On the Significance of Evaporite Lamination

John K. Warren
Department of Geological Sciences
University of Texas
Austin, Texas, USA

ABSTRACT

Primary lamination in an evaporite is caused by periodic changes in the brine chemistry. Some geologists interpret laterally extensive, horizontal mm laminae in ancient evaporites as subaqueous "deep water" phenomena; others have said evaporite laminae can form under subaerial conditions. This dilemma of interpretation is in part due to the lack of subaqueous Holocene analogs. However, laminated and non-laminated evaporites are forming subaqueously in some Holocene salinas (saline groundwater lakes) along the southern coastline of Australia.

The overall facies pattern in the South Australian salinas is a bull's eye. Laminated and/or fenestral carbonates containing stromatolites and tepee structures surround a more basinward, relatively pure, gypsum unit. In some salinas the bulk of the gypsum unit is a mm laminated gypsarenite, in others the unit is composed of bedded to finely laminated coarser grained gypsum (selenite). The laterally extensive, mm laminated gypsum forms in a subaqueous environment where the brine pond is subject to periodic (but not necessarily seasonal) freshening. However, not all the subaqueous salina gypsum is laminated. In the deeper portions (< 10 m depth) of these density stratified brine ponds there are large, poorly layered domes of gypsum forming under a regime of continuously subaqueous, stable brines. A laminated gypsum unit always passes up into a non-laminated, relatively pure gypsarenite unit which formed in a seasonally vadose to subaerial environment.

In South Australian salinas a gypsum unit with a laterally extensive mm lamination forms in a subaqueous, not intertidal, environment. But, a non-laminated gypsum does not always form subaerially. If a reliable palaeoenvironmental determination is made in ancient evaporites, where gypsum is now anhydrite, then the morphology and textural relationships in such ancient laminated and non-laminated evaporites must be considered as primary indicators of paleohydrological stability. Lamination in the anhydrite probably indicates subaqueous deposition, but water depth can be best determined by studying evaporite textures in conjunction with a study of the depositional environment of the laterally equivalent limestones.

INTRODUCTION

Thick beds of laminated $CaSO_4$ rich evaporites occur in many ancient sedimentary basins. One of the best known is the Castile Fm. (Upper Permian) in the Delaware Basin of West Texas and New Mexico. Most geologists accept the Castile as our best example of a "deep water" evaporite and the diagnostic anhydrite-carbonate (organic rich) laminae as annual evaporite varves (Anderson et al., 1972; Dean and Anderson, 1978). The latest studies on this sequence have shown deposition of the Castile was controlled by climatic changes which were related to Milankovitch cycles (Anderson, 1982). Laminated organic rich $CaSO_4$ sediments are also characteristic of the subaqueous Otto Fiord Fm. (Miss. -Penn.) of the Canadian Arctic Archipelago (Nassichuk and Davies, 1980) as well as the Middle Devonian Winnipegosis Fm. in Saskatchewan and the shallow-water lagoonal deposits of the Ordovician Red River, Stony Mountain and Stonewall Formations (Shearman and Fuller, 1969; Kendall, 1973). Laminated gypsum is found in many Late Miocene (Messinian) sub-basins of the Mediterranean where Schreiber et al. (1976) have shown the lamination formed in subaqueous, euphotic zones.

Many Pre-Quaternary laminated anhydrites such as those of the Castile Fm. and the Winnipegosis Fm. can be followed over thousands of square miles. In the Castile Fm. individual anhydrite-$CaCO_3$ couplets have been correlated over distances of greater than 100 km (Anderson et al., 1972). In their study of the laminated cycles in the Castile, Dean and Anderson (1978) conclude that "water depth may have varied during individual salinity cycles, but the sediment-water interface was always below base." They reasoned that any evaporite sequence above fair weather wave base would be subject to reworking, so destroying any widespread correlation of lamina thickness. Kendall (1979) proposes such widespread laterally extensive laminae are one of the better indicators of evaporite deposition in deep water. Anderson and Kirkland (1966) used a similar shallow water argument to explain the relatively poor correlation of laminae thickness in the Jurassic Todilto Fm of New Mexico.

Laminated evaporites, with or without dark organic films have also been interpreted as "of algal origin or association" and in some cases such laminae have been used as a signature for tidal-flat, algal-rich environments (Shearman and Fuller, 1969; Kendall, 1979; Dean et al., 1975). It seems laminae in evaporitic sequences have been used to interpret sequences as deep water, shallow water and intertidal. For example, the Winnipegosis Fm. has been interpreted as both a basinal, turbidite-mass flow deposit and as a sabhka evaporite (Kendall, 1973; Shearman and Fuller, 1969). It appears that little definitive information on the environment of deposition can be deduced from the presence of lamination in ancient evaporites. Conflicting opinions on the environment of deposition of a laminated evaporite sequence may be due, at least in part, to the lack of a Holocene analog for subaqueous laminar and layered evaporite deposits. However, there are a few Pleistocene analogs in both "shallow" and "deep" subaqueous environments. Schreiber and Kinsman (1975) have described shallow water, laminated gypsum sequences from the Pleistocene of Montallegro, Sicily, while Neev (1978) states coarsely crystalline halite, gypsum and aragonite are now precipitating in the relatively deep waters of the Dead Sea.

The present paper will discuss the significance of evaporite lamination based on the depositional regime now forming laminated, gypsum-aragonite sequences in many saline groundwater lakes along the south central coast of Southern Australia (Figure 1). This is one of the few areas in the world where thick (up to 10 m) beds of laminated, subaqueous gypsum have been deposited in the last 6000 years (Warren, 1982a). The depositional model deduced from this area can be used as an analogy for the depositional setting of some ancient laminated evaporites.

THE HYDROLOGICAL SETTING OF THE SOUTH AUSTRALIAN COASTAL SALINAS

Holocene salinas in South Australia are situated in the interdunal corridors of an extensive Quaternary beach-dune system. Many salinas have never had a surface connection with the Holocene ocean but form as sea-water-fed groundwater lakes in areas where the level of the dune corridor is below the present sea level. All the coastal salinas have a 'bull's eye' pattern of sediment distribution with a fringe of carbonate surrounding a central gypsum unit (Figure 2). Today much of the salina surface is within 0.5 m of sea level, but wherever the surface sediments of a salina are subaerially exposed they may be blown into lunettes which rise up to 10 m above the level of the undisturbed salina surface. The present paper considers only the laminated gypsum now usually found in the subsurface, not the near surface lunette gypsum. However, other gypsum textures, as well as aragonitic tepees, laminated stromatolites, intraclast breccias and many other interesting carbonates occur in these salinas (Warren, 1982a, b, 1983).

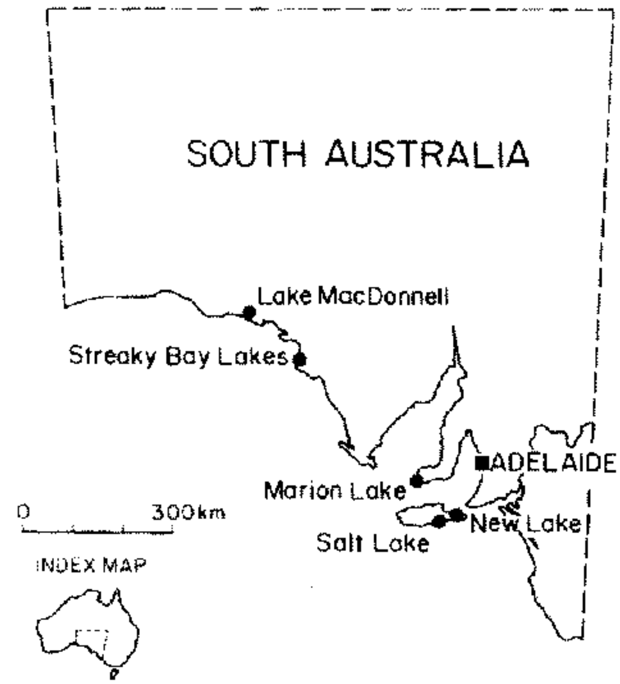

Figure 1. Locality map of the large gypsum-filled coastal salinas.

The climatic setting of the area is semi-arid and strongly seasonal with cool, wet winters alternating with hot, dry summers. Evaporation of ponded marine-derived groundwaters from 5000–6000 years ago to the present has filled the central portions of the salinas with subaqueous gypsum sequences up to 10 m thick. The gypsum fabrics change up sequence in a regular fashion, reflecting changes in the hydrologic conditions controlling sediment deposition. Six thousand years ago the lakes were relatively deep, the volume of a brine pond was large and the water was *density* stratified. Sediments forming on the bottom of the salina at this time were deposited from stable, probably gypsum-saturated, brines (Warren, 1982a). These 'deeper water' brines were little affected by seasonal input of less dense, meteoric waters into the near surface waters layers of the salina (Figure 3a). As the sediment column aggraded, the volume and depth of the brine pond decreased. Each winter a freshening of the surface water by meteoric water became more and more important in controlling salina sedimentation (Figure 3b). The shoaling sediment surface was not always covered by a gypsum

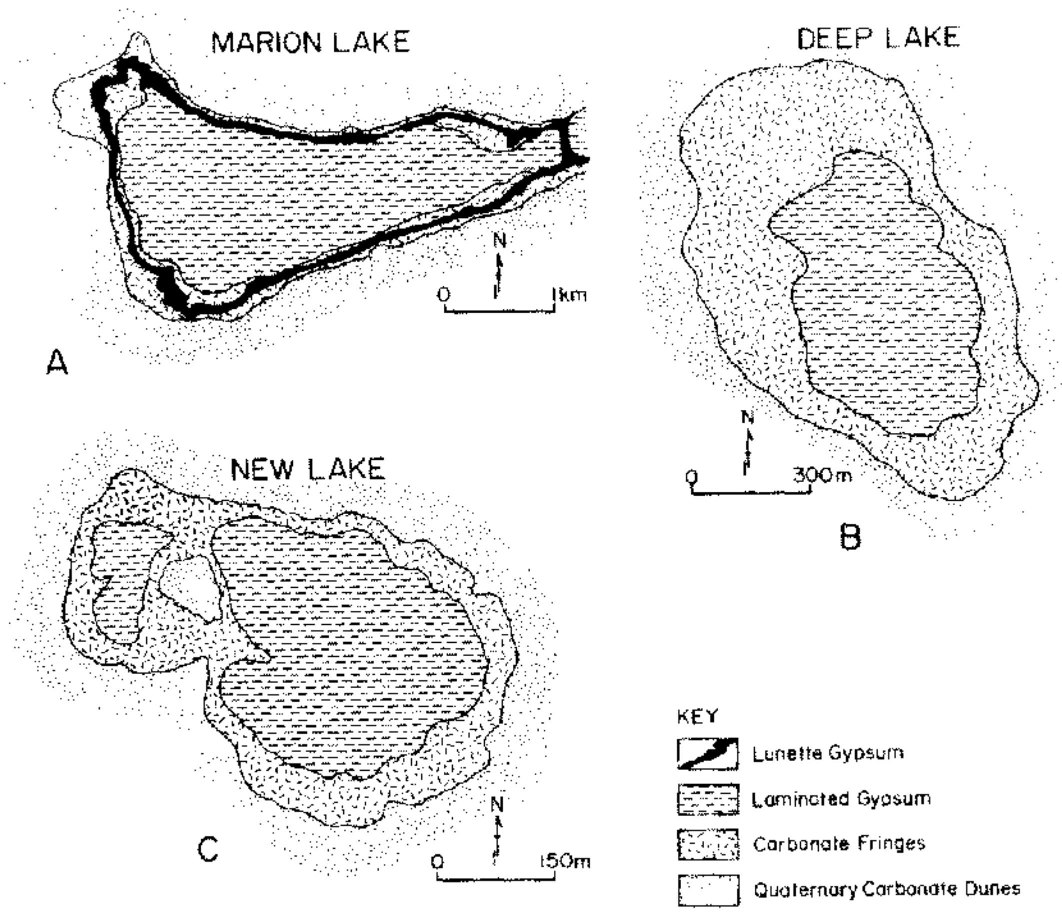

Figure 2. Geological maps of three salinas showing the bull's-eye pattern of sediment distribution. Deep Lake is a few km west of Marion Lake.

saturated brine; meteoric water mixing with the near bottom brines diluted them to a point where gypsum deposition slowed or ceased each year and definite times of aragonite deposition occurred. Finally as the sediment column approached a level equivalent to near sea level the brine pond became ephemeral (Figure 3c) and as is seen today chemical sedimentation stopped in the winter and some surface sediments were dissolved (Warren opp. cit.).

GYPSUM IN SOUTH AUSTRALIAN SALINAS

Attributes

In the South Australian salinas there are three types of gypsum: gypsite, gypsarenite and selenite. Gypsite is composed of mainly silt-sized gypsum crystals, gypsarenite of sand-sized crystals and selenite of coarser than sand-sized gypsum crystals (Warren opp cit.). Aragonite laminae only occur in the gypsarenite and selenite units, so only these units are detailed in this paper. For a comprehensive discussion of gypsum in the South Australian salinas the interested reader is referred to Warren (1982a). Laminae in both the gypsarenite and the selenite units are composed of layers of sand-sized aragonite pelletoids. In fact, aragonite is the major carbonate phase in all these gypsum depositing salinas; this is in marked contrast to the dolomite precipitating (non-gypsiferous) salinas of the Coorong Region some 100 km to the west (Eriksson and Warren, 1983; Warren, in prep.).

A vertical section in a mature gypsum precipitating salina often contains all three gypsum types. In a complete section a basal selenite unit passes up into a gypsarenite unit, which in turn may pass into a gypsite unit. Not all salinas contain a selenite unit; in fact, some salinas have been completely filled in by laminar gypsarenites. Likewise, not all salinas have a well developed gypsite cap; Warren (opp cit.) shows gypsite forms only where a soil moisture zone has developed, thus gypsite only occurs where stable gypsiferous areas are subjected to long periods of desiccation.

Although not all salinas contain a complete vertical suc-

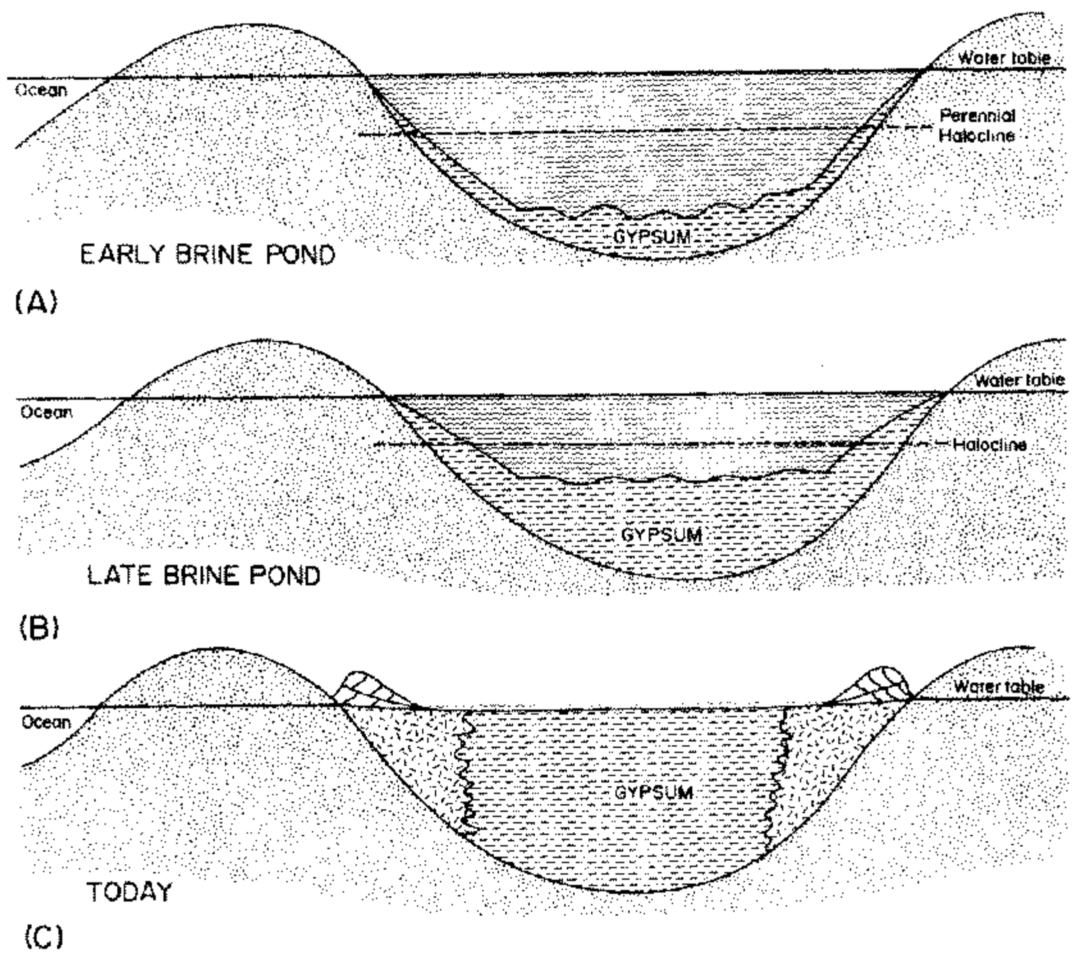

Figure 3. Schematic of the volume changes in the brine pond caused by the aggradation of gypsum unit to the sediment surface. a) Subaqueous gypsum deposition below a perennial halocline. b) Subaqueous gypsum deposition under influence of seasonal freshening. c) Subaerial-subaqueous deposition as seen today in most unmined salinas. Also shows the influence of inflowing fresher waters, as some gypsum is cannibalized by "fresher" resurging groundwaters (see Warren 1982b).

cession, this paper considers the general case and therefore will discuss the deposition and development of a complete subaqueous gypsum cycle as it exists in New Lake and parts of Marion Lake (Figure 4). The selenite unit at the base of the section is composed of domal cores of randomly-aligned, coarse-grained gypsum crystals forming bodies up to 40 to 50 cm across. These cores are the central portions of overlying poorly layered selenite domes. In three dimensions the domes have an egg-carton-like shape (Figure 5a). Aragonite pelletoids form the layering in the domes but are randomly distributed through the underlying nonlayered cores. Slightly higher in the section the dome amplitude decreases as the degree of layering increases; at the same time the relative proportion of aragonite pelletoids increases slightly (Figure 4b). At this level in the selenite unit the aragonite laminae have zig-zag or chevron-like outlines which mimic the crystallographic outline of the associated gypsum (Figure 5b). Higher in the section the dome amplitude decreases further as the zig-zag laminae pass into smooth, flat laminae (Figure 5c). Finally, dome amplitude decreases to a point where the domes disappear as they pass upward into horizontally laminated selenite (Figure 5d). At this level the zig-zag laminae have also disappeared and the aragonite laminae are smooth, mm-spaced horizontal layers.

As the dome amplitude decreases, the alignment and apparent size of individual gypsum crystals increases. Near the base of a selenite unit individual gypsum crystals are poorly aligned and up to 10 cm long. Higher in the section, in the upper parts of the domes and in the horizontally laminated selenites, the individual gypsum crystals are up to 2 m long. At this level individual crystals appear

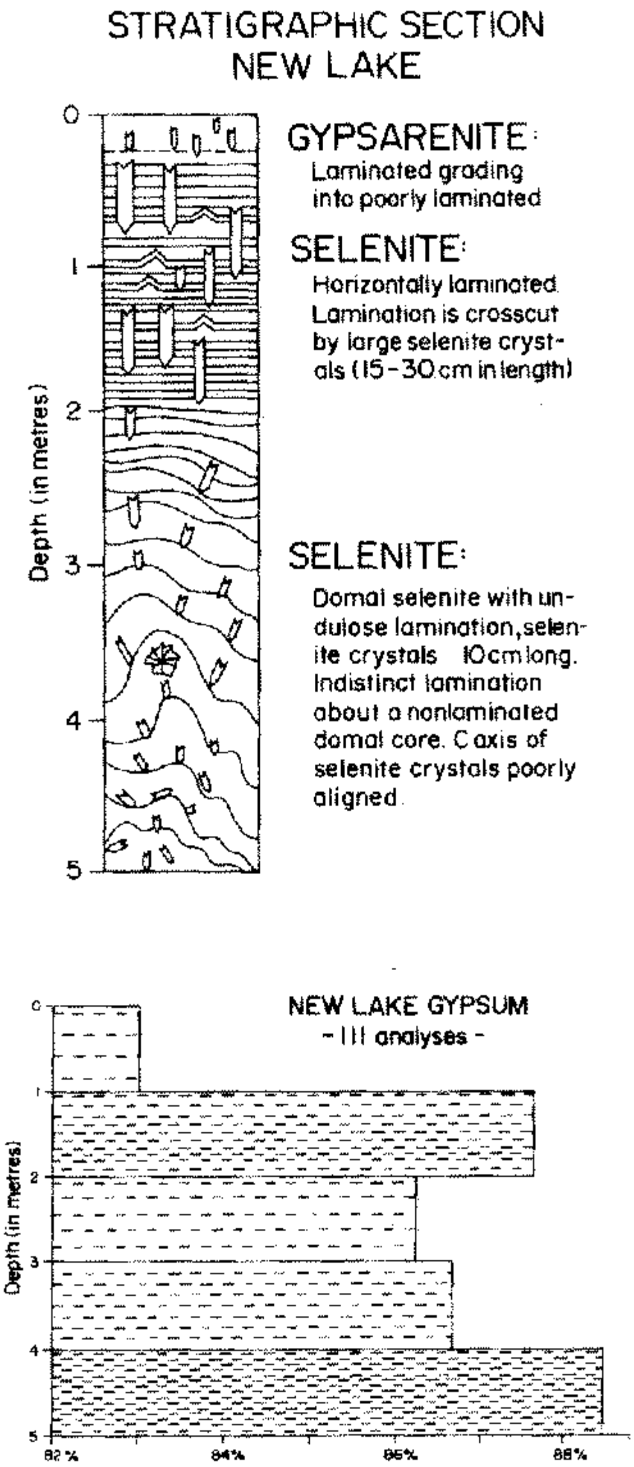

Figure 4. Stratigraphy of New Lake gypsum. a) Measured vertical section. b) Average weight percent gypsum versus depth in New Lake (111 samples).

to cross-cut the near horizontal aragonite laminae. However, a close examination of each selenite crystal shows it is constructed of smaller selenite subcrystals (Figure 6). The development of these subcrystals within the larger selenite crystals is critical in controlling the style of aragonite laminae (see later).

The laminated selenite passes up into a horizontal to undulose laminated gypsarenite. Ripples make their first appearance in these laminated gypsarenites and in some gypsarenite-rich areas such ripples comprise the bulk of the preserved salina section (Figure 5f). The rippled gypsarenites are composed of gypsum prisms strewn in the bedding plane, a result of mechanical reworking. In contrast the horizontally laminated gypsarenites are often composed of in situ prisms-gypsum crystals whose long axis are usually subperpendicular to the aragonite laminae. In a complete section the laminated gypsarenite passes upward into a non-laminated gypsarenite and then upward into a non-layered gypsite unit. However these units are not laminar and will not be further considered in this paper (see Warren, 1982a).

Mineralogically there are two important observations to be made on the gypsum sequences preserved in these coastal lakes. One, there is no anhydrite present in the sequence, and two, the proportion of aragonite increases toward the top of the section (Figure 4). The first implies that climatic conditions are not sufficiently hot or arid for anhydrite formation and the second that the waters depositing the salina evaporite sequence were progressively freshened toward the top of the sequence.

Significance

In the South Australian salinas selenite forms only under subaqueous conditions. To form it requires relatively stable bottom conditions where waters immediately above the sediment surface are not subject to rapid salinity changes. The poorly layered selenite domes formed below a perennial halocline where bottom waters were not subject to seasonal freshening. Layering in the domes began to form as waters beneath the halocline were freshened by a significant influx of near surface meteoric water. In the initial stages of salina sedimentation such fresher water influxes to the bottom waters were not necessarily annual events, and freshening of the sub-halocline waters to the point of the cessation of gypsum growth may have occurred during exceptionally wet years, perhaps only once every 10 to 20 years. Therefore, counts of the preserved layering in this portion of the section will not give a good estimate of the annual deposition rate, since we have no estimate of the frequency of freshening events. The zigzag shape of the aragonite laminae so common at this level reflects the outline of the growing depositional surface. That is, the large gypsum crystals were growing upward, with intact upper surfaces subjected to a periodic mantle of aragonite pelletoids. This depositional surface was not

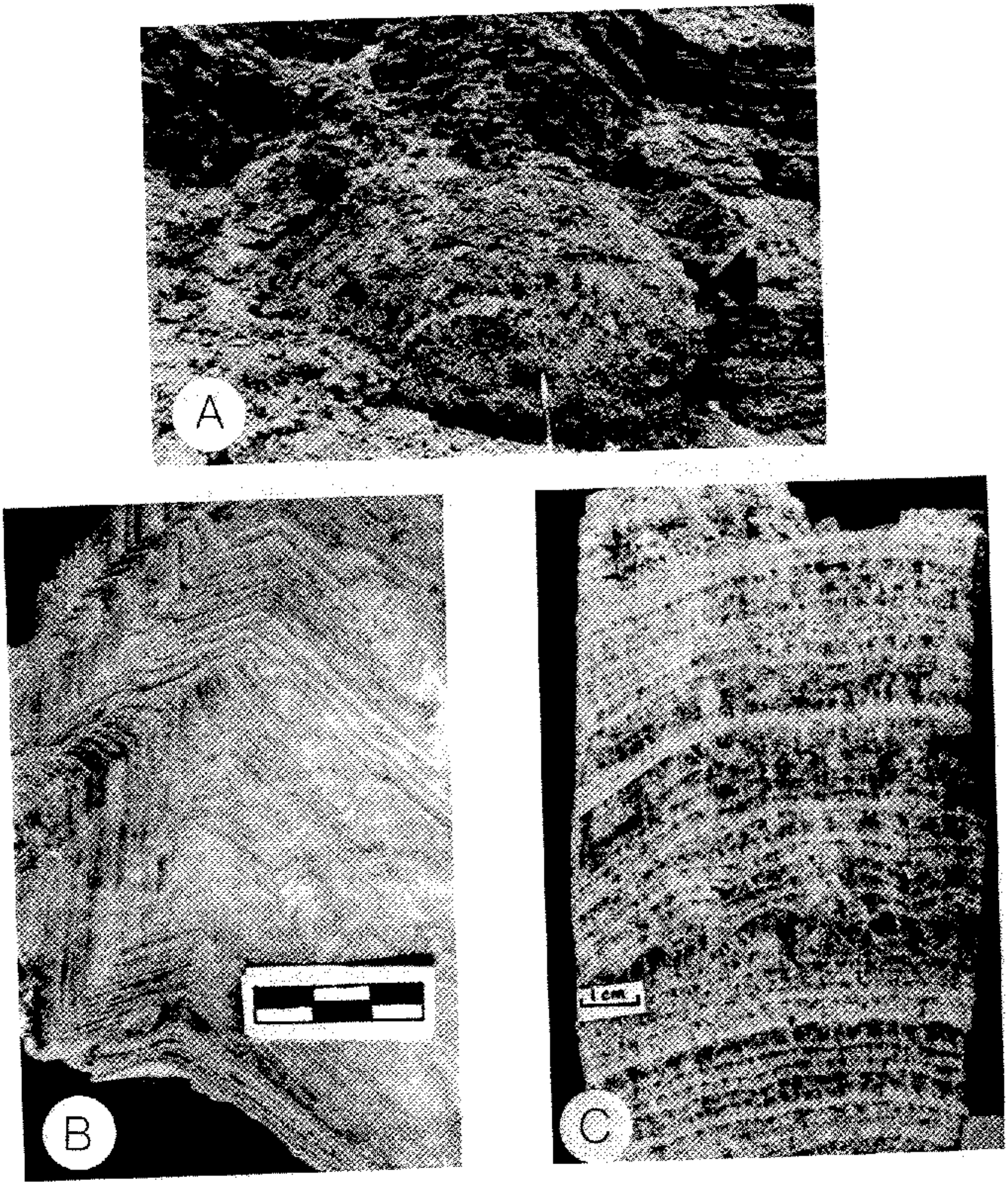

Figure 5. Gypsum textures. a) Domal or egg-carton gypsum showing the lower domal core composed of randomly oriented crystals passing upward into a more layered form. Basal part of New Lake Section (pen for scale). b) Zig-zag selenite where aragonite laminae mimic gypsum crystal outline. Note successive aragonite laminae change thickness due to changes in deposition slope on crystal surface. Marion Lake (scale is cm). c) Transition zone between zig-zag laminae and flat laminae. Sample taken near upper portion of a New Lake dome. d) Millimetre laminated selenite. Salt Lake. e) Horizontal pavement, a seasonal surface of both gypsum precipitation and dissolution. Marion Lake. f) Ripples in Marion Lake gypsarenite. View looking down onto mined vertical face.

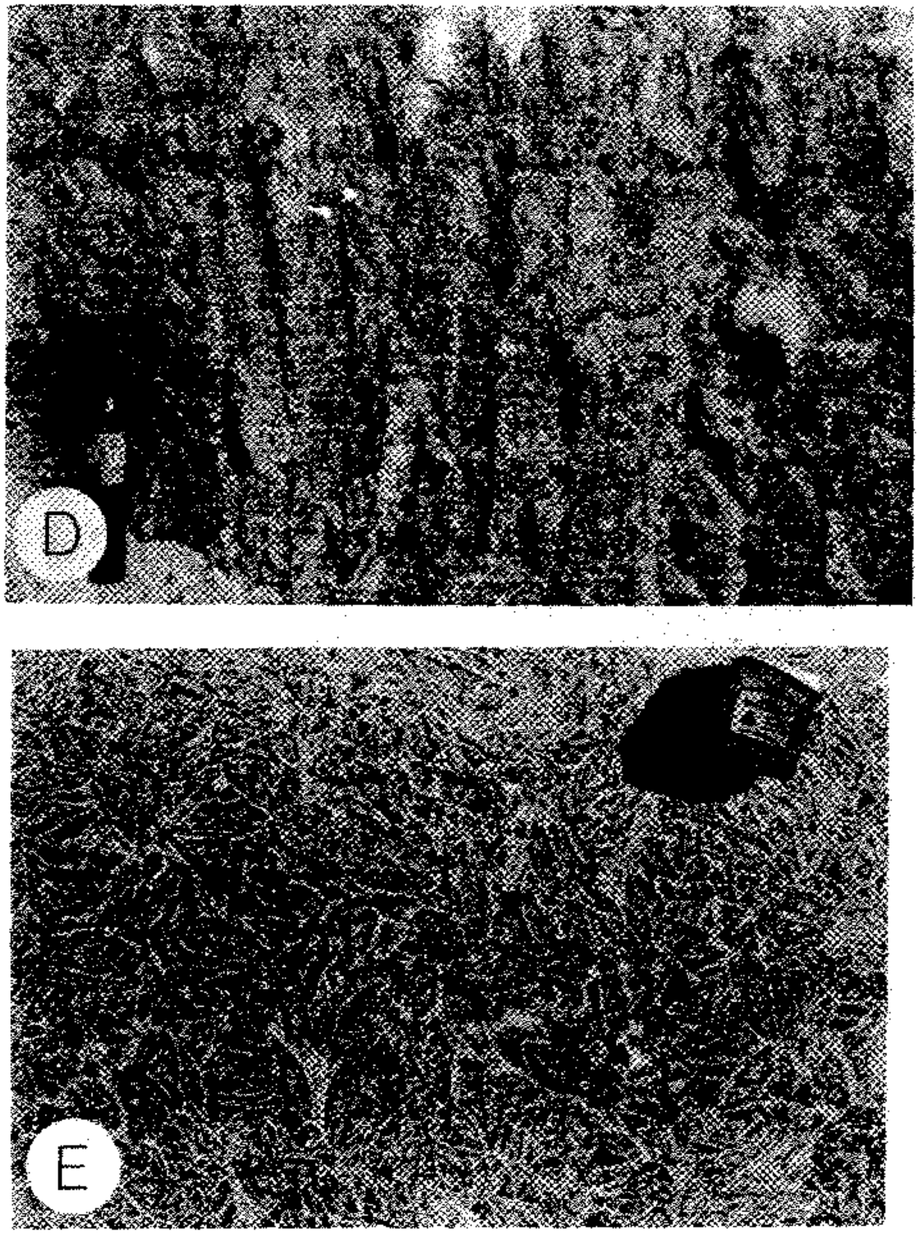

Figure 5. *(continued)*

subjected to prolonged periods of exposure to fresher waters.

As the salina continued to fill with sediment the volume of the brine pond decreased. Each year the effect of the winter input of meteoric water became volumetrically more important in diluting the predominantly marine-derived brine pond (Warren opp cit.). This had two effects: one, the relative proportion of deposited aragonite increased (Figure 4), and two, the sediment surface was seasonally covered by water undersaturated with respect to both gypsum and aragonite. In other words, there was a time each year when the halocline disappeared or was partially destroyed. It is at this point that the style of lamination in the selenite changed from a zig-zag to a flat laminae. The present three dimensional expression of such flat laminae is a horizontal pavement on some selenite units (Figure 5e). A fossil horizontal pavement is preserved about the margin of Marion Lake and an active pavement, cross cut by gypsum-carbonate pressure ridges, can be seen in the central portion of Deep Lake. An examination of the upper surface of these pavements shows they are composed of large, vertically aligned, truncated selenite

Figure 5. *(continued)*

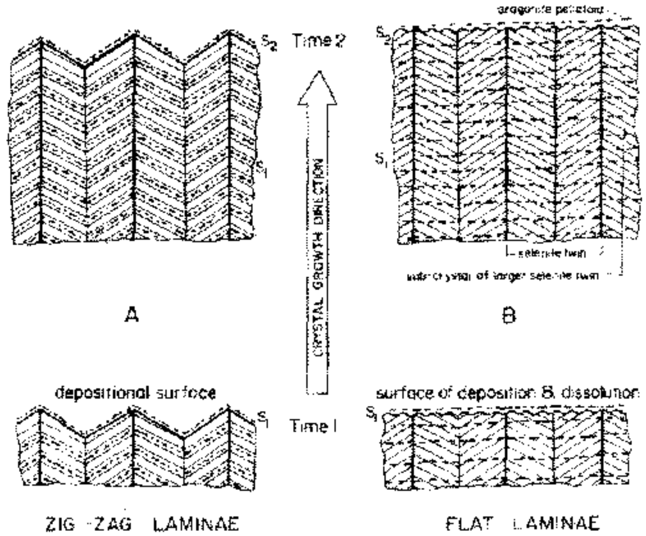

Figure 6. Schematic of gypsum growth (after Warren 1982a). a) Zig-zag lamination: the upper selenite surface is rarely dissolved by brackish waters. Each of the large cyrstals is actually composed of smaller sub-crystals. These sub-crystals grown in crystallographic continuity as they poikilitically enclose the seasonally deposited argonite pelletoids. The aragonite mantles the re-entrants of the large gypsum twins. b) Flat lamination: the upper selenite surface is flat. This is a result of seasonal dissolution of the sub-crystals when the growing surfacce is covered by brackish water. The surface is horizontal and aragonite is deposited as a thin horizontal covering. Subsequent growth of the selenite sub-crystals (in crystallographic continuity) passes up through this horizontal layer of aragonite. The end result is a flat lamination which appears to be cross-cut by larger selenite crystals.

prisms; each prism is in turn composed of smaller selenite subcrystals. The pavement is a surface of nondeposition when covered by brackish waters. As the overlying waters become more saline in the late spring and summer then aragonite pelletoids settle on the pavement. As the salinity of the brine pond increases further, gypsum is deposited on the pavement. In selenite depositing areas the bottom-water salinites increase slowly so that gypsarenite crystals are not found atop the pavement. Rather, the selenite subcrystals grow upward as they poikilitically enclose the recently deposited aragonite pelletoids. In Marion Lake and New Lake succeeding episodes of this growth cycle have deposited a number of meters of selenite; the gypsum forms a horizontally-laminated selenite unit cross cut by near vertical selenite crystals.

The continued deposition of subaqueous gypsum in the salina further decreases the volume of the brine pond (Figure 3). At the same time the relative seasonal importance of the meteoric input to bottom waters further increases. Most importantly, the annual rate of salinity change of the near bottom waters increases to a point where gypsum no longer grows in crystallographic continuity with the underlying selenite subcrystals. Instead a new crop of subaqueous gypsarenite prisms forms each year and the depositional style changes from flat-laminated selenite to flat-laminated gypsarenite. Some salinas do not contain thick selenite units but are filled with laminated gypsarenites. The difference in depositional style between such salinas reflects a relatively larger seasonal input of fresher water throughout the history of the salina and/or the lack of a well-developed vertical stratification of the salina water. Both processes will form a gypsarenite filled salina. Once laminated gypsarenite prisms form, then bottom sediment can be reworked into wave-rippled gypsarenites.

Within rippled gypsarenites the mechanically deposited prisms may have been reworked from more than one underlying aragonite layer. In such reworked sections the preserved individual aragonite laminae mark annual events, but averages over a number of laminae will not give reliable average deposition rates, because the total section has been erosively shortened.

The last stage of deposition, and in many salinas the present stage, is when the sediment fill in the salina has reached a point where the surface brine pond is an ephemeral rather than a perennial feature. Any gypsum deposited on or near the salina surface is now subject to desiccation, aeolian reworking and soil-forming processes. Gypsum formed in this environment is characterized by its lack of laminae, its aeolian bedforms and the development of gypsite crusts (Warren opp. cit.).

THE SIGNIFICANCE OF EVAPORITE LAMINATION

The gypsum deposited in the South Australian salinas was laid down under shallow water conditions (< 10 m depth). Depositional processes active in these salinas could have been active in many ancient laminated anhydrite sequences. An understanding of the significance of evaporite lamination is very important, especially where the primary gypsum structures (e.g., crystal morphology) have been at least partially destroyed by the processes of anhydritization, leaving only a laminar anhydrite unit.

Following are some of the major conclusions and inferences drawn from the study of gypsum in the South Australian Salinas:

(1) Gypsum units characterized by a laterally extensive, mm spaced $CaCO_3$ laminae are forming today in subaqueous, saline groundwater lakes, in ponds where the brine depth has never exceeded 10 meters.

(2) In these lakes there is coarse-grained gypsum forming both as non-laminated selenite beds (containing domes) below a perennial halocline and as laminated selenite where the bottom waters are subjected to seasonal freshening. Laminated fine-grained gypsum also occurs in subaqueous areas associated with relatively rapid salinity changes.

(3) The style of deposition, namely selenite versus gypsarenite and/or laminated versus non-laminated, is related to the stability of the brine pond profile. Within a single brine pond the bottom water stability can be roughly correlated with its depth. However, some brine ponds (such as the Streaky Bay Lakes) are filled with up to 9 m of laminated gypsarenite; in such brine ponds the relatively large volume of meteoric input or the lack of a well developed halocline has prevented the formation of extensive selenite units.

(4) In the semi-arid setting of South Australia the upsection decrease in laminae spacing is due to the decreasing volume of the brine pond and the concurrent increase in the relative import of meteoric waters within the pond. However, in an extremely arid setting one could expect greater salinity excursions with decreasing brine pond volumes. Under a regime of little or no meteoric input, the resulting salinity excursion into the extreme hypersaline could deposit halite and potash salts in the upper portions of a cycle.

(5) Dissolution and/or mechanical reworking means the laminated evaporite sequences are not always deposited as successive annual varves. An average depositional rate calculated from a laminated sequence will be a minimum rather than an absolute depositional rate.

(6) The lateral continuity of individual laminae in a selenite unit is not necessarily controlled by wave base. It may be related to the depositional style created by the presence of the laterally extensive, selenite pavement which, by its inherent wave resistive properties, can form above wave base as a laterally extensive horizontal surface.

(7) By itself, lamination in an ancient evaporite is difficult to interpret as either deep or shallow water. The thickness of evaporite laminae and layers in the South Australian salinas range from submillimetre to decimetres. Individual laminae are often characterized by a degree of lateral continuity not observed in storm deposited tidal flat laminae (Kendall, 1979). An interpretation of the depth of deposition of an ancient laminated evaporite must consider not only the evidence preserved in the laminite. It must also consider the environment of deposition of the adjacent carbonates as well as other geochemical and palaeohydrological data and the overall basin geometry.

ACKNOWLEDGMENTS

I wish to thank CSR for allowing me to study the New Lake gypsum deposit. I also wish to thank the Owen Coates Fund and the Geology Foundation of the University of Texas for their support. Finally, I would like to thank Martha Ladyman and Ann Cloud for typing the manuscript.

REFERENCES

Anderson, R. Y. 1982. Orbital and climatic control of Permian evaporite deposition, Delaware Basin, Texas and New Mexico. Geol. Soc. Am. 95th Annual Meeting (abst). New Orleans, Lousiana.

Anderson, R. Y., W. E. Dean, D. G. Kirkland and M. I. Snider. 1972. Permian Castile varved evaporite sequence, West Texas and New Mexico. Bull. Geol. Soc. Am. v. 83:59-86.

Anderson, R. Y. and D. W. Kirkland. 1966. Intrabasin varve correlation. Bull. Geol. Soc. Am. v. 77:241-256.

Dean, W. E. and R. Y. Anderson. 1978. Salinity cycles: evidence for subaqueous deposition of Castile Formation and lower part of Salado Formation, Delaware Basin, Texas and New Mexico. New Mexico Bureau of Mines and Mineral Resources Circ. v. 159:15-20.

Dean, W. E., G. R. Davies and R. Y. Anderson. 1975. Sedimentological significance of nodular and laminated anhydrite. Geology v. 3:367-372.

Eriksson, K. A. and J. K. Warren. 1983. A palaeohydrological model for early Proterozoic dolomitization and silicification. Precambrian Research, v. 21:299-321.

Kendall, A. C. 1979. Subaqueous evaporites. Geoscience Canada v. 5:124-139.

Kendall, A. C. 1973. Laminated ("Varvitic") carbonates and anhydrites from Ordovician and Devonian of Saskatchewan. Bull. A.A.P.G. v. 57:958-959.

Nassichuk, W. W. and G. R. Davies. 1980. Stratigraphy and sedimentation of the Otto Fiord Formation—a major Mississippian-Pennsylvanian evaporite of subaqueous origin in the Canadian Arctic Archipelago. Bull. Geol. Surv. Canada v. 286, 87 pp.

Neev, D. 1978. Messinian and Holocene gypsum deposits of relatively deep water. Abs. 10th Int. Cong. Sed., Jerusalem 2, 45 pp.

Schreiber, B. C., G. M. Friedman, A. Decima and E. Schreiber. 1976. Depositional environments of Upper Miocene (Messinian) evaporite deposits of the Sicilian Basin. Sedimentology v. 23:729–760.

Schreiber, B. C. and D. J. J. Kinsman. 1975. New Observations on the Pleistocene evaporites of Montallegro, Sicily and a modern analog. J. Sedim. Petrol. v. 45:469–479.

Shearman, D. J. and J. G. Fuller. 1969. Anhydrite diagenesis, calcitization, and organic laminites, Winnipegosis Formation, Middle Devonian, Saskatchewan. Bull. Canadian Petrol. Geol. v. 17:496–525.

Warren, J. K. 1982a. The hydrological setting, occurrence and significance of gypsum in late Quarternary salt lakes in South Australia. Sedimentology v. 29:609–637.

Warren, J. K. 1982b. The hydrological significance of Holocene tepees, stromatolites, and boxwork limestones in coastal salinas in South Australia. J. Sedim. Petrol v. 52(4):1171–1201.

Warren, J. K. 1983. Tepees, modern (Southern Australia) and ancient (Permian—Texas and New Mexico)—a comparison. Sedim. Geol. v. 34(1):1–19.