Introduction

This, the second in this series of articles discusses causes and effects of brine persistence. From part I (Salty Matters, March 31, 2020), we know that whenever brine salinity increases, brine density increases. A more saline brine has a lower freezing point and higher boiling point, as well as decreased specific heat and thermal conductivity, compared to a less salty brine. At the earth’s surface and nearsurface, this combination of physical properties means denser brine layers sit beneath less dense brine layers, and relatively narrow brine interfaces separate the layers. As a corollary, it means it is difficult for a less dense (fresher) brine inflow to displace a denser, largely impenetrable, brine mass. That is, a dense lower brine mass tends to persist.

Across time and burial depths, two significant outcomes tie to the contrasting physical properties of co-existing less dense and more dense brines in both evaporitic and cryogenic settings (Figure 1): 1) Brine stratification, sometimes

![Figure 1. The varied origins of dense and persistent hypersaline brines in both depositional and diagenetic settings.](image-url)
with heliothermy; 2) Bottom brine stagnation versus brine reflux. Ponding environments where layered brines occur have a multiplicity of origins, as well as a suite of indicative primary textures.

The most straightforward primary stratification setups occur in settings where brines concentrate either by solar-driven concentration - evaporite salts, or via brine freezing - cryogenic salts (Figure 1). The other significant source of layered brines (some with primary salt deposition) is from the dissolution of shallowly-buried salt layers and salt allochthons (e.g. DHALs on the deep seafloor or Romanian salt-doline lakes). If the mixing interface in the layered brine resides at water depths where light can penetrate, then the water column can become mesothermic and heliothermal.

There is an additional less sedimentologically significant syndepositional grouping of layered brine bodies and lakes, which set up in less-saline coastal settings tied to the intrusion of coastal marine groundwater wedges with meteoric pore waters floating above intrusive seawater. Some such intrusive marine wedges (Ghyben-Hertzberg lenses) subcrop in coastal lagoons, others in volcanic maar lakes. Where marine seepage hydrology sets up in temperate climates, the deposits found beneath layeredmeromictic lagoonal waters (where seawater underlies fresh water) do not precipitate evaporites or cryogenic salts (e.g. Lake Kaijke, Japan). In hydrographically-isolated evaporitic seepage sumps or salinas in arid or semiarid settings, they do (e.g. Lake Macleod, Marion Lake complex, the Coorong Lakes in Australia). In volcanic maar hydrologies, there can be a variable input of hydrothermal salts to the brine lakes (e.g. Cinder Cone Lake, New Mexico; Isla Isabel, offshore Mexico).

Both the depositional and diagenetic groupings of layered hypersaline brines can create saline minerals and textures indicative of the ongoing presence or persistence of a stable brine mass and associated chemical interfaces.

In this article, we shall focus on settings and outcomes related to the coming and going of brine stratification, especially in Quaternary evaporite and cryogenic settings, where formative hydrologies are still active. In the next article, we look at brine stagnation and reflux, both modern and ancient. The fourth article on brine persistence will focus on economic outcomes associated with subsurface chemical interfaces established by the contact of brines of differing densities and properties.

**Hydrology of stratification**

Hydrological conditions within perennial hypersaline seaways and brine lakes routinely fluctuate between stratified and non-stratified (Figure 2). In a layered saline brine system, an upper fresher (less dense) water mass sits atop a more persistent hypersaline (denser) lower water mass.

If chemical stratification persists for some time the hydrology is meromictic. Meromictic is a general term used to describe any chemically-stratified water mass where surface layers may mix, while the bottom layer persists, as in most perennial saline lakes and salterns. Oligomictic is used to describe stratified water masses that mix or homogenise for short irregular periods every few years. The upper water mass that periodically mixes is the mixolimnion; the lower permanent mass is the monimolimnion (Figure 2).

The narrow zone of transition between two saline water masses of different salinities in the brine column is called a halocline or more generally a chemocline (Figure 2). Hydrographically-isolated evaporitic solar lakes on the Sinai Peninsula.
Stratification and overturn (mixing)

Table 1 and Figure 2 capture language applied to density- and thermally-stratified lakes and periodic mixing (overturn) of their upper and lower water masses (after Wetzel, 2001). Amictic water columns are not subject to annual stratification, either thermally or chemically. Holomictic water masses are water masses that are vertically-mixed or chemically homogenous. In terms of a yearly stratification cycle, if mixing or overturn occurs once a year, the system is monomictic, twice a year - dimictic, and if mixing occurs more than twice a year, the system is polymictic.

Limnologists further divide meromictic systems into ectogenic and endogenic (Table 1). Ectogenic indicates stratification is a result of an external water or brine source. In contrast, endogenic means stratification relates to a brine or water source derived locally within the water mass or column. In an annual cycle, an ectogenic water mass tends to be permanently stratified, typically due to fresher or less saline-water spring seeps, or runoff-fed inflows, feeding an upper water layer overlying a more saline lower mass. This situation typifies many perennial coastal seepage sump lagoons and salina depressions in arid settings, where seawater either seeps into a hydrographically-isolated sump or occasionally breaches a coastal barrier during an intense storm. Breaching occurs times that often coincide with a storm surges or high spring-tides. The other ectogenic situation tied to evaporites, relates to the dissolution of a nearby salt mass, as in brine-filled salt-dissolution dolines, or DHALs (deep hypersaline anoxic lakes) atop shallow salt masses or allochthons on the deepsea bottom (Figure 1).

In continental ectogenic situations, such as the Dead Sea, the water source can be perennial, as in inflows from the Jordan River and several saline springs fed by the dissolution of shallow diapirc salt, or it can be from occasional wadi floods, fed by desert storms. Less-saline ectogenic situations in both marine and nonmarine settings can be a result of a turbidity flow setting up a lower water layer of particulate-laden water or brine. Turbid plumes can also augment an already existing brine bottom stratification, as in many DHALs on the floor of the Gulf of Mexico, the Mediterranean and the Red Sea.

Endogenic layered brines can be biogenically or cryogenically induced (Table 1). With biogenic stratification, there usually is a halophilic or halotolerant microbial biota flourishing at the halocline. Although a biogenic cause is widely cited for stratification in many meromictic lacustrine settings, such as Lake Mahoney and Soap Lake, in my opinion, the reality is more complex (Figure 3). Set up of an initial stratified biotic niche generally follows on from a preexisting physical stratification tied to longer-term isolation of the lower water mass (meromixis). The layered interface can be a salinity or chemical contrast that, with the activity of its anoxic versus oxic microbial community layers, becomes marked by significant changes in oxygen levels and metabolic segregation. Generally, in a saline setting, the primary chemical interface where a specialised biota flourishes, is ectogenically induced by salinisation or saline spring influxes, or endogenically by cryogenesis.

Biogenic stratification (e.g. Lake Mahoney)

Once a biological niche is established at a chemical interface, the favoured microbial population flourishes, as is the case with chemolithotrophic purple sulphur-oxidising

<table>
<thead>
<tr>
<th>Type of lake</th>
<th>Annual vertical mixing</th>
<th>Dominant factors contributing to or preventing vertical mixing</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Amictic</td>
<td>No appreciable amount</td>
<td>Permanent ice cover; slow internal mixing</td>
</tr>
<tr>
<td>2. Holomictic</td>
<td>Complete, at least once</td>
<td>Predominantly wind energy; convection currents (* mixing in a evaporite system is driven by solar evaporation increasing the salinity and density of the upper water mass until it attains that of the lower water mass and mixing occurs)</td>
</tr>
</tbody>
</table>

| a. Monomictic | Once |
| b. Dimictic   | Twice |
| c. Polymictic | More than twice |

<table>
<thead>
<tr>
<th>3. Meromictic</th>
<th>Permanently stratified or interruption of stratification patterns at irregular intervals</th>
<th>Chemically-enhanced density stratification</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Ectogenic</td>
<td>Permanently stratified</td>
<td>1. Surface inflow of (a) fresh water overlying a pre-existing more saline stratum, (b) hypersaline water underlyng a somewhat fresher stratum, or (c) basal turbidity currents of particulate-laden water. 2. Subsurface inflow of fresher or saline waters (= crenogenic)</td>
</tr>
<tr>
<td>b. Endogenic</td>
<td>Permanently or temporarily stratified</td>
<td>Chemically-enhanced density stratification contributed by biological processes with accumulations of bicarbonate or iron/manganese ions in lower stratum and shelter afforded by morphometry of lake basin and surrounding topography</td>
</tr>
<tr>
<td>i. Biogenic</td>
<td>Permanently stratified</td>
<td>Same factors as biogenic meromixis, but borderline stability conditions where unusual climatic conditions can lead to omission of spring or fall overturn and accumulation of hypolimnetic ions</td>
</tr>
<tr>
<td>ii. Temporary biogenic</td>
<td>Temporary elimination of complete circulation (spring or fall)</td>
<td>Same factors as biogenic meromixis, but borderline stability conditions where unusual climatic conditions can lead to omission of spring or fall overturn and accumulation of hypolimnetic ions</td>
</tr>
<tr>
<td>iii. Cryogenic</td>
<td>Permanently stratified</td>
<td>Deep-water accumulation of salts precipitated by freeze concentration from a surface ice layer</td>
</tr>
</tbody>
</table>

Table 1. Classification of lake types with respect to origin of layering in water column (after Wetzel, 2001, with slight modification by author)
bacteria inhabiting the chemoclines of Lake Mahoney and Soap Lake.

Mahoney Lake is a small, up to 15 m-deep meromictic oligotrophic mesohaline lake, located near Okanagan Falls in British Columbia, Canada (Figure 3a). The lake originated as a glacial kettle, after the retreat of the Wisconsin ice sheet some 13,000 years ago. Today, a halocline at a depth of around 6 m in the lake brine column, separates a variably-oxygenated and seasonally ice-covered mixolimnion from a permanently-anoxic, sulphidic (H\textsubscript{2}S-rich), saline monimolimnion (Figure 3b). Total dissolved solids vary from 10,000 mg/litre near-surface to 85,000 mg/litre near-bottom, with rapid changes across the halocline (for reference, seawater = 35,000 mg/l). The high salt content of the bottom waters in this small endorheic basin is thought to indicate endochemical weathering of alkali-rich Tertiary-age rocks of the Marron Formation.

Mahoney has been a saline meromictic/holomictic lacustrine system for the last 9,000 years, with some meromictic episodes lasting as long as 1,100 years. The oldest Lake Mahoney sediment layers containing okenane are 11,000 years old. Okenone is a carotenoid molecule (pigment) that diagenetically alter to the biomarker okenane, which is a purple sulphur bacteria biomarker. Okenane sedimentation likely indicates ongoing times of brine stratification, with persistent dysaerobia to anoxia in bottom brines (Figure 3b; Overmann et al., 1993, 1996; French et al., 2015).

Heterotrophic bacterial production in the lower mixolimnion of Lake Mahoney at times exceeds concomitant primary production in the upper waters of the same mixolimnion by a factor of 7. In this highly productive sulphidic interface lives an extremely dense population of the phototrophic purple sulphur \textit{Lamprocystis purpurea} (aka \textit{Amoebobacter purpureus}), which is present year-round as a dense purple layer or "bacterial plate" centred on the lake halocline (in part after Overmann et al. 1993, 1996). Bacteriochlorophyll\(^2\) is the pigment utilised by \textit{Amoebobacter sp.}, when during anaerobic photosynthesis it best absorbs light in the purple and infrared ranges (Figure 4b).

The Mahoney Lake halocline harbours the densest population of phototrophic sulphur bacteria ever reported in a natural body of water. The bacteria are sufficiently abundant to form the base of a chemosynthetic food chain, where bacteria constitute 70% of the diet of planktonic copepods living in the upper water mass.

**Light penetration and coloured brine layers**

The evolution of a halocline niche for purple sulphur-oxidising bacteria at the low-light Lake Mahoney halocline is in part related to their characteristic bacteriochlorophyll pigmentation. Bacteriochlorophyll facilitates anoxygenic photosynthesis, a microbial metabolism exploiting the nutrient-rich low-light interface between oxic waters and anoxic brine. In general, a loss of various colour spectra as white light penetrates deeper into a brine column or sediment controls the evolution of most halotolerant light-adapted layered photosynthetic microbial communities. These communities of photosynthesisers and heterotrophs occupy a set of vertically layered niches by utilising a range of colour-specific pigments in increasingly deeper and darker brine interfaces.

Even in the absence of a photo-responsive biota, the short-wavelength reds and yellows in incoming solar white light are attenuated within a few metres of the brine surface (Figure 4a). Infrared wavelengths are absorbed in the upper metre or so of penetration. In contrast, longer wavelengths in the blue/violet colour spectra can penetrate up to 100m in a transparent brine column, depending on water turbidity (Figure 4a). A similar microbial community-layered response to light absorption also explains mm-
scale coloured layers in microbial laminites and mats (see Warren, 2016, Chapter 9 for microbial detail). Although cyanobacteria are prokaryotic, like eukaryotic algae and higher plants, they are photoautotrophs that produce oxygen via chlorophyll-facilitated photosynthesis. Cyanobacteria also utilise the pigment phycocyanin, while red alga utilise phycoerythrin. Chlorophyll-based photosynthesisers live in oxic settings where light, nutrients and CO₂ are available, and the chlorophyll pigmentation absorbs a range of light energies (Figure 4b). In the upper parts of the oxygenated brine column, chlorophyll (a & b) absorbs red and blue wavelengths much more strongly than green, so chlorophyll-bearing cyanobacteria and most photosynthesising halotolerant plants appear green (Figure 4b).

Thanks to the presence of chlorophylls and C-40 carotenoids (mostly all-trans- and 9-cis b-carotene), halotolerant photosynthetic cyanobacteria and eukaryotes contribute green-blue to the coloration of layers hypersaline waters. Whenever the Dead Sea blooms across a freshened and oxygenated upper water layer, the spread of *Dunaliella sp.* is mapped by the expansion of zones of green colour. These expanding greenplanktonic blooms are sourced in the Sea’s strandzone, from local spring-fed brackish refugia. In refugia, populations survived and thrived year-round, isolated and cached in shallow lit spring-fed bottoms and fissures, while across the rest of the Sea holomictic surface salinities were too high for *Dunaliella* to endure (Haüsler et al., 2014; Salty Matters, September 30, 2018).

Carotenoids and phycobiliprotein pigments strongly absorb green wavelengths (Figure 4b). Hence, hypersaline waters supporting microbes and algal cells with large amounts of carotenoid pigments appear yellow to brown. Those with large amounts of phycocyanin appear blue, and those with large amounts of phycoerythrin pigmentation appear red.

Thus, the pink to purple colours that typify biotal adaption to elevated salinity and lower light levels in many hypersaline waters and haloclines comes from concentrations of mostly carotenoid pigments in the

Figure 4. Light and life (in part after Warren, 2016; Chapter 9). A) Spectral attenuation of the spectra in sunlight penetrating water varies with depth, showing different wavelengths penetrate to different depths (from Wikipedia - Tomemorris). B) Absorption spectra of the chlorophylls (a & b), b-carotene and phycobilisomes (phycoerythrin is found in blue-green coloured cyanobacteria and phycocyanin in red alga). C) Temperatures attained during the course of a day by flasks of brine of saltern crystallizer brines of the same specific gravity but enriched with different densities of red halobacteria (Data of Hilario Estrada, Exportadora de Sal, Baja California and reported in Javor, 1989).
Table 3. Heliothermal layered water bodies and their origins (extracted from SaltWork 1.7 database)
cytoplasm of halophilic microorganisms inhabiting the lit upper part in the stratified brine column. Lit brine layers rich with halocarchaea are red, due to a high content of C-50 carotenoids of the bacterioruberin series in the cell membrane (Warren, 2016; Chapter 9 for biogeochemical detail).

Microbes that undertake anoxic photosynthesis can do so in deeper waters in oxygen-depleted brines if they contain blue or purple pigments, as is the case with the sulphur-oxidising bacteria thriving at the dimly-lit haloclines in Soap Lake and Lake Mahoney. Light absorption by their purple pigmentation likely contributes to the in-column temperature peak (heliothermal-biogenic) layer in these and other biogenically stratified saline lakes (Figure 6). Thus, pigment levels in any photoresponsive layered halobiota can be a pointer to density stratification in the brine column.

An interesting experiment confirming pigment-related brine heating was conducted by H. Estrada and published in Javor (1989, p. 17). Estrada collected flasks of hyper-saline brine from the Exportadora de Sal saltern in Baja California, Mexico. Flasks of crystallizer brine with various halobacterial enrichments corresponding to red halobacterial densities were achieved by including 0, 0.1, 0.5 or 1.0% peptone in the sampled brines. Flasks were placed in the sun and temperatures recorded over a 6.5-hr period (Figure 4c). Redder, more turbid brines not only heated faster but attained higher temperatures than more transparent brines, even though all the brines were heated significantly over the maximum ambient temperature of the day (23.3 °C). Estrada’s experiment supports the general observation among saltern workers that saltern crystallizer brines, which are coloured red by halobacteria, retain more heat than clearer brines, due to lower reflectance of the reddened brines.

Biogenic stratification with photic layering of pigment-rich lifeforms, and heat absorption by mineral particulates suspended at the halocline, helps explain mid-column biogenic heat spikes observed in heliothermal systems. A

<table>
<thead>
<tr>
<th>Name &amp; maximum temp. (°C)</th>
<th>Country</th>
<th>Koeppen-Setting</th>
<th>Hydrology</th>
<th>Area (km²)</th>
<th>Comment_1</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Cnei (54)</td>
<td>Romania</td>
<td>Dfb</td>
<td>Salt diapir doline</td>
<td>0.18</td>
<td>Small lakes in salt dissolution dolines atop 2 cropping salt domes occurring near the city of Turda and mined since Roman times. There are about 20 small ponds on the crests of these domes.</td>
<td>Kirkland et al., 1980</td>
</tr>
<tr>
<td>Lake Kuchuk, (31) (Kuchukskoye)</td>
<td>Russia</td>
<td>Dfb</td>
<td>Hypersaline lake</td>
<td>51.43</td>
<td>Cryogenic NaSO₄ lake with water mirabile altering to thenardite. Halite and gypsum are co-precipitants</td>
<td>Sonnenfeld and Hudec, 1980</td>
</tr>
<tr>
<td>Lake Chapchachi, Tuva region</td>
<td>Russia</td>
<td>BS</td>
<td>Salt diapir doline</td>
<td>0.79</td>
<td>Solution lake on the Chapchachi salt dome</td>
<td>Sonnenfeld and Hudec, 1980</td>
</tr>
<tr>
<td>Lake Dus-Khol, Baikal region</td>
<td>Russia</td>
<td>Dwc</td>
<td>Cryogenic</td>
<td>5.1</td>
<td>Cryogenic NaSO₄ lake</td>
<td>Oidupor et al., 2014</td>
</tr>
<tr>
<td>Lake Goluboye (9)</td>
<td>Russia</td>
<td>Dfb</td>
<td>Carbonate karst doline</td>
<td>0.21</td>
<td>Small stratified lake in karst doline. 256 meters maximum depth (40 meters avg) and just 15 minutes to walk around. Maintains bottom temp 9°C in winter increased to 16°C in 20°C in summer</td>
<td>Sonnenfeld and Hudec, 1980</td>
</tr>
<tr>
<td>Solar Lake (52)</td>
<td>Sinai</td>
<td>BWh</td>
<td>Coastal marine lake</td>
<td>0.38</td>
<td>Marine seep saline with mid summer temp around 52°C, 5 m deep pond. Chlorinity increases from 42.6 g Cl/l to 90.7 g Cl/l at bottom.</td>
<td>Por, 1963; Eckstein (1970)</td>
</tr>
<tr>
<td>Lake Mahega (40)</td>
<td>Uganda</td>
<td>Aw</td>
<td>Volcanic maar lake</td>
<td>1.49</td>
<td>A rare type of thermal stratification with the warmest water at 1 meter depth (40°C) in this crater lake located in the Rift Valley of Uganda. Northupite is accumulating the the lake sediments</td>
<td>Kilham and Melack 1972; Melack and Kilham 1972</td>
</tr>
<tr>
<td>Hot Lake, Washington State (60)</td>
<td>USA</td>
<td>Dfb</td>
<td>Salt mine sump</td>
<td>0.68</td>
<td>Lies atop an abandoned epomolite mine, is the lake develops the warmest “under ice” temperatures of any lake in the world (&gt;60C)</td>
<td>Zachara et al., 2016</td>
</tr>
<tr>
<td>Red Pond, Arizona USA (40)</td>
<td>USA</td>
<td>BS</td>
<td>Saline seepage</td>
<td>0.3</td>
<td>Small 2.2 m deep pond on Long-H ranch, with halocline around 1 m. Red pond is highly saline with constant top brine temperature 40°C, surface ranges 2-25°C.</td>
<td>Cole et al., 1967</td>
</tr>
<tr>
<td>Cinder Cone Pool, USA Zuni Salt Lake, New Mexico (40)</td>
<td>USA</td>
<td>BS</td>
<td>Volcanic maar lake</td>
<td>0.16</td>
<td>Saline maar pool on southern edge of Zuni Salt Lake. Bottom brine layer temperature 40°C. Salinity in maar and salt lake from salt springs, possibly sourcing Permian Salt in Holbrook Basin.</td>
<td>Bradbury, 1971</td>
</tr>
<tr>
<td>Soo Lake, Wash. USA</td>
<td>USA</td>
<td>BS</td>
<td>Saline seepage</td>
<td>9.1</td>
<td>Biogenic, not heliothermal, like Lake Mahoney. Monimolimnion, is hypersaline (140 g litre⁻¹), cold (6 to 8°C), and highly sulphidic, with anaerobic waters containing up to 200 mM sulphite. Mixolimnion, is brackish (around 15 g litre⁻¹) and aerobic.</td>
<td>Anderson, 1958; Sorokin et al., 2007</td>
</tr>
<tr>
<td>Lago Pueblo, Grand Rosary Island (45)</td>
<td>Venezuela Antilles</td>
<td>Oceanic</td>
<td>Coastal marine lake</td>
<td>0.96</td>
<td>Winter rainfall floats on seawater in in 5m deep portion of lagoon. This is followed by solar heating of bottom waters to 44-47°C.</td>
<td>Hudec and Sonnenfeld, 1974</td>
</tr>
<tr>
<td>Lakes Malu Raisol, Abalah, Tsv-Kef, Moskogolouch</td>
<td>Yakutia</td>
<td>Dfc</td>
<td>Salt diapir dolines</td>
<td>0.9</td>
<td>Located in the Kempendyay depression; the lakes are positioned next to salt diapirs and are fed by the ascending brine sources.</td>
<td>Sonnenfeld and Hudec, 1980</td>
</tr>
</tbody>
</table>

Table 3 (Cont’d). Heliothermally layered water bodies and their origins (extracted from SaltWork 1.9 database).
portion of the sunlight that penetrates a pigment-coloured bio-zone or particulate layer is absorbed and transformed into heat, either directly or by metabolic reactions including anoxic photosynthesis and various types of decomposition. The remainder of the light is reflected into the atmosphere either from particulate matter suspended in the column or, if shallow, from the bottom of the water body, especially if covered by a high-albedo mineral layer such as halite crust.

**Cryogenic stratification**

In cold saline lacustrine climates, the dense lower portion of a cryogenically layered brine system tends toward permanent stratification (meromixis) in an annual cycle. Layering sets up when the upper part of a saline water mass freezes and floats, resulting in sub-ice brine plumes and fingers, brine icicles and a denser colder basal brine cover (see Part 1 of this series for detail of physical properties of freezing hypersaline waters). When the ice cover later melts, it transforms into a layer of freshwater, that cannot easily penetrate the underlying dense lower brine layer.

Meromictic cryogenic stratification is present, not just in relatively small Antarctic desert valleys, but also in some of the earth's largest modern continental salt accumulations (especially of NaSO₄ salts - mirabilite and thenardite). Mined and quarried mirabilite (salt-cake) deposits are cryogenically produced by winter freezing of hypersaline lake brines, as in Lake Kuchuk (=800 km²) and Korabogazgol (=17,500 km²) (Warren 2016, Chapter 12).

**Lake Kuchuk, Russia**

During the winter and occasional cool summer evenings, mirabilite (Na₂SO₄·10H₂O) crystallises from cryogenically-stratified Lake Kuchuk brine, potentially producing some 340-580 thousand mt/yr. Then, during the warm summer months, some of the mirabilite deliquesces to thenardite (Na₂SO₄). Associated dissolution and alteration deposits a limited amount of insolubles, creating thin layers of mud intercalated with the thenardite. Brine from Kuchuk has a 10-31% soluble salt content, depending upon the sea-son and lake level. Mirabilite precipitates annually in Kuchuk during the chilly winters, while, during summers, the level of the lake drops due to evaporation and surface brine becomes NaCl saturated, driving the transformation of mirabilite into thenardite across the lake floor (Stankevich et al., 1990). For most of the year, the brine is of the magnesium chloride type, but during the summer it changes to a sodium sulphate brine as the underlying mirabilite, thenardite, and glauberite (CaSO₄·Na₂SO₄) dissolve (Table 2).

Mirabilite is cryogenically produced for economic extraction, not in Lake Kuchuk, but the nearby pans of Lake Selitrennoe (Figure 5a). Every three years, at the end of summer, around 30 million tons of hypersaline Lake Kuchuk brine is pumped from the lake (Figure 5b) to cryogenic ponds in the nearby Selitrennoe Lake, in order to crystallise mirabilite during the autumn (Figure 5a,c). Residual brine in the Selitrennoe ponds is returned to the lake before winter sets in, and the ponds are harvest-

<table>
<thead>
<tr>
<th>Density</th>
<th>Viscosity</th>
<th>Na₂SO₄</th>
<th>KCl+NaCl</th>
<th>MgCl₂</th>
<th>MgSO₄</th>
<th>Mg(HCO₃)₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>1.218</td>
<td>2.33</td>
<td>6.64</td>
<td>15.55</td>
<td>4.39</td>
<td>-</td>
</tr>
<tr>
<td>Early winter</td>
<td>1.178</td>
<td>1.85</td>
<td>0.27</td>
<td>18.20</td>
<td>4.66</td>
<td>-</td>
</tr>
<tr>
<td>Mid winter</td>
<td>1.310</td>
<td>8.30</td>
<td>-</td>
<td>1.20</td>
<td>25.70</td>
<td>2.50</td>
</tr>
<tr>
<td>Lake winter</td>
<td>1.332</td>
<td>11.90</td>
<td>-</td>
<td>-</td>
<td>32.80</td>
<td>1.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.50</td>
<td></td>
<td>0.40</td>
</tr>
</tbody>
</table>

Table 2 Evolving chemical proportions in lower brine, Lake Kuchuk, Russia (after Strakhov, 1970).

Figure 5. Lake Kuchuk, Russia. A) Aerial view showing positions of perennial brine-filled Lake Kuchuk and nearby cryogenic mirabilite production pans that cover Lake Selitrennoe (©Bing image). B) View of shoreline of Lake Kuchuk (summer). C) Mirabilite/thenardite extraction from the Selitrennoe pans.
ed as needed to produce sodium sulphate (Charykova et al., 1996). Product purity from the ponds is quite high as much of the clay has already flocculated, and the brine inflow is pre-concentrated by solar evaporation in Lake Ku-chuck. Production in Seltrennoe Lake uses a combination of solar preconcentration and cryogenic precipitation.

**Heliothermal brines heating and heat loss**

The zonation of salinity within heliothermic brine masses is tripartite, as shown in figure 1. The upper least-saline water layer, the mixolimnion, is a zone of uniform salinity in which currents (generated either by wind or differences in water temperature) are free to circulate. The middle layer, the halocline or chemocline, is the zone responsible for the trapping and retention of heat. Salinity increases progressively with depth within the halocline, and this zone forms a transition between the mixolimnion and the underlying monimolimnion, which like the mixolimnion, tends to be isohaline. In general, the monimolimnion is a chemically-stable zone of relatively dead or stagnant (persistent) anoxic brine in the lower part of a heliothermic lake (Figure 7). Mesothermic is a more general descriptor of any water mass that has a temperature maximum at some depth below the water surface.

By definition, a heliothermic water body is a layered meromictic water body containing an internal zone of warmer water created by the absorption of sunlight in an

![Figure 6. Heliothermal layered lakes on a Koeppen climate base (re-plotted on Koeppen base from SaltWork database, version 1.9) See Table 2.](image)

![Figure 7. Brine column profiles of representative heliothermal water bodies (see Table 2). A) Ursu, Romania (von Kalecsinsky, 1901); B) Solar Lake, Sinai (Cytryn et al., 2000); C) Hot Lake, USA (Anderson, 1958).](image)
interval of persistent brine. Heliothermal water bodies develop across a range of climatic settings; all are the result of solar heating of a brine layer situated below a fresher water layer (Figure 6, Table 3). Lake Ursu, Romania, is a thick body of brine capped by a thin layer of much fresher water that fills a collapse doline in subcropping halokinetic halite. Ursu sits in a Dfb (snowy, humid with dry summer) Köppen belt (Figure 7a). Solar Lake on the Sinai peninsula is a hydrographically-isolated marine-fed coastal sump in a hot arid desert (BWh) climate belt (Figure 7b). Hot Lake, USA, is a hypersaline water body atop an abandoned epsomite mine in a former glacial kettle, also in a Dfb climate belt (Figure 6c).

Sunlight that penetrates into or through a heliothermal halocline zone can be reflected into the atmosphere from particulate matter floating at the halocline, or from the bottom of the lake, or it is absorbed and transformed into heat in the brine layers (Kirkland et al., 1980). The halocline of a heliothermic lake acts somewhat analogously to the glass panes of a greenhouse, in that it prevents heat loss by suppressing convection and radiation (Kirkland et al., 1983). Any heat from sunlight reflecting off the pan floor is mostly captured in the monimolimnion. Garrett (1965) calculated that a hypersaline salt pond covered with 15 cm of brine and a perfectly reflective bottom should retain >96% of the incoming solar radiation. Heat retention is even higher if the brines are turbid (Figure 4c). A relatively small amount of solar energy may be tied up as chemical energy by photosynthetic organisms.

Heat loss is greatly impeded in a saline brine mass below a halocline. Loss of heat by convection through the halocline is slowed because of the salinity-induced increase in specific gravity with depth and the resultant density induced layering. This compensates for any increase in mixing at the interface via Brownian motion related to a rise in water temperature in the denser brine. In addition, warmer water within and beneath the halocline will lose little heat via radiation as water is virtually opaque to long-wavelength infrared radiation (Figure 4a; Kirkland et al., 1983).

Convection occurs internally in both the monimolimnion and the halocline if they are of uniform density, but there is little convective mixing between layers. Heat is lost from the monimolimnion to the atmosphere by radiation, conduction, and evaporation. In contrast, heat is lost from below the halocline only by conduction through the halocline, or to the sides and bottom of the lake. Loss of heat by conduction through the halocline proceeds at a slow rate because any all brines, even when saturated with sodium chloride (Kaufmann, 1960), are poor conductors and thermal conductivity decreases with increasing salinity. Rabl and Nielsen (1975) noted that one metre of nonconvecting brine is as good an insulator as a five-cm layer of styrofoam.

Heliothermal waters showing the highest temperature contrasts have hypersaline lower water masses and formed in steep-sided sumps and dolines, where wave mixing is minimal (Table 3). Providing the halocline resides and persists at water depths where sunlight can penetrate, preferential heating of the upper part of the denser brine layer is the result of light penetration and heat retention, due to its lower specific heat capacity and lower thermal conductivity.

![Figure 8. Selected heliothermal waters, quantified (see also Table 3). A) Latitude versus temperature of lower water layer B) Area vs depth to halocline (replotted from data in SaltWork database 1.9)](image-url)
The majority of heliothermal settings tend to be steep-sided and with small areas (<3 km²), creating a combination that minimises the effects of wind and wave mixing (Table 3, Figure 8a). Depth to the halocline is independent of climate (Figure 8b) and is more related to the clarity of the water mass atop the halocline. Accordingly, ice-covered Lake Vanda, which is perhaps the most transparent water body in the world, has a halocline some 50 metres below the ice surface and a perennial 26°C, CaCl₂-rich bottom brine (Figure 9a). Relatively-deep lit and heated haloclines are also set up in brine-filled solution dolines in carbonate or halite karst terranes, as in South Andros Island and the halite-floored Romanian dolines, respectively (Figure 8b). Settings with highly-saline brine understories that are open to wind and waves can remain layered, even when the halocline is only tens of centimetres deep. Worldwide, this proves persistent bottom brine stability inherent to a sharp salinity/density contrast. A strong halocline makes it difficult for the freshwater cap to mix with a perennial brine, especially the understorey at salinities near halite saturation. The upper fresher brine in such hydrologies is usually lost and mixing occurs once the upper layer is heated and concentrated via ongoing evaporation to levels where the upper and lower densities equalise.

Heliothermal temperature contrasts and absolute temperatures in saline mesothermic zones can be substantial (=60-70°C; Table 3). Worldwide most heliothermal locations, even those with robust temperature contrasts, are unrelated to nonsolar heat sources. That is, there are no effective inflows of warm juvenile or magmatic-hydrothermal waters (Figure 6, Table 3).

This is true even for the ice-covered Lake Vanda in Antarctica. In the decade after its discovery, many invoked some degree of geothermal input to help explain perennial 26°C temperatures in the deep bottom brines in the perennial polar frost (EF) climate of Antarctica. But geothermal sources were not found. The heating of the Vanda bottom brine is a response to sunlight passing into the water column, via a 4m-thick ice cover, and the cryogenic fractionation as saline water freezes, creating a dense bottom brine some 50 m below the ice-covered surface (Figure 9a; Bydder and Holdsworth, 1977). There, this unusually arid Antarctic desert (Wright Valley) has created a CaCl₂ brine hydrochemistry in the perennial glacial meltwater lake and the surrounding groundwaters (Figure 9b). Similar brines are precipitating antarcticite, a hydrated CaCl₂ mineral, in the nearby Don Juan saline pan or pond, (Salty Matters, May 31, 2017).

Elsewhere, there are other warm brine-covered mesothermal bottoms, well out of the reach of sunlight, such as the DHALS of the Atlantis II Deep, the Mediterranean Ridges and the Gulf of Mexico. These are not heliothermal hydrologies. Rather, escaping basinal, hydrothermal and juvenile waters explain elevated temperatures in these layered perennial brine lakes on the deep seafloor (see Salty Matters April 29, 2016; August 31, 2018).

Timing of meromictic hypersaline overturn is not yearly

Salinity zonation in a meromictic or heliothermal brine body may be ephemeral or perennial, with the bottom brine layer tending to be longer-term than the overlying fresher water or brine. Longevity of heliothermic conditions tends to depend on the degree of protection from processes that breakdown the salinity stratification and (or) temperature gradient and thus permit convection or vertical mixing. The most common driver of vertical mixing in perennial evaporitic settings is no the loss of the lower brine layer, but the concentration of the upper water mass driven by solar evaporation.

And so, there is a significant difference when using Wetzel’s (2001) meromictic lacustrine classification in modern and ancient stratified evaporitic brine hydrologies. That difference is the lack of annual timing to overturn events due to
the persistence of a bottom brine layer. Biologists and limnologists, especially those working in temperate freshwater lakes, tend to think of a lake’s layered column in terms of climate-driven annual changes (Table 1). The presence or absence of annual stratification (mixing) in the lake water column is generally driven by a combination of wind/wave energy and seasonal changes in ambient air temperature over the water body. Likewise, in temperate colder climes with seasonally cryogenic overprints on the water column, like Lake Kuchek or Hot Lake (Dfb climates), there are significant seasonal changes between winter and summer temperatures in the upper water mass. As well, there is an increased volume of fresh water entering the lake during seasonal times of more intense precipitation or ice melt (e.g., Lake Mahoney).

In contrast, long-term layered water masses accumulating evaporite beds tend to typify arid warm to hot desert and steppe conditions in steep sided sumps (Warren, 2016; Chapter 2). There, the timing of major influxes of freshened less-dense waters can be further apart than annual and the volumes of inflow are much less predictable. Freshening events can be driven by occasional desert storms or hurricanes or extreme sea floods. For example, continental evaporites accumulating in the Dead Sea are a response to decades to centuries-long alternations between meromictic and holomictic periods (Figure 10, Warren, 2016; Chapter 4).

Until 1979, Dead Sea waters were meromictic or "permanently stratified" and had been so for 300 years (Stiller and Chung 1984; Neev and Emery 1967). Density measurements between 1864 and the mid-1970s document a well-developed permanent halocline and thermocline at a depth around 50 metres (Figure 10a). The average temperature of the upper 50 m of the water body was between 16 and 36 °C and density around 1.205 g/cc, while at brine depths greater than 50 m, the temperature was a constant 21.5 °C and the water density was 1.232 g/cc (Figure 10b). But in the 1960s and 70s, the lessening inflow from the Jordan River meant the surface water mass became increasingly saline, and the permanent pycnocline deepened. In 1975 the halocline (’pycnocline’) was some 100 m below the lake surface, and the upper water mass had a density of 1.229 g/cc. (Figure 10a) In February 1979 the densities of the upper and lower water masses equalised and the lake overturned, whereby the lower water mass mixed with the upper water mass and, for the first time in centuries, the Dead Sea became holomictic (Figure 10b, Steinhorn, 1985).

Overturn was marked by a strong and persistent H2S smell as bottom waters came into contact with the atmosphere for the first time in hundreds of years. Before the 1979 overturn and since its last holomictic period some 300 years earlier, the lake had been continually stratified

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3 Pycnocline is a layer in an seaway or other body of water in which water density increases rapidly with depth.
Overturn has occurred several times in the lake's Holocene history and these episodes are marked by beds of massive coarsely-crystalline deepwater halite. Such a bed has been accreting on the Dead Sea floor for the past 40 years (Salty Matters, August 31, 2018).

Textures indicative of stratification timing

Mixing in a saline water mass is controlled by the evaporation and concentration of the upper water mass and mixing (holomixis) occurs once the upper brine layer concentrates to where it reaches a density equivalent to the lower water mass (Figures 10, 11). With equilibration, mixing or overturn occurs. The lower water mass in a density-stratified saline system is a stable system, so that where a hypersaline water mass is density-stratified, there is little bottom precipitation of salts as there is no regional concentration mechanism increasing the salinity or saturation of the lower brine mass (Figure 11; Briggs, 1958). Subaqueous sedimentation is mainly from a pelagic rain of crystallites, which first precipitated either in the uppermost part of the upper water mass or by brine mixing at the halocline.

Whenever the upper and lower water masses equilibrate and homogenise, bottom nucleation of salts is possible even at the base of deep brine columns, as is occurring in the Dead Sea today (Sirota et al., 2017). Whenever a homogenised water mass restratifies, the rate of brine reflux into sediments below the sediment-brine interface slows and ultimately stops, for there is no ongoing mechanism to resupply brines denser than pore waters in the substrate to the dense lower water mass.

Refluxing brine plumes beneath homogenised surface water masses sink and at the same time start to spread laterally toward the basin fringes where they mix with incoming forced-convection waters of the seaway or playa margin. Ultimately, dense plume waters can return to the surface in a diluted form as a component of spring or seep waters, or they can be lost to the regional hydrological flow. Reflux-driven convective flow is an effective way of moving salt load through large volumes of basin sediments in modern saline depressions (e.g. Lake Tyrell, Australia: Warren 2016, Chapter 2) and also explains the distribution of salts, pseudomorphs and dolomites in ancient sediments that underlay or were adjacent to areas accumulating bedded salts (Part 3 in this series of articles).

Textures indicative of brine stratification

The hydrology at the depositional surface in an evaporite basin controls the textures of the accumulating salt bed, independent of the salt's mineralogy. I will focus on textural evolution of the infill in a Holocene gypsum salina. Gypsum coastal sumps are perhaps one of the more accessible natural hydrologies across various modern evaporite settings. Most gypsum-filled coastal salinas in southern Australia preserve a sediment pile exposed when the phreatic surface fell below the highest level of the salina water table. For simplicity, the carbonate rim is not shown.

![Figure 11. Water mass zonation and sedimentation in a perennial brine lake or seaway. A) Nonstratified or holomictic. B) Chemically stratified or meromictic (after Warren 2016).](image-url)

![Figure 12. Gypsum facies in South Australian salinas, after Warren 1982, showing domes overlain by laminites and the eolian reworking of upper portions of the salina sediments into gypsite-capped lunettes. For simplicity, the carbonate rim is not shown.](image-url)
atic beds are pumped down to be quarried for wall-board manufacture, so exposing vertical faces that preserve a variety of gypsum textures in the quarried faces. The same is not true of modern halite, NaSO$_4$ or NaCO$_3$ plants, where product is recovered via the construction and scraping of anthropogenic saline pans, typically with sequential gravity and sluice-gated brine feeds, along with periodic pumping of pooled brine from one pan into another. This brine plant is dominantly a two-dimensional exposure and does not give exposed vertical faces in these mineralogies. However, the same principles of textural response to brine stability and permanence of chemical/hydrological layering are preserved in vertical sequences from all primary evaporite beds, be it composed of gypsum halite, trona, etc (e.g. Quaternary halite cores documented in Death Valley and Salar de Atacama, Lowenstein et al., 1999 and Bobst et al., 2001, respectively).

Once sealevel returned to its present level around 6000 years ago, Holocene gypsum salina sedimentation along the southern and western coasts of Australia began in hydrographically-isolated coastal sumps (Warren, 2016; Chapter 4). The rise in sealevel to its current coastal position set up marine seepage-fed brine-filled meromictic sumps, with salina water surfaces maintained, via evaporative drawdown and brine replenishment, within 0.5 m of present-day sealevel (e.g. Lake McLeod, Lake Macdonnell, Marion Lake Complex - see Warren 1982, 2016 for geological detail). Over the next few thousand years, as the sedimentation surface rose toward the seepage-maintained longterm water surface, conditions at the depositional surface evolved from deeper subaqueous to ephemeral. Various coastal salinas filled with mostly subaqueous gypsum beds preserving characteristic vertical and lateral changes in texture and mineralogy that directly tie to the formative hydrology.

With coarsely crystalline gypsum fills (selenite-dominant), the most common vertical transition is from domes to layers, in turn passing up into variable laminated and cross-bedded gypsarenite beds (Figure 12). Laterally the lithofacies change from a perennial brine sump composed of gypsum beds to a freshened marine spring-fed aragonitic margin. Overall, the vertical shift in textures in coarsely crystalline gypsum units in the central sump positions shows the following: 1) Degree of lamination increases and dome amplitude decreases upwards as domes of gypsum crystal meshworks pass into sub-horizontally layered and laminated units made up of sub-vertically aligned gypsum crystals (Figure 13 a,b). 2) Higher still, individual enclosed-laminae of pelletal and micritic aragonite appear to crosscut large upwardly-aligned gypsum crystals (Figure 13c).

Gypsum is not only deposited as coarse-grained gypsum (selenite) in central sumps South Australian coastal lakes. Salinas are filled with laminated gypsarenites and are probably as common, if not more common, than those filled with the geologically purer, and hence more economically compelling, coarsely-crystalline gypsum selenite. Laminated gypsarenite fills large interdunal corridors near Streaky Bay and Point Fowler in South Australia and Hutt and Leeman Lagoons in Western Australia (Warren, 2016; Chapter 4).

In salinas with coarse-grained fills, the coarsely-crystalline laminated selenitic gypsum unit, punctuated by carbonate laminae, is in turn overlain by a mm-laminated, sand-sized gypsarenite accumulations (Figure 12). Parts of the
horizontally-laminated gypsarenite unit, especially near asalina strandzone, can be reworked into wave-oscillation ripples (Figure 14).

Laminated and rippled gypsarenite is in turn overlain by a thin, massive, poorly-bedded gypsarenite unit deposited under seasonally vadose or subaerial conditions and represents accumulation in the salina capillary fringe. This is the style of sedimentation that characterises the current saline pan stage of salina fill.

Topping the whole succession is a supra-sealevel unit of cross-stratified eolian gypsum and, in areas stabilised by vegetation, a pedogenic cap of silt-sized gypsite (Figures 12, 13d)). Throughout coastal and inland Australia, this gypsum soil is a degradational profile that is slowly cannibalising depositionally inactive regions of both lacustrine and eolian gypsum lunettes (Salty Matters, June 30, 2017).

Formative hydrology

Early stages of subaqueous infill in a Holocene coastal salina are characterised by a sedimentation surface that accreting as aggrading gypsum domes. The constituent gypsum is euhedral, and the degree of crystal alignment increases with the upward passage in a dome. The domes accreted when the overlying water column was holomictic and brines were at gypsum saturation (Time 1). While bottom crystal precipitation occurred, the dome’s crystallisation surface was never in contact with undersaturated bottom water. The end-result of this meromictic bottom hydrology was a coarsely layered porous euhedral growth-aligned crystal meshwork made up of palmate and aligned swallowtail gypsum (Figure 15 - time 1).

As the salina fills with coarsely-crystalline gypsum, vertical accretion toward a hydrological base level (sealevel) and mixing (possibly annual) means the base of the monolimnion comes into contact with the aggrading crystallisation surface. Accretion in the brine lake decreases the volume of free water; this contact and mixing with freshened water can happen before the holomictic (mixed) water stage reaches gypsum saturation (time 2). Such contact with undersaturated waters creates subaqueous horizontal planation surfaces. Subhorizontal planation occurs both in saline basins subject to complete desiccation and in those parts of evaporite seaways covered by perennial brine sheets (tens of cm deep) subject to periodic freshening (Warren 2016, Chapter 2 for more detail).

The freshened free water layer (time 2) only dissolves the uppermost portion of the accreting gypsum bed; it does not displace the much denser pore brines that saturate the bulk of the underlying bed. A characteristic horizontal planation surface defines the top of saturated pore brines. These flat, laterally extensive dissolution surfaces typically truncate the tops of previously growing crystals, be they trona, halite, gypsum or any other bottom nucleating salt (Figure 15; Time 2). As the freshened water body begins to concentrate, it firsts precipitates a less saline mineral phase (aragonite in the coastal salinas), and this aragonite ultimately settles onto the planation surface (generally after its pelletisation by either the pelagic or grazing benthic halobiota).

As the freshened water body continues to concentrate into salinities that precipitate the gypsum, the aggrading, aligned, coarse-grained gypsum sub-crystals that underlie the planation surface now poikilitically enclose a layer of less saline precipitates (e.g., laminae of aragonite pellets in laminated coarse-grained gypsum; Figure 13c - Time 2 in Figure 15).

Such large aligned gypsum crystals, crosscut by carbonate laminae, at first sight, appear secondary and their Miocene equivalents in the Sicilian Basin were once interpreted as secondary gypsum after anhydrite (Ogniben, 1957). But the identical Holocene gypsum in the South Australian salinas is primary with is long axis sub-perpendicular to bedding, the result of primary crystal impingement and growth alignment (Figure 13c).

Gypsum sediment continues to fill the salina beyond the laminated selenite up to its hydrological base level. As the sedimentation surface in the perennial water body aggrades toward the seepage-controlled base level, the volume of free-standing brine decreases, and the proportion of fresh-
er (meteoric) water in the annual brine volume increases. This leads to the deposition of laminar gypsarenite above the selenite unit, and ultimately, when the surface becomes seasonally vadose, to the drying of the uppermost part of the sediment column. Desiccation of sediment above the capillary zone facilitates aeolian transport into lunettes, which form best along the downwind edge of the salina.

In any marine-seepage fed salina, the hydrological base level of the free-standing water surface is a few centimetres to tens of centimetres below sealevel. This base-level is finite within each interglacial fill cycle as the free-water surface in any marine-seep fed coastal salina must always be just below sealevel. The pull of gravity and a liquid’s inability to support shear, means the surface of an unconfined marine phreatic aquifer will forever remain potentiometrically downdip of sealevel (Warren, 1982).

Not all gypsum salinas are filled with coarse-grained growth-aligned selenitic gypsum; some are dominated by mm-laminated gypsarenite. The difference in crystal texture of the salina infill relates to the rate of transition of the brine body into gypsum saturation (Warren, 1982). If the annual rate of salinity passage is gentle and slow, as it is at the bottom of a stable holomictic water body, that is metres deep, then coarse-grained holomictic gypsum textures dominate. They nucleate off, and grow in, crystallographic continuity with a preexisting gypsum substrate. If the passage to gypsum saturation is more rapid, then coarse-grained holomictic gypsum textures dominate. They nucleate off, and grow in, crystallographic continuity with a preexisting gypsum substrate.

Figure 15. Growth-aligned gypsum shows internal textures are controlled by the gypsum growth surface interacting with the stability and salinity of bottom brines. In the early stage of fill (Time 1), when the brine lake is deeper, the bottom brines are stable and salinities do not ever decrease to where they become undersaturated with respect to gypsum. “Mantled” textures result. When the sediment surface aggrades to where bottom brines freshen (Time 2), then the periodic dissolution of the upper part of the growth surface dissolves and mm-laminated textures form. The present stage of sediment fill (Time 3) is where the brine lake has been filled to equilibrium with the local marine-seepage watertable, eolian reworking of seasonal gypsarenite precipitates is the dominant mode of deposition (after Warren, 1982, 2016).
shallower perennial water bodies, then multiple nucleation sites and multiple sand-sized gypsum prisms characterise bottom sedimentation. When the uppermost layer of such a shallow hypersaline water body freshens with meteoric input, then pelagic lamina of aragonite pellets settle out, prior to the next holomictic gypsum stage. This is why the gypsum fill in some South Australian salinas is dominated by laminar gypsumrenite, not laminar selenite. In such sand-sized gypsum-infill systems, there was insufficient topography or insufficient rates of marine groundwater inflow to maintain a stable, deep- perennial gypsum-saturated basal brine layer. In other salinas, beds of laminar selenite are interlayered with beds of laminar and wave-ripped gypsumrenite, reflecting differing topography in the depositional setting, or millennial-scale changes in climate.

Broader implications of texture in variably layered depositional hydrologies

All primary evaporite textures indicate hydrology in the depositional setting. Both gypsum and halite can grow displacively in the zone of capillary evaporation above a saline water table. Figure 16a illustrates displacive or capillary growth of halite in a core of Quaternary continental playa sediments from the Dallol depression. Worldwide, the gypsum desert roses that grow at the water tables of modern sabbhas, salinas and salina pans, are another example of capillary concentration of brines at a water table. In some perennial brine bodies (not the Holocene gypsum salinas of coastal southern Australia), gypsum can be a pelagic precipitate in the monimolimnion prior to the holomictic stage. In the holomictic stage in such settings, perennial bottom brines may attain halite saturation. Then pristine chevron halites are mantled by a pelagic combination of aragonite and fine-grained gypsum (e.g. current hydrology of the Northern Basin in the Dead Sea, some coastal sumps south of Khobar in Saudi Arabia - pers. obs, as well as the halite textures below the primary Neogene potash (kainitite) interval in the Dallol depression, Ethiopia - Figure 16b).

Crystal texture transitions also reflect the hydrology forming primary textures in a bedded potash deposit. For example, figure 16c illustrates the primary bedded nature of the Eocene sylvinite ore (at three scales) from a now-abandoned potash mine in the Mulhouse Basin, France. Two things are immediately apparent in this ore, even at the hand-specimen scale.

First, the ore body is constructed of multiple layers made up of brining-upward saline triplets. The base of each cm-scale triplet is composed of a sheet of fine-grained grey mud (dolomitic) and minor gypsum/anhydrite. This passes up into a layer of cloudy, bottom-nucleated and growth-aligned chevron halites. The abundance of brine inclusion layers, within each of the chevron layers, likely indicates daily (evening-cooling) prograde deposition. There is little evidence of any short-term (diurnal) dissolution of halite. As halite chevrons were aggrading, the depositional setting was likely a brine-covered saline pan with shallow halite-saturated holomict brines covering the depositional surface.

A sylvite layer mantles the halite layer in each triplet, with its underside covering the halite portion of the triplet, and infilling furrows on the halite triplet’s upper surface. The upper side of the sylvite portion of each triplet tends to be flat. The contrast in boundaries between the lower and upper sides of the sylvite portion triplet implies sylvite was a pelagic cumulate phase, precipitated at the air-brine interface, and it was not a bottom precipitate.

The second thing obvious at the hand specimen scale is that the ore bed is crosscut by numerous and multiple dissolution surfaces. These dissolution surfaces are not part of each triplet’s deposition, but cut down into one of more triplet layers. These dissolution surfaces always pass up into a grey carbonate mud layer that forms the base of a sylvinitie triplet horizon.

The illustrated textures indicate that two hydrological associations were creating the sylvinitie ore beds in the Mulhouse Basin. The first was a shorter-term triplet-creating, brining-upwards, subaqueous hydrology that deposited each cm-scale triplet. The second was the slightly longer-term set of freshening events creating numerous stacked dissolution surfaces throughout the ore beds. In combination, the textures imply the brine hydrology at the depositional site was subaqueous shallow and holomictic, and that many times in its history this saline pond was subject to freshening events that tended to dissolve and recycle preexisting potash triplets.

Then there are even longer-term freshening events not illustrated by the primary ore textures shown in Figure 16c. These longer-term events are associated with eogenetic evaporite drawdown and even later mesogenetic freshening episodes. These too alter the geometries and economics of a potash deposit and are discussed in Warren 2016, Chapter 11. We shall return to this topic of alternating deposition separated by longer-term dissolution events in the fourth of this series of articles on brine permanence in the section dealing with ore-enrichment processes.

Summary

Hypersaline brine layers below a less-saline and less-dense brine layer characterise depositional settings across many evaporite and cryogenic salt deposits. The halocline that separates the layers tends to prevent convective mixing and slows heat loss from the lower brine layer. If the halocline resides at depths where sunlight penetrates, then it can set up a long-term reverse or heliothermal stratification. In any perennial brine body (evaporitic or cryogenic) the
Secondary halite precipitated in clays in the capillary zone (above the water table).

Primary-aligned subaqueous halite beds (chevrons and cornets) precipitated in holomictic bottom brines at the base of a periodic meromictic set up. Mantling of halite and lack of dissolution surfaces imply the depositional surface was permanently below the halocline but with the occasional emplacement of a less saline upper water mass (mixolimnion), when pelagic CaSO₄ crystallised in the upper waters. This was before the onset of next holomitic stage when primary bottom-nucleated euhedral chevron halite grew once more.

Potash ore shows primary interlayers of growth-aligned chevron halite (cloudy white) and sylvite (red) with carbonate/insolubles (thin grey) illustrated at three scales (i, ii, iii). The depositional surface was subjected to ongoing and repeated freshening with dissolution scouring and etching prior to the onset of the next cm-scale brining cycle of carbonate (dolomitic and organic enriched) then aligned chevron halite then sylvite. The repeated alternation of freshening events followed by a concentration cycle of carbonate-halite then bitterns implies very shallow to ephemeral waters likely accumulating in an ephemeral saline pan.

Figure 16. Hydrological significance of selected halite textures. A) Quaternary capillary or skeletal (pagoda) halite growth in muds in the Dallol Depression, Ethiopia. Core depth 45 m depth) B) Neogene subaqueous aligned halite in the Dallol Depression, Ethiopia (core at 150 m depth). C) Eocene potash ore exposed in the mine wall. Mulhouse Basin, France. (see Warren 2016, chapter 11 for more details (Sylvite-halite photomicrograph after Lowenstein and Spence, 1990)).
lower hypersaline brine layer (monimolimnion) tends to persevere, while the upper layer (mixolimnion) comes and goes. Evaporite and cryogenic textures accumulating on the bottom of a perennial brine lake or seaway reflect the presence or absence of meromictic or holomictic conditions in the column. As an evaporite bed infills its accommodation space, there is a predictable upward transition in crystallisation textures, indicative of evolution in hydrogeochemistry and permanence of formative brine layers and the level of freshening that can reach down to an accreting sediment surface. Primary evaporite textures in all evaporites are direct indicators of the hydrological state and the presence or absence of brine layering at the time of salt deposition.

References


