. 190-195.

Sonnenfeld, P., P.P. Hudec, A. Turek, and J.A. Boon, 1977, Base metal concentration in a density stratified evaporite pan: *in* James H. Fisher, ed., Reefs and Evaporites – Concepts and Depositional Models: Amer. Assoc. Petrol. Geol., Studies in Geology, v. 5, p. 181-186.

Stern, M.E., 1978, Mixing mechanisms in stratified fluids: *in* A. Nissenbaum, ed., Saline Lakes and Natural Brines, Amsterdam, Elsevier, in press.

Sturani, C., 1973, A fossil eel (*Anguilla* sp.) from the Messinian of Alba (Tertiary Piedmontese Basin): paleoenvironmental and paleogeographical implications: *in* C.W. Drooger *et al.*, eds., Messinian Events in the Mediterranean, Geodynamics Sci. Rept. No. 7, Kon. Nederl. Akad. Wetensch. Amsterdam, North-Holland, p. 243-255.

Vallette, J.N., 1972, Étude minéralogique et géochimique des sédiments de mer Alboran: résultats préliminaires: Acad. Sci. (Paris), C.R., v. 275, p. 2287-2290.

Vergnaud-Grazzini, C. and C. Bartolini, 1970, Évolution paléoclimatique des sédiments wurmiens et post-wurmiens en mer d'Alboran: Rev. Géogr. Phys. Geol. Dynam., Sér. 2, v. 12, p. 325-334.

MS received January 17, 1979.
Revised March 1, 1979.
