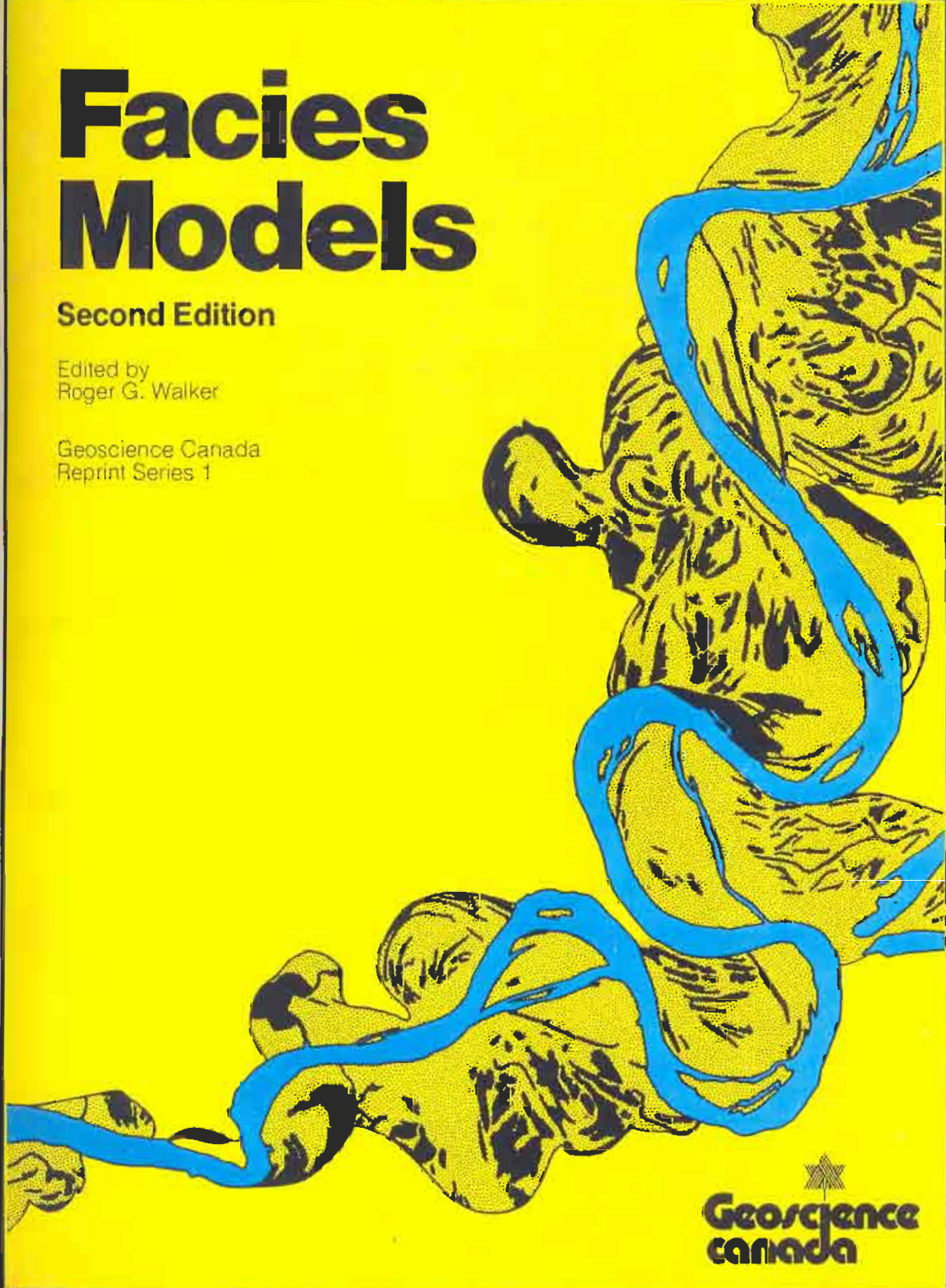


Facies Models

Second Edition

Edited by
Roger G. Walker

Geoscience Canada
Reprint Series 1




Geoscience
Canada

Geoscience Canada, Reprint Series 1

Facies Models, Second Edition

Edited by

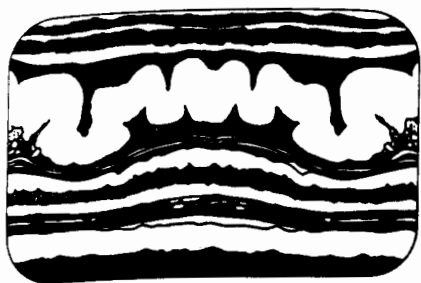
Roger G. Walker
Department of Geology
McMaster University
Hamilton, Ontario L8S 4M1 Canada

1984

A fully rewritten version of the first edition, with several new contributions. Most of the papers in the first edition appeared originally in Geoscience Canada, 1976-1979, published by the Geological Association of Canada.

Contents

	Page
1. General Introduction: Facies, Facies Sequences and Facies Models <i>Roger G. Walker</i>	1
2. Improved Methods of Facies Sequence Analysis <i>Charles W. Harper</i>	11
3. Glacial Facies <i>Nicholas Eyles and Andrew D. Miall</i>	15
4. Volcaniclastic Rocks <i>Jean Lajoie</i>	39
5. Coarse Alluvial Deposits <i>Brian R. Rust and Emlyn H. Koster</i>	53
6. Sandy Fluvial Systems <i>Roger G. Walker and Douglas J. Cant</i>	71
7. Eolian Facies <i>Michael E. Brookfield</i>	91
8. Deltas <i>Andrew D. Miall</i>	105
9. Barrier Island and Associated Strand-Plain Systems <i>G.E. Reinson</i>	119
10. Shelf and Shallow Marine Sands <i>Roger G. Walker</i>	141
11. Turbidites and Associated Coarse Clastic Deposits <i>Roger G. Walker</i>	171
12. Trace Fossil Facies Models <i>Robert W. Frey and S. George Pemberton</i>	189
13. Introduction to Carbonate Facies Models <i>Noel P. James</i>	209
14. Shallowing – Upward Sequences in Carbonates <i>Noel P. James</i>	213
15. Reefs <i>Noel P. James</i>	229
16. Carbonate Slopes <i>Ian A. McIlreath and Noel P. James</i>	245
17. Evaporites <i>Alan C. Kendall</i>	259
18. Subsurface Facies Analysis <i>Douglas J. Cant</i>	297
19. Seismic-Stratigraphic Facies Models <i>Thomas L. Davis</i>	311



Evaporites

ALAN C. KENDALL
Sohio Petroleum Company
 50 Fremont Street
 San Francisco, California 94105

INTRODUCTION

Evaporites are rocks composed of minerals that form by precipitation from concentrated brines (Table 1). Concentration necessary for this precipitation is generally attained by evaporation at the air-water interface but can also be achieved by brine freezing or by subsurface processes such as ion-filtration of residual connate fluids. The usual source for aerially-extensive evaporite deposits is seawater, but saline ground waters are the sources of many smaller evaporite deposits in continental settings. Evaporite minerals may precipitate within a saline water body, at the brine surface, at a sediment-brine interface, or interstitially within the sediment, either beneath a body of brine or sub-aerially. They may develop anywhere there is a substantial deficit in the water budget due to evaporation. Many evaporites are not strictly primary precipitates, but are diagenetic minerals emplaced within non-evaporite sediments. Still others are diagenetic replacements of true primary precipitates.

Evaporites can be viewed in terms of two classes of models: 1) sedimentary models that relate structures and textures to hydrodynamic and other depositional parameters, and 2) post-depositional models that relate present mineralogical compositions to the physico-chemical environments of diagenetic processes. Because evaporite deposition is controlled mainly by physico-chemical parameters and because many changes occur during early diagenesis (where they are controlled by depositional settings), the dis-

Table 1
Major Constituents of Marine Evaporites

Sulphates	
Anhydrite	CaSO ₄
Gypsum	CaSO ₄ ·2H ₂ O
Langbeinite	K ₂ Mg ₂ (SO ₄) ₃
Polyhalite	K ₄ CaMg(SO ₄) ₄ ·2H ₂ O
Kieserite	MgSO ₄ ·H ₂ O
Kainite	KMg(SO ₄)Cl·3H ₂ O
Chlorides	
Halite	NaCl
Sylvite	KCl
Carnallite	KMgCl ₃ ·6H ₂ O

A fuller listing of evaporite minerals can be found in Stewart, 1963.

inction between the two classes is blurred. This paper discusses sedimentary models but will mention diagenetic changes when these are early, or when the origin of the diagenetic change is disputed.

Evaporite Models

Four main factors make evaporites probably the least suitable of sedimentary rocks for facies modelling.

- 1) Only recently have evaporites been considered as sediments rather than just chemical precipitates. The initial success of the chemical approach caused this to dominate evaporite studies and only recently have sedimentary aspects been stressed. For many evaporite deposits therefore, the basic data upon which facies models are based is lacking. When models have been constructed they all too commonly have been based upon a few occurrences. Thus distillation of essential from local details may be far from complete. The chemical approach has also generated a host of depositional models based upon theoretical concepts of seawater evaporation but which ignore sedimentological evidence. These cannot rightly be considered facies models, yet these aspects cannot be ignored.
- 2) Observations upon evaporites may be limited. Only rarely are unaltered evaporites exposed in outcrop. Most evaporite studies are confined to subsurface materials - cores or mine openings. Drill cuttings rarely provide enough information. For many poorly sampled evaporite units the gross three-dimensional characteristics are established but internal details (upon which facies modelling depends) are poorly known.
- 3) Areas of present day evaporite deposition comparable in size with those of the past are absent. The Holocene transgression has not been conducive to the formation of large-scale evaporitic environments. Ancient evaporite deposits reach stratigraphic thicknesses and aerial extents up to two or three orders of magnitude greater than those forming today. It is uncertain whether or not modern small depositional areas (or even artificial salt-pans) are fully representative. Thus the opportunity to utilize modern sediments to construct facies models is either denied to us or is controversial.
- 4) Lastly, but most importantly, evaporites are most susceptible to wholesale post-depositional change. The solubility of evaporite minerals, the tendency for metastable hydrates to be precipitated, and the susceptibility of many salts to flowage under burial conditions, are features unique to evaporites and have the common result of obliterating original sedimentary characteristics during diagenesis. The profound effects of these changes mean that some evaporites are better considered metamorphic rocks than sediments. Recognition of primary features and formulation of depositional models for many evaporites may thus be impossible. The situation with respect to many bittern salt deposits is most extreme for

they commonly lack any vestige of original fabrics, structures or mineralogy. They commonly are also the products of diagenetic/metamorphic processes rather than being primary sedimentary accumulates. There is a corresponding dearth of facies models for these deposits.

In the light of these four factors it is hardly surprising that basic disagreements exist about almost all aspects of evaporite genesis. Most significant amongst them are whether basin-central evaporites were deposited in deep or shallow water, and whether many evaporite structures and textures are of primary or post-depositional origin.

There is probably not a single Holocene depositional environment that is strictly analogous to those that generated most ancient evaporite sequences. Although there may be many similarities, there are always one or more aspects (commonly scale) that cannot be fitted into the analog scheme. The technique used to interpret ancient evaporites is to take items of information from several modern settings and relate them to their ancient counterparts.

No single facies model can be applied to so heterogeneous a grouping of rocks as the evaporites. A persistent dogma since the 1960s that evaporites represent deposits of supratidal or sabkha environments became much too one-sided. Yet today we face the danger of the other end of the pendulum, for some supratidal evaporites appear to be interpreted as subaqueous on insufficient grounds.

Given the correct environmental conditions, evaporites can mimic most other sediment types. There are evaporite turbidites and oolites; 'reefs' composed of huge gypsum crystals that formed mounds standing proud of the basin floor, and shallow-water clastic evaporites that resemble in texture and sedimentary structure their clastic or carbonate equivalents. Since evaporites may exhibit detrital as well as crystalline precipitate textures, these sediments constitute one of the most variable of sedimentary rock groups.

Evaporite minerals may form only a minor component of some deposits (isolated gypsum crystals in continental redbeds would be an example) and these are best considered part of other facies models.

At the present day, areas of sufficient evaporation (and negative water balance) to cause evaporite deposits to form are present between 10 and 40° north and south of the Equator (sub-tropical high-pressure atmospheric circulation zones). These zones have been wider in the past, particularly during periods of low sea level. The presence of evaporitic sodium sulfate deposits in seasonally-frozen lakes in Antarctica and Western Canada demonstrate that negative water balances are not exclusively a condition of low latitudes.

DEPOSITIONAL ENVIRONMENTS OF EVAPORITES

Evaporite sequences have been generated in a variety of geographic settings (Fig. 1): 1) coastal intertidal and supratidal environments (marine sabkhas), 2) lagoons on coasts, 3) large basins, with brine level below sea-level and marine inflow; brine level within the basin may be high (giving deep-water evaporites) or low, and 4) non-marine interior basins. These environments may be present in a wide spectrum of tectonic settings. They occur within 1) continental margins and shelves, 2) interior cratonic basins of varying

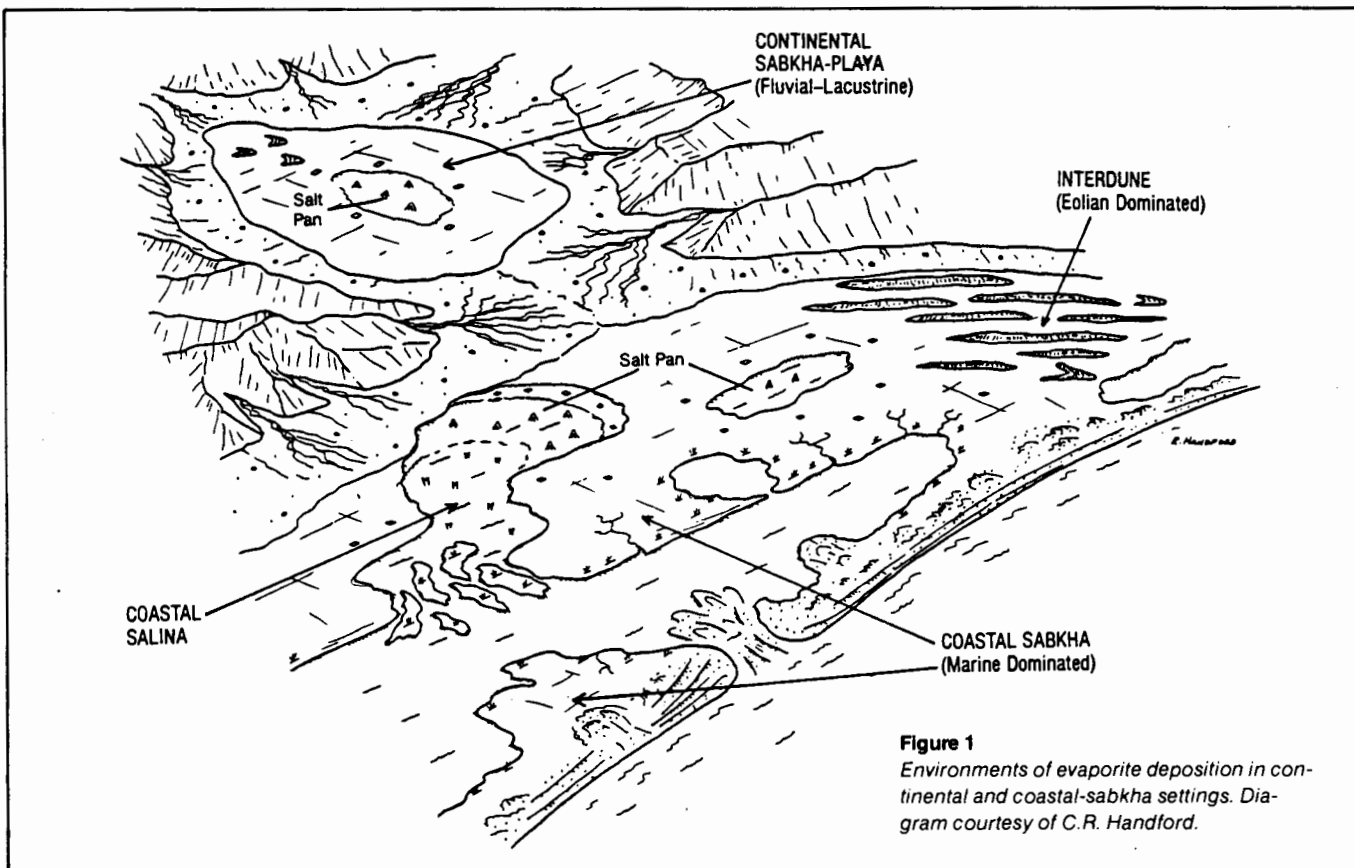


Figure 1
Environments of evaporite deposition in continental and coastal-sabkha settings. Diagram courtesy of C.R. Handford.

depths and 3) rifted continental margins - in which case evaporites may be present in areas that are now oceanic.

Of the many possible environments of evaporite precipitation, five major categories (or regimes) were identified by Schreiber *et al.* (1976) with a further subdivision in each category as to whether the evaporites are calcium sulphates or halides (with or without complex sulphates) (Fig. 2). Regimes grade into each other such that the identification may depend more upon associated facies than upon internal characteristics. Continental sabkha deposits commonly are internally identical with coastal sabkha deposits, differing only by being inserted within continental deposits. Furthermore, the degree of restriction required to generate halite and/or subaqueous sulphate deposits ensures that all these environments have some of the attributes of the continental regime. Distinction between large hypersaline inland lakes and partially desiccated small seas can be a somewhat academic exercise.

Three main environmental groupings are recognized here: continental, coastal sabkha, and subaqueous marine.

Many ancient evaporites were deposited subaqueously within enclosed and hypersaline basins. The primary composition, textures and form of these subaqueous deposits are now only partially understood because, in part, so few hypersaline water bodies occur at the present day for study; none of them of large size.

The origins of small, thin evaporite deposits and marginal-marine evaporites composed of numerous superimposed sabkha cycles are readily discernable. In contrast, the formation of vast, thick, basin-central evaporites, some which cover millions of square kilometres and exceed several kilometres in thickness or which may directly overlie oceanic basement, present very different problems.

Some authors suggest that the enormous evaporite deposits form by lateral and vertical accretion within depositional environments similar to those of

the present time (in supratidal flats, lagoons and salinas; Shearman, 1966; Friedman, 1972) whereas others consider that the great difference in scale between recent and ancient deposits requires explanations that are drastic departures from the present day settings of evaporites. They suggest either that precipitation occurred from vast bodies of hypersaline water (Schmalz, 1969; Hite, 1970; Matthews, 1974), or that evaporites were precipitated on the floors of desiccated seas (Hsu *et al.*, 1973).

Theoretical models, which were developed to answer the major compositional problems posed by large evaporite bodies, must be integrated with evidence from rock textures and structures (facies models). Unfortunately this integration is not yet possible because of basic disagreements concerning the depositional paleogeography of evaporites, and because many evaporite rock characteristics still have to be studied in detail or have disputed origins. Many evaporites are not just passive chemical precipitates or displacive growth structures, but are transported and reworked in the same ways as siliciclastic and carbonate deposits. For these sediments, sedimentary structures are a major key to unravelling the facies and will be emphasized here. Internal characteristics of evaporites alone can provide the necessary information about depositional environments. The most pressing environmental concern has been, and still is, the depth of water in which evaporites form.

Schreiber *et al.* (1976) recognize three main environmental settings for subaqueous evaporites. These are identified on the basis of sediment characteristics, believed to reflect the depth at which deposition occurs. Criteria used include: 1) structures indicative of wave and current activity, identifying an intertidal and shallow subtidal environment; 2) algal structures (in the absence of wave and current-induced structures), which are believed to identify a deeper environment but one that still resides with the photic zone; and 3) widespread evenly-laminated sediments (rhythmites) that lack evidence of current and algal activity (perhaps associated with gravity-displaced sediments), and characterize the deep, subphotic environment.

Considerable difficulty exists in using

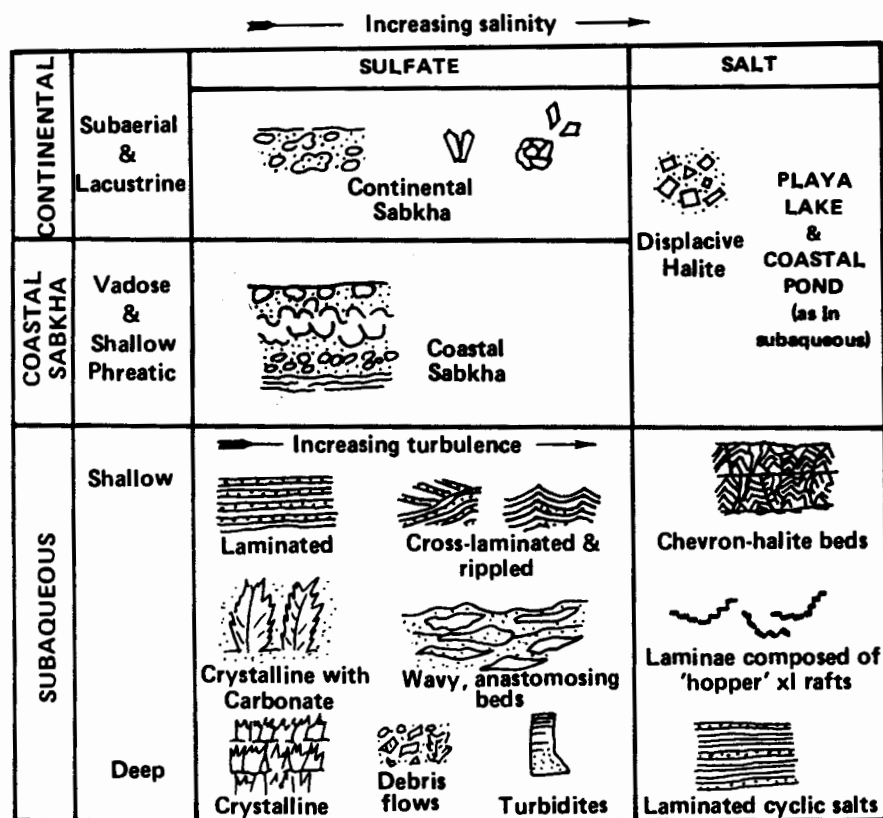


Figure 2
Summary of physical environments of evaporite deposition and the main facies present (modified from Schreiber *et al.*, 1976).

the presence or absence of algal and current structures as relative depth indicators. Because stromatolites commonly grow in protected, quiet-water, shallow environments, the absence of current structures from algal-bearing sediments is no criterion of greater depth. In addition, the photic limit in hypersaline waters probably always occurs at shallow depths, because suspended organic residues (preserved because of the poorly-oxygenated nature of brines), surface nucleated and floating evaporite crystals, and numerous anaerobic bacteria (commonly red in colour) all reduced light penetration – sometimes to depths of only a few decimetres. Such turbid brines also trap radiant heat and may reach temperatures of up to 90°C; another adverse environmental factor that will inhibit or curtail algal growth.

The presence of widely-correlatable laminations is not a definitive feature of deep-water environments because such laminations have also been found in evaporites that were deposited in sub-aerial, but ephemerally flooded, environments.

For these reasons, only two sub-aqueous environments are here distinguished; the deep-water environment characterized by the presence of laminites and gravity-displaced sediments and the shallow-water environment that represents a plethora of subenvironments which, as yet, are poorly characterized.

CONTINENTAL EVAPORITES

Evaporites formed exclusively from continental groundwaters are not commonly recognized in rock record. Many evaporites formed in continental settings were derived partly from marine input, but it is difficult to identify the relative importance of continental and marine influences. Compared with seawater, river waters are generally richer in calcium bicarbonate and calcium sulphate than sodium chloride. Non-marine evaporites thus commonly contain sodium carbonates (such as trona, $\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$) or sodium sulphates (such as mirabilite, $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$). The presence of these minerals, which are not precipitated from seawater, is evidence that non-marine waters were important in the evaporite basin. An association of evaporites with alluvial fan and fluvial dep-

osits, aeolian sediments, redbeds and lacustrine carbonates all suggest non-marine origins.

The rarity of continental evaporites (particularly pre-Tertiary) also reflects the ephemeral nature of many evaporite minerals in the depositional environment. Many are recycled or moved upwards at the same rate as sediment accretion and are thus non-accumulative. Their former presence may leave evidence in the form of crystal molds or disrupted lamination.

Continental evaporites occur in saline soils and as sedimentary bodies in central parts of playa (continental sabkha) basins, particularly in association with playa lakes. With the possible exception of gypsum crust (gypcrete) which forms in the same manner as caliche (calcrete) but in more arid areas, the accumulation of pedogenic evaporites is unlikely to be preserved in the rock record. Watson (1979) describes several proposed origins for gypsum crust in areas peripheral to hot deserts.

PLAYA (CONTINENTAL SABKHA) EVAPORITES

These evaporites, whether precipitated from brine lakes or emplaced within desiccated sediments, are usually precipitated in the lowest areas of enclosed area drainage basins – environments that are characterized by almost horizontal and largely vegetation-free surfaces of fine-grained sediments (Figs. 3 and 4). These base-level plains are a distinctive feature of arid regions and are

given many different names (sabkha, sebkha, playa, salinhan, chott). The name playa is employed here for these features. Playa evaporites are one component of a complex of different subenvironments, of which Hardie *et al.* (1978) recognize 10: 1) alluvial fan, 2) sandflat, 3) mudflat, 4) ephemeral saline lake, 5) perennial saline lake, 6) dune field, 7) perennial stream floodplain, 8) ephemeral stream floodplain, 9) springs, and 10) shoreline features. Sediments deposited in subenvironments 1, 6, 7, and 8 are covered in other chapters of this book.

Alluvial fans at basin edges trap most coarse detritus so that only the finest material is carried into the basin. Apart from sheetwash flow during storms, water circulation is generally confined to the subsurface although ephemeral or perennial streams may cross the playas.

At the base of the fans occurs a flat sandy apron where the braided channels of the fans lose their identity and sheetflow during flooding-events is the dominant depositional process. Sediments are planar and wavy-laminated sands (Fig. 5a) which may become cemented by carbonate or gypsum if groundwaters are already concentrated.

Some playas have water tables so deep that no groundwater discharge occurs at the surface. These playas possess smooth, hard and dry surfaces and evaporites are commonly lacking. Most evaporites accumulate within playas where groundwater discharge

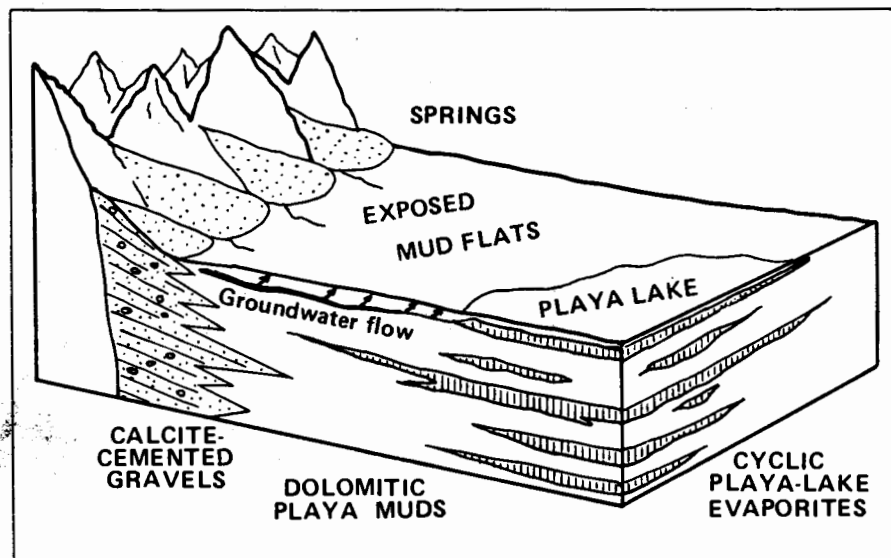


Figure 3
Schematic block-diagram showing depo-

sitional framework in the Playa Complex model (after Eugster and Hardie, 1975).



Figure 4
View to the west over Bristol Dry Lake (California) toward alluvial fans. Photograph courtesy of C.R. Handford.



Figure 5
A) Flaser-bedded clastic playa sediments with clay drapes (5 cm coin for scale).

B) Contorted gypsum and red mud (5 cm coin for scale). Both photographs from Bristol Dry Lake and courtesy of C.R. Handford.

occurs and this may be: 1) indirect, caused by capillary rise, evaporative pumping or evapotranspiration by phreatophytes from a shallow water table, or 2) directly from the water table (perennially or seasonally at the playa surface) or from springs. Many playas are equilibrium deflation-sedimentation surfaces with topography controlled by the water table level and its gradients.

The closeness of the water table to the surface allows great evaporative loss and concomitant concentration of pore fluids. Playas are thus sites of brine formation irrespective of the salinities of peripheral groundwaters that feed into them. The brine type and the mineralogy of evaporites that precipitate are, however, dependent upon the chemical composition of the groundwater supply.

Hydrographic lows on the surface may be occupied by perennial or seasonal bodies of shallow water (playa lakes), fed directly by groundwater seepage, by springs or by accumulation of storm waters. Playa lakes exist only at times when water input (precipitation and inflow) is less than the water lost by evaporation. The latter is dependent upon climate, water salinity and the geometry of the water body.

Continuing evaporation and evapotranspiration generate a pronounced groundwater concentration gradient towards the basin centre or along the flow paths taken by the groundwater. Saturation with respect to calcium and magnesium carbonates is reached at an early stage, causing precipitation of calcite cement and caliche layers in alluvial fans, or of soft micron-sized high Mg-calcite and protodolomite in playa fringes, or of travertines and pisolitic caliche when precipitation occurs from surface waters associated with peripheral springs (Fig. 7A). Deposition on playa flats occurs as a mud because sediments here are kept permanently moist by the groundwater discharge (Eugster and Hardie, 1975). The carbonates should be considered evaporites because they form in exactly the same manner as gypsum and more saline minerals further into the basin. Together with any detrital sediments, the carbonate muds are transported toward the basin centre by storm sheet-floods which imparts the laminated or cross-laminated (Fig. 7B) structure. This lamination, however, is also continuously being disrupted and destroyed by

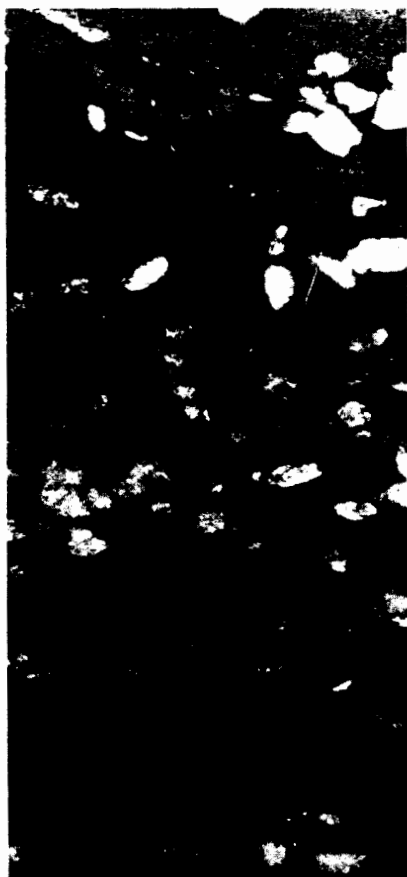


Figure 6
Red dolomitic mudstones with anhydrite pseudomorphs after gypsum crystals. Watrous Formation, Saskatchewan. Probable playa flat deposit. Slab 9 cm wide.



Figure 7
Anydrite (after gypsum crystals) displacing (and replacing?) pisolitic caliche in (A) and possible laminated dolomite-calcium sul-



phate playa flat deposits in (B); both from the Whitkow Anhydrite (Prairie Evaporite Formation; Middle Devonian), Saskatchewan. Slabs about 9 cm wide.

further groundwater discharge (creating porous 'putty-ground' surfaces), by the growth and dissolution of ephemeral evaporite crystals and crusts, and by episodes of surficial drying that cause extensive and multiple mud-cracking. Mine tailings on playas have been destroyed by these processes in less than 50 years.

Hardie *et al.* (1978) distinguish between two types of mudflat. The first, (the dry mud-flat) lying closer to the basin edge is characterized by preservation of sedimentary structures (Fig. 5a), whereas in saline mudflats all structures are destroyed by growth of evaporite crystals (Fig. 6). Dry mudflats are commonly covered with thin saline efflorescent crusts and are composed of laminated sediments which may be partially disrupted by mudcracks, sheetcracks and saline mineral growth.

Removal of the less soluble mineral

phases (Ca-Mg carbonates and calcium sulphates) profoundly modifies the groundwater composition and thus the sequence and type of saline minerals that will precipitate in the basin centre. A mineral zonation is formed with the most soluble minerals located at the most distal parts of the groundwater flow and segregated from the less soluble phases.

Drying of the playa surface may cause sediment deflation. Gypsum crystals, precipitated displacively in the uppermost playa sediments, are concentrated as lag deposits and may be swept together to form gypsum dunes. Surficial gypsum may also dehydrate to bassanite or anhydrite and, in some playas, calcium sulphate is emplaced directly as nodular anhydrite that is seemingly identical with that in coastal sabkha environments (Fig. 5b).

Efflorescent crusts of saline minerals

accumulate on playa surfaces during groundwater discharge and evaporation, or by the evaporation to dryness of ponded stormwaters. Because evaporation is rapid and complete, the crusts include metastable and highly soluble salts. Rain and storm waters dissolve the most soluble saline minerals of the crusts to form concentrated, but chemically 'simple', brines that owe their highly modified compositions to this fractional dissolution. Ultimately these brines, which are dominated by only one or two major solute species (e.g., NaCl, Na₂SO₄ or Na₂CO₃), reach the basin centre.

Evaporite crusts may reach 30 cm or more in thickness. Continual growth of salt crystals causes great volume increases and formation of salt-thrust polygons (and other types of patterned ground) or highly irregular surfaces with relief perhaps reaching several



Figure 8

Cores exhibiting upward passage from displacive halite (haselgeberge)—some crystals

with hopper morphology—into bedded halite with thin anhydrite and clay laminae. Sequence marks the change from a saline

mud flat to a salt pan deposit. Lotzberg Salt, northern Alberta.

metres.

Even the salts that initially survive dissolution by storm waters and become buried are ephemeral if underlying groundwaters are undersaturated. Upward movement of the less saline water dissolves the salt crust and reprecipitates it at the new surface. Towards the basin centre groundwaters become increasingly saline and calcium sulphate and even halite may become stable in the sediment. It is important to note that minerals in surface crusts do not necessarily reflect the character of evaporite minerals that are preserved in underlying sediments. Many fine-grained dolomitic red-bed sequences, such as the Keuper of Europe and the Watrous-Amaranth-Spearfish Formation of the Williston Basin (Fig. 6), probably represent deposits of these evaporitic but essentially non-evaporite-preserving environments. Halite within playa sediments has been described from modern environments by Gornitz and Schreiber (1981) and Handford (1982), but the details of its precipitation are still unclear. Smith (1971) described displacive halite in Permian red mudstones which he interprets as forming in a playa flat. Euhedral to subhedral halite cubes occur in abundant matrix but with increasing halite content the matrix becomes discontinuous, then confined to isolated polyhedral pockets as the halite becomes a near-continuous interlocking mosaic (Fig. 8). In more coherent sediments, however, halite occurs interstitially, as veneers around sand grains or as skeletal 'hopper' crystals (Fig. 9) - the last mentioned sometimes assuming extreme forms.

Playa lakes lie at the termination of groundwater flow paths and also accept concentrated brines formed when overland flows dissolved efflorescent crusts on the playa flats. These ponded brines continue to suffer evaporation and saline minerals are precipitated on the brine surface, at the brine-sediment interface and, perhaps also within the bottom sediments to form bedded crystal-brine accumulates. The characteristics of these accumulates are similar to those of marine-derived subaqueous evaporites.

Shallow playa lakes expand enormously during flooding events so that the saline mudflats, and perhaps parts of the dry mudflats, become inundated. Sediment deposition during such times

is largely the result of "settle-out" after the turbulence of the floodwaters subsides, giving rise to laminae of mud (which may be reworked by waves) that become disrupted by saline crystal growth and mudcracking as the evaporating lake retreats. Bacterial reduction of sulphate to produce H_2S and iron sulphides in the mud layers makes them black and anaerobic. Blue-green algae may bloom in the freshened lakes to form lake-bottom mats. However, these form after sedimentation has occurred. As the lake slowly evaporates and shrinks in size, the ponded brines eventually precipitate halite or trona.

In the saltpan single storm sheets thus result in deposition of a couplet of a thin mud layer (mm-scale, iron-sulphide-rich) overlain by a thicker crystalline salt-layer (upper part of Fig. 8). Repeated storms will superimpose couplets upon each other, although continued growth of salt crystals from groundwater after the lake completely dries up may destroy this bedding.

Evaporation in perennial playa lakes (lasting all year) produces an orderly succession of saline minerals with the more soluble overlying the less soluble. Freshening of lakes after storms or during the 'wet' periods dissolves the uppermost, more soluble minerals if water mixing is complete (as in shallow lakes). In deeper playa lakes the brine may become stratified with less saline water overlying a denser, more saline brine which protects the salt-layer from dissolution.

The crystal accumulates become exposed to the air during 'dry' episodes



Figure 9
Displacive halite hopper crystal in dolomite, Souris River Formation (Upper Devonian), Saskatchewan. Core is 12 cm across.

in many shallow playa lakes. The interlocking salt crystals have high porosities and interstices between crystals are occupied by saturated brine. The salt surface is kept moist by evaporative draw and by precipitation of dew on hydrophilic salt surfaces during cold nights. The evaporation rate falls to values as low as 1/170th of the rate from standing bodies of the same brine, and thus the brine level rarely drops more than a few metres beneath the surface. The crystalline surface is dissected by salt-thrust polygons and much eolian dust is trapped on the rough and damp surface. During 'wet' episodes or seasons, lakes are flooded by storm waters which dissolve surficial salts and introduce clastic material. Since new saline material is introduced during such times, generally less salt is dissolved than was precipitated during preceding 'dry' seasons. Evaporation during the succeeding 'dry' period creates a new salt layer. Each salt layer is thus largely composed of recycled material. Layers are separated by mud partings composed of detrital material introduced by storm waters and the eolian sediment deposited on the emergent salt surfaces.

The order of salt deposition in ephemeral playa-lake deposits is commonly not that which would be predicted by the theoretical crystallization sequence from the brine. More soluble salts are found beneath less soluble, forming 'inversely stratified' salt deposits. Such sequences form because: 1) the more soluble salts in surface layers are dissolved during lake-flooding episodes, and 2) concentrated, dense brines created by evaporation during the emergent episodes sink through the crystal accumulate and displace the less concentrated brines, which emerge to the surface, there to cause further dissolution of more saline phases. It is from the descending, dense brines that the permanent, more saline salts precipitate. They must be regarded as early diagenetic additions. Density mixing of brines during emergent phases probably also encourages the replacement of metastable by stable minerals and the recrystallization of earlier formed salt; it thus contributes towards the early diagenetic lithification of the salt deposit. These effects are absent or less efficient within deposits formed from permanent brine lakes.

Perennial saline lakes, that persist for tens to thousands of years without drying up, require substantial perennial inflow, usually a large river which keeps the lake supplied with water, solutes and clastic sediment. Solute may also be supplied by springs, and flashfloods introduce clastic sediments.

Evaporation occurs from the lake surface and creates a concentrated surface brine within which saline minerals nucleate and grow. The concentrated brine and the saline crystals sink toward the lake bottom and less-dense and less-concentrated inflow floats in over the brine, there to suffer evaporation. Unless the entire brine is saturated throughout, however, the crystals will dissolve before reaching the lake bottom. This will increase the brine concentration until, ultimately, the crystals no longer dissolve and begin to accumulate on the lake floor.

The minerals that precipitate from the surface waters depend upon the evaporation/inflow ratio, the chemical composition of the inflow and the stage in history of the lakes. If evaporation only slightly exceeds inflow, only minerals of low solubility (for example, alkaline earth carbonates) will be precipitated; but in order to precipitate a highly soluble mineral (such as halite) not only must the evaporation/inflow ratio be higher, but also the bottom brine must be dense enough to support the concentrated surface brine for a sufficient time to allow it to become supersaturated with respect to the saline material. If the bottom brine is not dense enough, the surface brine will sink before saturation is reached.

A lake that suffers a progressive decrease in its inflow will show a progressive change in chemical sedimentation from low to highly soluble salts. In contrast, a perennial lake that experiences a short-term decrease in inflow may experience no change in precipitation because the change in evaporation/inflow ratio is not matched by a sufficient change in the concentration and density of the lake brine which would allow more soluble precipitates to form in the surface brines.

Perennial saline deposits are laterally continuous, comprising saline mineral layers and clastic (mud) partings. Because evaporation is normally continuous throughout each year, the layering does not represent annual varves.

Instead it appears to result from non-periodic storm-influxes of mud that interrupt, or punctuate, the continuous rain of chemical sediment. Some clastic influxes could be seasonal, but are more likely to be irregularly spaced. Thicknesses of chemical layers are normally fractions of a millimetre for carbonates; several millimetres for gypsum laminae and thin beds of several centimetres for halite.

Where organic matter has accumulated in the bottom sediment, interstitial brines undergo sulphate reduction so that sulphate minerals dissolve. Gypsum precipitated from surface brines of the Dead Sea is absent in the bottom sediments. Sulphate reduction may result in the precipitation of iron sulphides, calcium carbonates or phosphate.

Variations in the Playa Model

Climate, groundwater source and composition, and the size of the playa complex are the main factors that dictate the type and distribution of evaporites within the playa setting.

A) Geologic/Geographic Setting. Three main settings are distinguished by Hardie *et al.* (1978), each characterized by associations of subenvironments.

- 1) Rain-shadow tectonic basins, like the block-fault desert basins of the western U.S.A., where there is both arid climate and hydrologic closure. The environment is characterized by huge alluvial fans and salt-encrusted ephemeral saline lakes ringed by narrow dry-mudflats and sandflats. Inflow into the lake is confined to groundwater influx and ephemeral storm runoff.
- 2) Wide shallow basins, which are dominated by ephemeral stream flood plains and dunes. Large areas become episodically inundated by ponded floodwaters which slowly evaporate, precipitating a saline crust. Complete desiccation gives rise to a salt pan (perhaps only one hundredth the area of the inundated region) fringed by a saline mudflat. The Lake Eyre basin of Southern Australia is a recent example of this association.
- 3) Perennial lakes, supplied by perennial streams, vary considerably according to the steepness of the basin flanks. Steep-sided basins

with perennial lakes (e.g., Dead Sea) are unlikely to change into ephemeral lakes and accumulate massive evaporite deposits. In contrast, wide basins have shallow perennial lakes (e.g., Lake Chad; Great Salt Lake, Utah) and decreased inflow rates cause significant lake shrinkage, exposing large parts of the lake bottom, or may cause the lake to dry up completely, converting it into an ephemeral lake.

B) Climate. Temperature influences evaporation rate but may also control the type and sequence of salt deposition more directly (Fig. 10). For example, in warm climates brines may precipitate halite before any sodium sulphate is deposited as thenardite (Na_2SO_4). Lakes in colder climates (as in the Prairie Provinces) precipitate mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$) prior to halite.

Water input into the playa basin determines whether evaporites will precipitate and be preserved or not. They accumulate only at times when the water budget is a negative one. The history of playa lake complexes is one of alternating wet (pluvial) and dry (arid) conditions with corresponding transgressive, freshened, non-evaporite-precipitating lakes and regressive (shrinking) saline lake or dry playa stages. Pluvial phases (Fig. 10) are marked by partial to complete dissolution of earlier formed salts, by deposition of basal transgressive conglomerates and beach deposits over former playa flat deposits, and by deposition of non-saline lacustrine sediments (among which oil-shales may be conspicuous). Increasing aridity (Fig 10A) is recorded by shrinkage of the lake area, a decrease in lake depth, and an increase in salinity ultimately leading to bedded evaporite deposition.

Climate changes may also be reflected in non-lacustrine playa sediments. Widespread rhythms of increasing evaporite content in red, dolomitic mudstones and siltstones of the Keuper (Upper Triassic) of Europe can be interpreted as indicating gradual reductions in the water influx to the depositional site and a corresponding increase in the persistence of evaporites in the sediments (Wills, 1970). Similar cyclic-Keuper sediments (alternations of laminated and structureless

mudstone/siltstones; dry mudflat-ephemeral halite saline mudflat deposits?) have recently been beautifully documented by Arthurton (1980). Cycles, however, are attributed to eustatic control (with sea-level perhaps controlling groundwater residency and concentration?).

Playas fed by artesian flow or from rivers may possess water tables that are located higher than those of neighbouring areas. Groundwater moves and becomes compositionally modified towards the basin-edge - in directions opposite to that in the ideal model. Mueller (1960) has shown that saline waters from the Andes evaporate on the floor of the central valley. Residual brines containing nitrates and iodates move upslope through the soil of the coastal mountain slopes by capillary migration and eventually evaporate to complete dryness.

C) Groundwater Composition. The mineralogy of salts precipitated in closed basins is controlled by the groundwater composition which, in turn, depends mainly upon the rock types in the source area and their mode of weathering. Commonly the evaporite minerals are similar to those precipitated from oceanic waters (hence the difficulty of distinguishing between them) and there is a predominance of alkaline-earth carbonates and various sulphates. This reflects the dominance of the same ions (Ca, Mg, Na, CO₃, HCO₃, SO₄, Cl), but they may be in different proportions from those in sea water. Such differences are most evident when the more saline salts are precipitated. Commonly calcium, sodium,

and bicarbonate are present in excess, leading to precipitation of salts such as pirssonite (CaCO₃·Na₂CO₃·2H₂O), gaylussite (CaCO₃·Na₂CO₃·5H₂O), and trona (Na₂CO₃·NaHCO₃·2H₂O). When groundwaters are sulphate-rich then (dependent upon the dominant cations) glauberite (CaSO₄·Na₂SO₄), epsomite (MgSO₄·7H₂O), bloedite (MgSO₄·Na₂SO₄·4H₂O), thenardite (Na₂SO₄) and mirabilite (Na₂SO₄·10H₂O) may be precipitated. Variation in playa and playa-lake mineralogy constitutes a vast field of study, one that cannot be discussed here. Reference should be made to Hardie and Eugster (1970) and Eugster and Hardie (1978).

D) Groundwater Source. It has been assumed that groundwaters move radially from the hinterland, converging toward the basin centre, which also marks the hydrographic low point of the basin. Flow is also assumed to be essentially horizontal and shallow subsurface (except during storms). This produces a concentric pattern of increasing groundwater salinity and a 'bull's-eye' pattern of salt deposition (more saline salts in the centre, Fig. 11). When the deepest part of the basin floor is not centrally located, or when groundwater enters the basin from one side, this ideal pattern is disturbed and becomes asymmetric. The compositions of brines in lakes fed by rivers are not modified by the prior precipitation and retention of less saline salts in peripheral playa flats. These brines retain their carbonate and sulphate contents and low-solubility salts may precipitate within the lake. Consequently there is less mineral

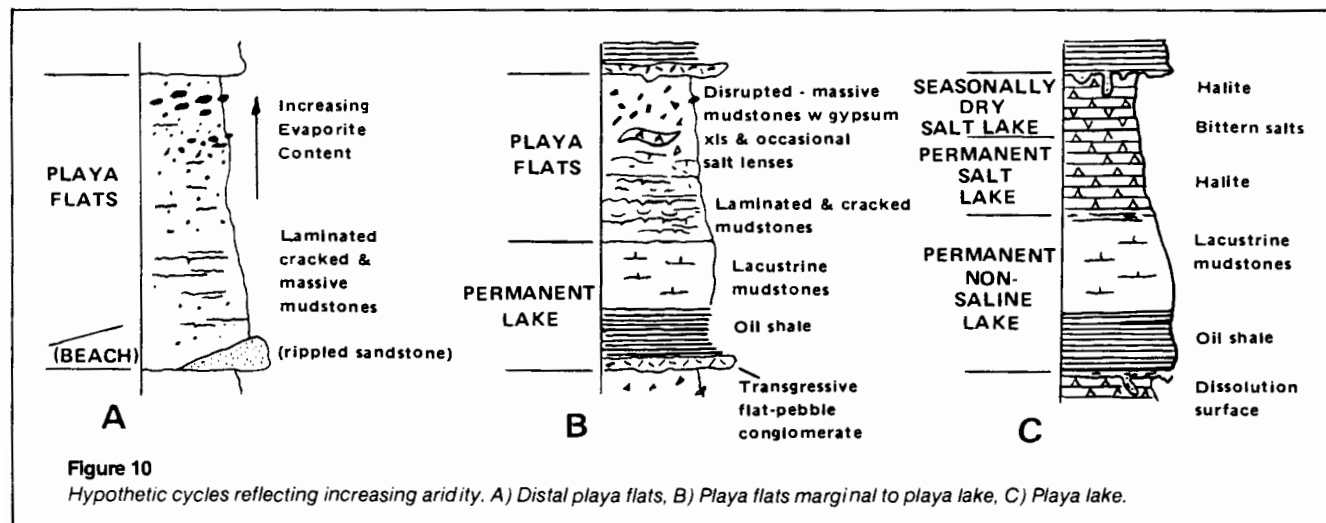
segregation in river-fed than in groundwater-fed playa systems.

Chaotic and disturbed sediments with irregularly distributed salt lenses occur beneath playas fed by artesian groundwater. The rise of less saline water dissolves previously deposited evaporites except where they are protected by impermeable clay seals. Removal of deep-lying salts results in localized subsidence, creation of depressions occupied by small playa lakes and pools, and deposition of small, isolated salt deposits.

E) Size of the Playa Complex. Much of the surface water introduced during storms will reach the basin centre in small playa basins. Lakes will thus exhibit many cycles of salt dissolution and precipitation and the efficiency of leaching salts from playa flats will be high. In contrast, storm waters may not reach playa lakes that are surrounded by vast playa flats: the water evaporates before it reaches the basin centre. Even during the 'wet' seasons waters may fail to reach lakes, which then become flooded only during exceptional circumstances. Such 'lakes' spend much of their time with emergent salt surfaces. Salt leaching on adjacent playa flats is inefficient and crystal accumulates will suffer more early-diagenetic changes at depth than those deposited in small playa basins.

SUPRATIDAL (COASTAL SABKHA) EVAPORITES

Coastal sabkha evaporites were briefly described by James (this volume) under the heading of arid-zone variants of



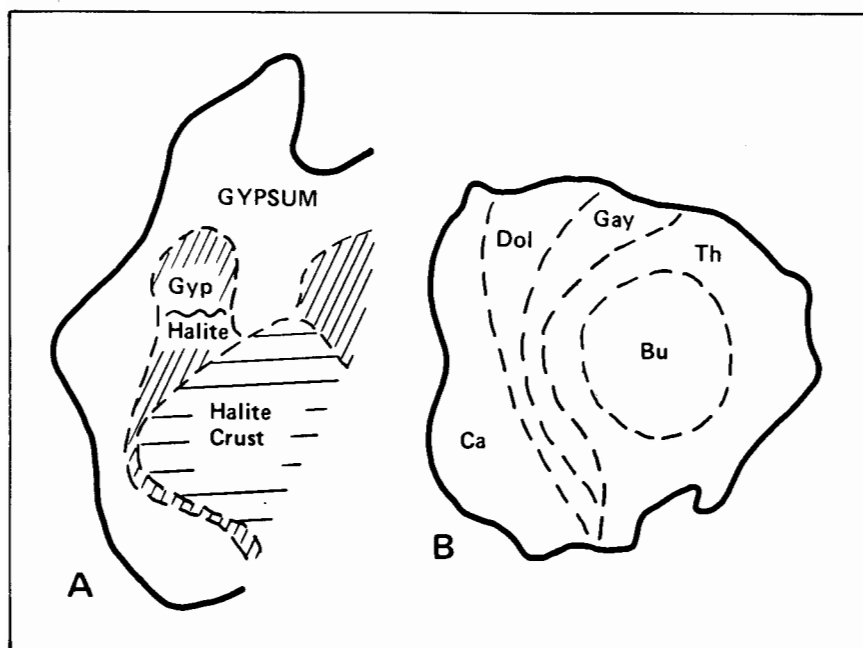


Figure 11

Saline mineral zonation in playas. A) Yotvata Sabkha (Israel) after Amiel and Friedman (1971). B) Deep Spring Lake, California. Ca =

calcite/aragonite. Dol = dolomite. Gay = gaylussite. Th = thenardite. Bu = burkeite (after Jones, 1965).

carbonate shallowing-upwards sequences. This style of shallowing-upward sequence (Fig. 12) is composed of (in upwards sequence): (1) carbonates, or less commonly clastics, (2) similar sediments but with angular anhydrite nodules, pseudomorphic after gypsum crystals (Fig. 13), and (3) nodular-mosaic anhydrite, commonly terminated by a sharp erosive contact (Fig. 14). The evaporites are interpreted as diagenetic emplacements within supratidal environments because of their close resemblance to the sequence of lithologies in the progradational wedge along the Abu Dhabi coast of the Persian Gulf (Fig. 15) (Shearman, 1966; Kinsman, 1969; Butler, 1970; Bush, 1973). Our knowledge of these important sedimentary environments is dominated by the results of the numerous studies of the sabkhas at Abu Dhabi. This probably gives an unbalanced view of sabkha systems as a whole.

On shallow stable shelves with arid climates and low eolian sand influx the seaward progradation of subtidal and intertidal facies generates broad coastal flats (or sabkhas) that lie just above high tide level and extend between the offshore water body (commonly with coastal lagoons) and regions of arid contin-

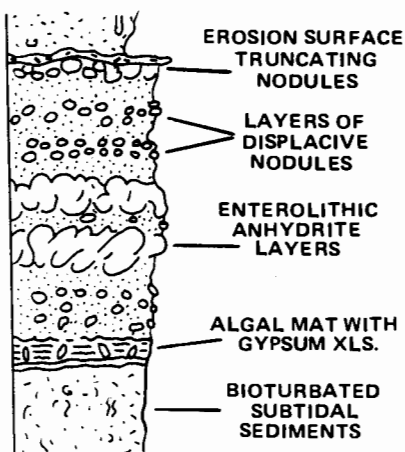


Figure 12

Characteristic features of coastal sabkha evaporites (after Shearman, 1966).

ental sedimentation. This environment is a product of both depositional and diagenetic processes, the most important of the latter being the displacive growth of early diagenetic calcium sulphate (or halite). Modern cratonic areas, such as the Arabian coasts of the Persian Gulf and the coasts of Australia and North Africa, provide the most favorable settings for Recent sabkhas and are associated with wide offshore



Figure 13

Laminated microdolomites (probably hypersaline lagoonal) overlain by algal mat, with gypsum pseudomorphed by anhydrite, and nodular and mosaic coastal sabkha anhydrite. Frobisher Evaporite (Mississippian) Saskatchewan. Core fits together but was rotated during slabbing—slab is 10 cm wide.



Figure 14

Upper part of sabkha cycle illustrated in Figure 13. Mosaic anhydrite cut across by erosion surface and surmounted by laminated micrites (with late-diagenetic anhydrite) of next lagoonal member. Frobisher Evaporite, Saskatchewan. Slab is 10 cm wide.

platforms or shelves. The sabkha is an equilibrium geomorphic surface whose level is dictated by the local level of the groundwater table. Sediment above the capillary fringe dries and is blown away by the wind unless cemented by salt.

Indigenous sediments of the supratidal flats are a reflection of the offshore sediment mosaic but may contain a substantial proportion of detrital sediment from the hinterland. Offshore sediments are washed over the sabkha during storms that periodically inundate seaward parts with marine floodwaters. Depressions (filled and buried tidal channels) act as conduits for flood and seepage waters.

Groundwaters beneath the sabkha are responsible for transporting materials precipitated as solid phases (evaporites, dolomite) and for removing by-products of diagenetic reactions and non-accumulating ions. These waters become progressively concentrated as



Figure 15

Oblique view of NW of Abu Dhabi sabkha environment. Sabkha in foreground; intertidal algal belt is the dark zone (1 to 2 km

wide) and seaward is the lagoon, barrier islands and the open Persian Gulf shelf in the far distance. Photograph courtesy R.K. Park.

they advance into the interior of the sabkha and all but the very seaward and landward margins may be saturated with respect to halite. Concentration occurs by evaporation from the capillary fringe and by dissolution of earlier-formed evaporites (particularly halides). Groundwaters lost by evaporation are replenished by: 1) downward seepage of storm-driven floodwaters (flood recharge), 2) gradual intrasediment flow, fluxing from the seaward margin, and 3) intrasediment flow, fluxing from a continental groundwater reservoir that affects landward parts of the sabkha (Fig. 16). Renfro (1974) believes that groundwater flow through continental clastics adjacent to coastal sabkhas (flow induced by evaporative pumping from the sabkha surface) is an important feature in the reddening of these sediments.

Our information about the hydrology of sabkhas is based almost entirely upon studies undertaken in Abu Dhabi (Kinsman, 1969; Butler, 1969; McKenzie *et al.*, 1980; Patterson and Kinsman, 1981). After marine flooding, seawater sinks into the sabkha sediment, raising the water table. Capillary evaporation subsequently lowers the water table, increases salinity and promotes upward water movement within the phreatic

zone by evaporative pumping.

The water table inclines seaward (Patterson and Kinsman, 1981) but the seaward migration of interstitial brines is slow and is insufficient to explain the extensive dolomitization that occurs in the sabkha sediments. Salinity also decreases downwards (caused by the effects of surface evaporation and the upward movement of less saline brines induced by evaporative pumping). Such upward movement precludes evaporative reflux of the dense brines.

Interstitial water movement is limited by the impermeable nature of the sediments (commonly carbonate muds in part compacted by displacement growth of evaporites) and impermeable barriers in the form of buried algal mats (Bush, 1973) and cemented layers (McKenzie *et al.*, 1980) act as aquitards and divide the sabkha sedimentary prism into several hydrostatic zones. Upward movement of groundwater between these zones only occurs where these impermeable barriers are broken.

The relative importance of the groundwater sources is dependent upon local geomorphic conditions. Beach ridges seaward of the sabkha prevent inundation by marine floodwaters, whereas lack of hinterland relief will restrict continental groundwater

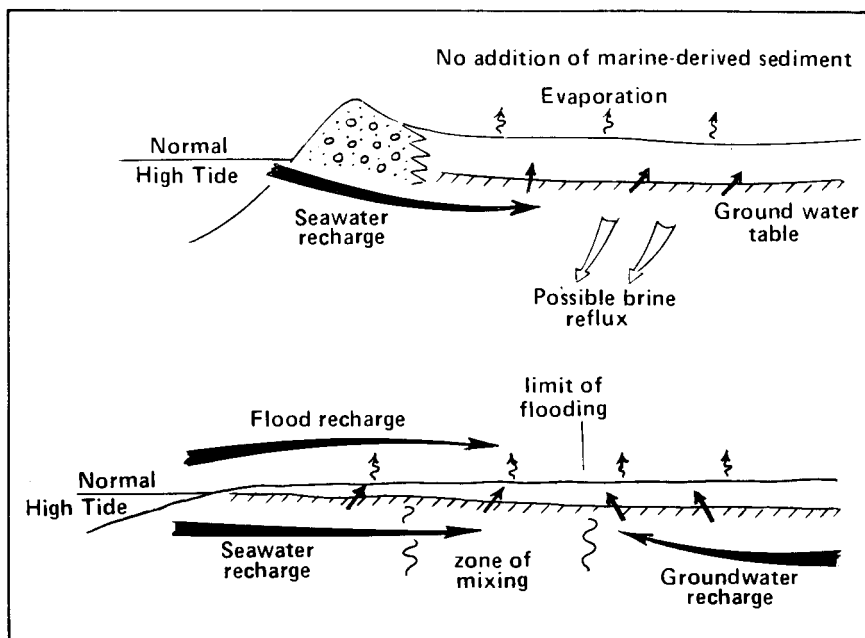


Figure 16
Constraining water supply in sabkhas. Above sabkha plain bordered by beach ridge. Seawater recharge is entirely intrasediment flow (based upon a Sinai coastal sabkha; Gavish,

1974). Below, sabkha groundwaters are replenished by flood recharge and seepage from seawater and continental reservoir (based upon Abu Dhabi sabkha).



Figure 17
Mosaic anhydrite (displacing subaqueous laminated anhydrite) with individual nodules distorted against each other (a natural consequence of displacive growth). Ordovician Stonewall Evaporite, Saskatchewan. Slab is 8.5 cm wide.

inflow. Marine waters have greater effects along the seaward edge of sabkhas and along former tidal channels (which are still depressions on the sabkha surface) while inner parts of the sabkha are less prone to marine influence as the sabkha becomes wider as a result of sedimentary accretion. Cemented sediment layers and algal mat sediments beneath the sabkha surface inhibit upward movement of deeper-lying groundwaters, thus increasing the importance of marine flooding.

Concentration of groundwater causes precipitation of diagenetic minerals: some as direct precipitates, others

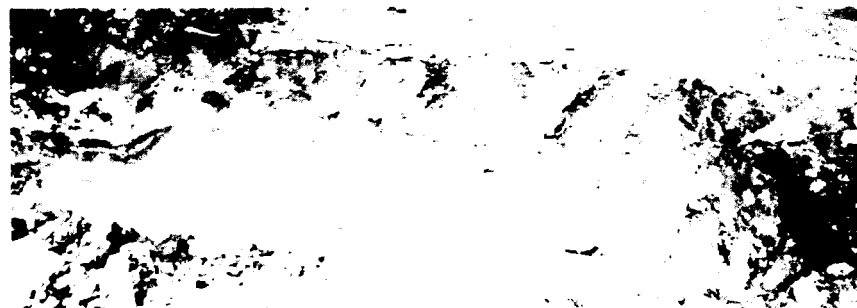


Figure 18
Surface trench about 50 cm deep in Abu Dhabi sabkha with diapiric layers of anhydrite (after gypsum); upper layer truncating

as products of reactions between ground-water brines and earlier-deposited sediments. Gypsum is not precipitated on the exposed sediment surface but grows displacively within algal mat or other upper intertidal sediments (forming crystal mushes up to 1 m thick) or grows poikilolithically within supratidal sand sediments where it occurs as large, lenticular crystals that include sand grains arranged in herring-bone patterns.

Gypsum precipitation in the intertidal and near-shore supratidal environments causes groundwaters to become depleted in calcium. The increased Mg/Ca ratio of brines induces dolomitization of pre-existing aragonite and the precipitation of magnesite. The dolomite is calcium-rich and poorly ordered. Dolomitization of aragonites releases strontium that is precipitated as celestite. Dolomitization may be favored by the 1) increase in the Mg/Ca ratio of the brine (to about 10), 2) the presence of organic matter within the fine aragonitic muds, or 3) to the removal of sulphate ions - the presence of which inhibits dolomite precipitation.

In the Abu Dhabi sabkha, anhydrite first appears one km inland from the normal high water mark, in the capillary zone. It occurs as discrete nodules and as bands of coalesced nodules, some of which may take the form of ptygmatic (enterolithic) layers. Growth of nodules occurs by host sediment displacement and by replacement of the intervening sediment matrix. Dilution of the host sediment may occur to such an extent that it is relocated to internodule areas and its fabrics are destroyed. In extreme cases host sediments are confined to mere partings between the anhydrite nodules (mosaic anhydrite; Fig. 17). Some nodules are formed by alteration

anhydrite is a storm washover and aeolian carbonate-clastic unit. Photograph courtesy R.K. Park.

of earlier formed gypsum crystals (Butler, 1970). Pseudomorphs lose shape because of flowage (adjustment during compaction) and the continued growth of primary anhydrite laths in and between pseudomorphs. Some doubt concerning this mechanism of anhydrite nodule formation has arisen following the discovery by West *et al.* (1979) of primary gypsum nodules from an Egyptian sabkha. The possibility exists that some of the anhydrite nodules from the sabkhas of Abu Dhabi also possessed a gypsum *nodule* precursor. Composite anhydrite nodules are remnants of gypsum crystal clusters and massive-appearing anhydrite forms from gypsum mush in former upper intertidal sediments. Such soft anhydrite layers become deformed into enterolithic folds and microdiapers (Fig. 18). The displacive growth of anhydrite and gypsum in intertidal and supratidal sediments is believed to raise (jack-up) the sediment surface. If the water table does not rise a corresponding amount, the upper parts of the sediment dry out and blow away. Deflation exposes anhydrite and gypsum at the surface, concentrating nodules and crystal fragments as a regolith, or breaking up nodules into laths that become strewn across the sabkha surface. Isolated anhydrite laminae at the top of some ancient sabkha sequences may have formed by such nodule and crystal destruction.

Halite occurs as salt crusts on the surface, as veneers around grains in the upper part of the capillary zone and as solid cubes in sand sediments. High humidities, particularly at night, contribute to surface water supply (as dew) and result in the diurnal dissolution of surface halite crusts. Within fine grained sediments the displacive halite cubes assume a skeletal hopper form commonly to extreme degrees (Fig. 8). In most described modern sabkhas halite is not an accumulative phase but is blown away or dissolves in floodwaters. Repeated growth and dissolution of halite can so disrupt the host sediment that all its original fabrics are destroyed.

VARIATIONS IN THE COASTAL SABKHA MODEL

Variations in size and setting of sabkhas, the nature of the host sediment, the character of the offshore water body, the type of diastrophic control and the

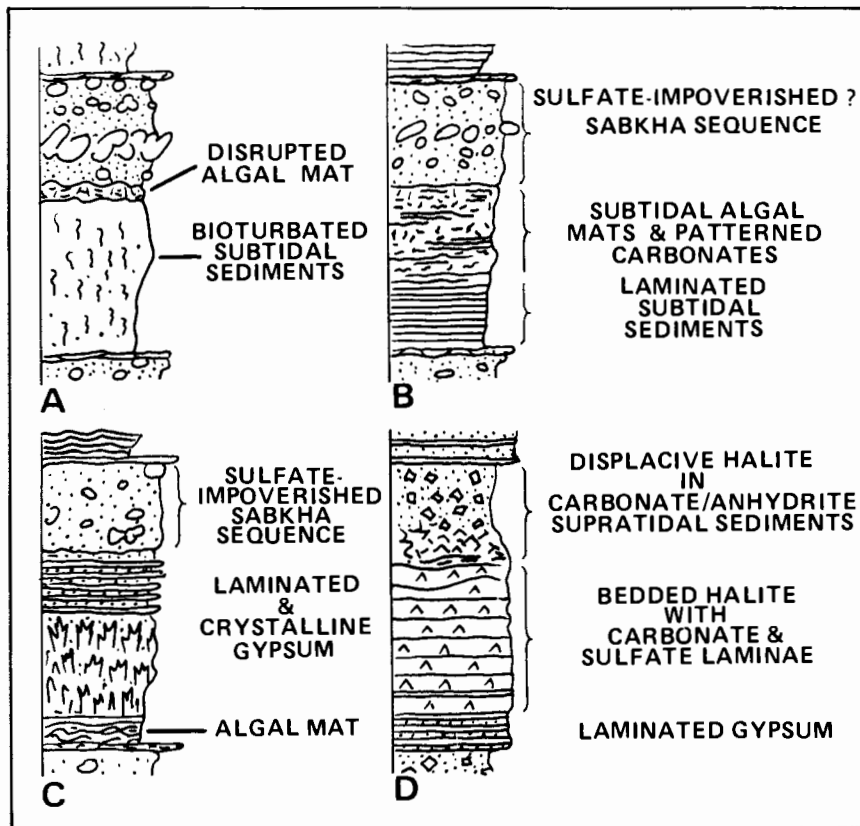


Figure 19

Hypothetical shoaling-upwards cycles: A) marginal to a normal marine to slightly hypersaline water body; B) marginal to a hypersaline water body within which sulphates are bacterially reduced; C) marginal

water body precipitates and preserves gypsum; D) marginal water body is salt-precipitating supratidal sequence largely composed of displacive (and replacive?) halite.

effects of differing local topography all may cause profound modifications from the 'norm', as represented by the Abu Dhabi sabkha (Fig. 19).

A) Size and Setting of Sabkhas. Since coastal sabkhas form the uppermost parts of accreting sedimentary bodies the development and size of sabkhas is dependent upon the topography off- and on-shore. Only narrow, discontinuous sabkhas are to be expected at locations where the offshore gradient is steep (such as the coasts of the Red Sea or Iran) whereas broad sabkhas can form on low gradient, stable shelves. Patterson and Kinsman (1981), however, sound a word of warning for they maintain that a regional groundwater flow system that causes the water table to rise as the sabkha progrades is necessary for the preservation of broad sabkhas. Without such a groundwater system evaporative losses in the areas beyond the zone of seawater flood-

recharge would lower the water table, resulting in deflation and removal of the sabkha sedimentary sequence. The requirement of a seaward dipping gradient to the sabkha groundwater surface requires the presence of a large landmass with sufficient relief to act as a recharge area for the groundwater system.

Small sabkhas, such as Sabkha Faishakh in Qatar may be more frequently flooded by marine waters and thus generally have lower interstitial-water salinities. This may partly account for why, despite the almost identical climate to that of Abu Dhabi, the sabkha contains only minor traces of anhydrite.

B) Nature of the Host Sediment. This determines the amount of drainage, the subsequent history of sabkha brines and the compactional history of the evaporite deposit. In some cases evaporites may not form in sabkha settings, despite elevated salinities well above



gypsum saturation. Amdurer and Land (1982) describe the situation in part of Laguna Madre (Texas) where so much calcium has been removed from the brine by algal precipitation (which subsequently blows away in the wind) that gypsum is unable to precipitate. Doubtless the high resultant sulphate concentrations in the brine prevent dolomitization of any carbonate that does survive. Impermeable sediments inhibit brine reflux and, by curtailing downward seepage of floodwaters, extend the width of the area affected by flood recharge. This surface flooding, however, causes little dilution of existing groundwaters. Finer grained sediments also allow thicker capillary fringes to form. Thicker evaporite sequences should be formed in fine-grained sediments because of this but the control has yet to be demonstrated in ancient examples.

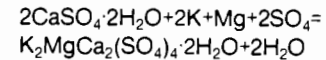
Sabkhas composed of permeable sands may allow brine reflux. DeGroot (1973) identified a downward and seaward increase in salinity of interstitial brines within the Umm Said Sabkha of Qatar. This suggests the presence of a reflux system of brine movement but dolomitization as a result of this still has to be demonstrated.

Carbonates (particularly aragonite) in host sediments are of major importance. Dolomitization of carbonates releases calcium which reacts with sulphate in groundwaters to form more gypsum and anhydrite. This additional sulphate precipitation and dolomitization reduces the sulphate and magnesium content of brines in carbonate sabkha interiors to low levels and causes magnesite (precipitated earlier) to redissolve. In non-carbonate sediments, dolomitization does not occur, the sabkha interior brines retain 60 to 70 per cent of their sulphate, much less gypsum and anhydrite is emplaced, and brines remain magnesium rich so that magnesite remains stable. The sulphate

Figure 20

Alternations between mosaic anhydrite (top and bottom) and microdolomites much disrupted by growth of halite (now pseudomorphed by anhydrite) and gypsum crystals (now anhydrite). Dolomite intervals probably represent former inter- and subtidal sediments partially obliterated by sulphate growth during reflux dolomitization, Frobisher Evaporite (Mississippian), Saskatchewan. Slab is 10.5 cm wide.

and magnesium rich brines formed in non-carbonate sabkha sediments react with earlier-formed gypsum to form polyhalite (Holser, 1966):



gypsum + brine = polyhalite

Reflux of brines capable of dolomitizing deeper-lying carbonates (well beneath the sabkha vadose zone) causes calcium sulphate precipitation (gypsum, perhaps anhydrite) in these deeper-lying sediments. Growth of sulphates in subtidal carbonate intervals between sabkha evaporites by this reflux dolomitization may obliterate evidence of the cyclic nature of an evaporite deposit and create a single thick, composite unit of nodular anhydrite. Alternations between nodular and mosaic anhydrites and disrupted dolomite intervals full of gypsum pseudomorphs in parts of the Mississippian Frobisher Evaporite in Saskatchewan may represent such partially obliterated cycles (Fig. 20).

Differences in sediment coherency dictate subsequent compactional history. Lithified or coherent sediments preserve gypsum pseudomorphs or the moulds of dissolved halite crystals. Compressible sediments (particularly organic-rich varieties), on the other hand, allow anhydrite nodules to grow, to coalesce and compact perhaps to form vuggy or even laminar anhydrites (Shearman and Fuller, 1969). Mossop (1979) believes laminar anhydrites in the Ordovician Baumman Fiord Formation (Fig. 21) were originally nodular and have been drastically altered by early diagenetic compaction and flowage.

C) Nature of the Offshore Water Body. Most commonly the offshore water body is normal marine to slightly hypersaline (well below gypsum saturation). Here subtidal-intertidal sediments are bioturbated and skeletal rich, and algal mats (if present) are confined to upper intertidal to low supratidal environments (Fig. 19A) where they may become disrupted by subsequent growth of gypsum (James, 1977).

When sabkhas border hypersaline (gypsum precipitating) water bodies, the sediments beneath sabkha evaporites are laminated (burrowing biota absent) and algal mats extend well into



Figure 21
Numerous superimposed sabkha cycles.
Baumann Fiord Formation, Ellesmere Island
(photo courtesy G. Mossop).

subtidal environments where they may be preserved. When precipitated gypsum persists in the bottom sediment, the overlying sabkha sequence forms the upper most member of a largely subaqueous evaporite sequence (Fig. 19B). However, the abundance of organic matter and dissolved sulphate in hypersaline waters normally induces reducing conditions within which sulphate-reducing bacteria thrive. Their activities cause reduction of gypsum, the formation of hydrogen sulphide with precipitation of carbonates and pyrite as by-products (Friedman, 1972) and perhaps formation of patterned carbonates (Dixon, 1976; Kendall, 1977; Fig. 19B). Removal of calcium and sulphate from the offshore water body may severely restrict gypsum and anhydrite formation in adjacent sabkha environments (Fig. 19R and C). On the other hand, the shallow subaqueous evaporites may be transported onto the sabkha by storms, there to form clastic beds of gypsum, anhydrite or even halite debris. Such sabkhas could be largely composed of such beds (which would be difficult to distinguish from shallow subaqueous evaporites) or the clastic units could be intercalated with non-storm sabkha sediments.

The atmosphere adjacent to large bodies of normal marine water is too humid for halite to persist in the sub-

aerial environment (Kinsman, 1976). If the water body is a concentrated brine, however, its water vapour pressure may be low enough not to increase atmospheric humidity. Halite can thus become an accumulative phase in sabkhas that neighbour hypersaline water bodies (particularly those saturated or near-saturated with respect to halite). Shearman (1966), Friedman (1972) and Smith (1971, 1973) have described halite rocks that appear to have formed by displacing or replacing earlier carbonate-sulphate sabkha sediments. Such sediments form adjacent to halite-precipitating water bodies (Fig. 19D).

D) Diastrophic Control. Shoaling-upwards sequences terminated by coastal sabkha deposits can form as a result of three different events. The most commonly offered interpretation is that each sequence is a separate progradational event. Sabkha plains are generated by sediment accretion with little or no significant sea-level fall. Mossop (1979) and Ginsburg (*in* Bosellini and Hardie, 1973) have independently developed hypotheses which generate successive shoaling-upwards cycles in carbonate-producing areas in a regime of continuous subsidence.

On the other hand, sediment emergence, with formation of supratidal surfaces, can also be achieved by relative falls in sea-level, independently of any sediment up-building. Sea-level changes may be the result of external events (glaciations?) or of restriction of the water body from the world ocean and subsequent removal of water by evaporation (evaporative drawdown). Criteria for distinguishing cycles that form from progradational events from those that reflect episodes of evaporative drawdown are not evident. Taylor (1980) argues that cycles resulting from sealevel falls (or drops in the brine level within isolated evaporating basins) will be stunted. Rates of evaporation would cause rapid regression and basinward migration of the shoreline. Taylor calculated rates of shoreline regression that could have occurred during deposition of the Werraanhydrit (Permian) of the North Sea of 150 m/year – 20 times as fast as the progradation of the Trucial Coast sabkhas. Meagre algal mat development, precipitation of small quantities of calcium sulphate and only

negligible dolomitization would be expected for such single-batch dessication cycles. On the other hand, evaporative drawdown need not be as fast as Taylor suggests. Evaporation may be reduced by high humidities (Kinsman, 1976), or evaporation losses may be more nearly balanced by marine inflow or seepage. In either case, rates of shoreline retreat might be more compatible with those caused by sediment progradation in which case the sabkha sequences may be difficult to distinguish.

When greater subsidence occurs towards the basin centre it is possible to recognize distal from proximal locations (Mossop, 1979). Basinwards the cycles are thicker and are dominated by thick subtidal units. Short-lived or less extensive transgressive events may not reach basin margins so that marginal successions contain fewer and thinner cycles that are dominated by supratidal (sabkha) members. Coalescence of several supratidal units may also generate thick evaporite sequences at marginal locations.

E) Topographic Control. The Abu Dhabi 'norm' is associated with a relatively simple progradational sediment wedge undivided by active channels, maritime lakes or ridges formed by former beach or offshore spit deposits (Fig. 22). This situation reflects the constant conditions (slightly falling sea-level) that have occurred since the sabkha began to form and the protection afforded by an offshore island chain. When protective barriers are absent, or if sediment supply or rates of sea-level change are variable the accumulation of supratidal sabkha sediments are more discontinuous and parts of the intertidal and subtidal environment are isolated by growth of beach bars and spits. Here we have an arid-zone equivalent of the chenier plain – an environment recently described by Picha (1978) from Kuwait but to date one that has not been recognized in the ancient.

Drowned valleys or former tidal channels, isolated by spit development or by the formation of beach barrier ridges, may occur within the sabkha environment. If connection is retained with the sea, flow into the former channels occurs in response to a lowered water level caused by evaporation from the standing body of water. Such

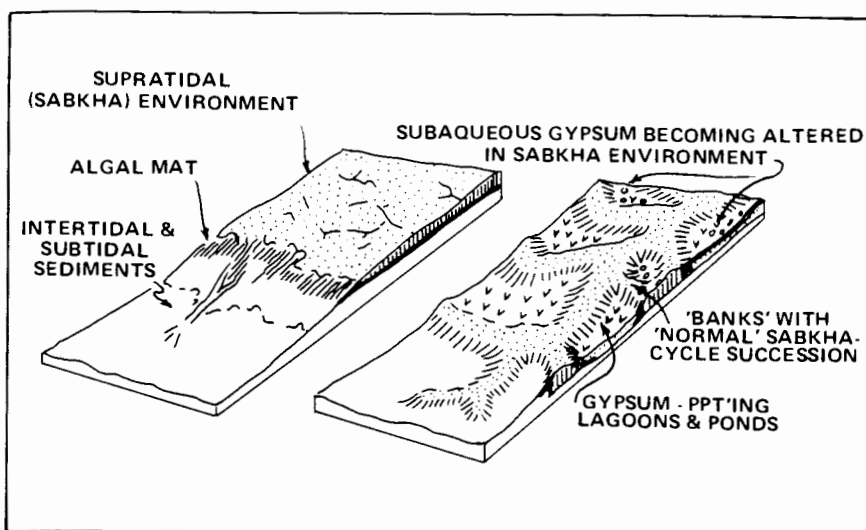


Figure 22
Contrasting patterns of supratidal sedimentation. A) simple sediment wedge. Recent Abu Dhabi sabkha; B) inferred environment for

part of Frobisher Evaporite (Mississippian) in southeastern Saskatchewan—numerous shallow maritime lakes isolated by narrow strips of supratidal sabkha.



Figure 23
Displacive gypsum crystals (centre) distorted by growth of later but still early-diagenetic anhydrite nodules. Frobisher Evaporite. Saskatchewan. Slab is 10.5 cm wide.

depressions will also attract groundwaters from beneath the surrounding sabkha and disrupt the more normal pattern of groundwater flow. The Sebkhah el Melah (Busson and Perthuisot, 1977) was such a depression but has since been filled with evaporites including a halite sequence 30 m thick. Beds of subaqueous gypsum, patterned dolomites (representing bacterially-reduced calcium sulphates) or halite beds within 'normal' sabkha deposits may represent the fills of depressions on the sabkha surface.

The evaporite portion of sabkha cycles in the Mississippian Frobisher Evaporite of Saskatchewan (Figs. 13, 14, 20, and 23) is dominated by large, subaqueously-precipitated gypsum crystals (now pseudomorphed by anhydrite). They pass laterally into more 'normal' sabkha sequences composed of nodular and mosaic anhydrite. The former gypsum crystals are also deformed by anhydrite nodule growth (Fig. 23) indicating they were transformed to anhydrite or bassanite during early diagenesis. Since more than 90 per cent of the sulphate was precipitated subaqueously a provisional environmental reconstruction having resemblance to the humid sub-tropical environment of Florida Bay is suggested. Deposition occurred in hypersaline lagoons separated by narrow barriers upon which 'normal' sabkha sequences were formed. The gypsum crystals were precipitated in the lagoons

but as progradation of the lagoon complex occurred, older lagoons became more distant from the open sea and dried out to become part of the sabkha plain. In this desiccated environment gypsum dehydrated and new anhydrite grew displacively as nodules.

It is probable that most environments which include supratidal sediments have arid-zone equivalents within which evaporites have formed. We have still to look for them in the rock record.

SHALLOW WATER EVAPORITE FACIES

Deposition of shallow-water evaporites occurs in brines that were at or near saturation with respect to gypsum or halite and in environments that may have been subject to strong wave and current action, causing sediment scour, transport and redeposition. Algal activity was significant in more protected (or deeper?) environments and many sediments were subject to periodic drying. Whereas water depths may range from a few centimetres to 20 m or more, most facies probably formed in water less than 5m deep. In fact, many evaporites considered subaqueous may have been deposited on evaporitic flats that only became flooded during storm surges or particularly high tides. Since all depositional events are subaqueous, the interpreted environment is so identified even though the depositional site may have been subaerially exposed for most of the time. Evaporite precipitation may occur at the air-water interface, at the sediment-water interface or beneath the sediment surface and varying amounts of continental and marine-derived sediments may be periodically transported into the evaporitic environment.

Most of our knowledge of shallow water evaporites has come from the interpretation of ancient examples—particularly from the Miocene of the Mediterranean (Schreiber *et al.*, 1973, 1977; Hardie and Eugster, 1971; Vai and Ricci Lucchi, 1977; Garrison *et al.*, 1978). More recently, however, studies of Holocene and Recent salinas (saline lakes adjacent to the ocean in which the salina water level is below that of the ocean and is replenished by seawater seepage; Warren, 1982; Kushnir, 1981 and Arakel, 1980) have provided valuable information confirming the older interpretations of ancient evaporites and suggesting others.

A) *Laminated Sulphates*. These may be similar in character and origin to deep-water sediments but most apparently consisted of current-deposited micrite and clastic gypsum particles in reverse and normally-graded laminae. Laminae were originally composed of silt and sand-sized gypsum crystals or cleavage fragments which grew: 1) as crusts on the depositional surface and so were easily broken and reworked, or 2) as acicular crystals precipitated at the air-water interface which sank and became reworked on the bottom. Other crystals may have grown displacively within the bottom sediment and then were reworked. All crystals and fragments suffer overgrowth on the bottom and laminae become converted into interlocking gypsum mosaics.

In some sediments the gypsum crystals have suffered little if any transport, and in many the crystals displace or poikilitically enclose algal mat carbonate and organic material. Lamination in these sediments is largely a reflection of algal mat lamination (Fig. 24). Similar algal-laminated gypsum may form by the encrusting of mats, or the mats may act as sediment traps for carbonate or gypsum muds and silts. Conversion of the gypsum to anhydrite during burial will normally obscure the differences between these types of laminites.

Cross-bedding, ripple-drift bedding (Fig. 25), basal scoured surfaces and rip-up breccias testify to environments with periodic high energy events, such as storms. Some small asymmetric ripple-marks with oversteepened sides at the tops of some laminae may represent adhesion ripples and indicate deposition of wind-blown gypsum detritus onto moist surfaces. Shallow-water deposition is also shown by the occurrence of micritic, organic-rich stromatolites between, or within, some laminae; by bird or dinosaur footprints, or by fossil brine shrimp.

Clastic sedimentation is apparently a dominant feature in the shallower, higher-energy environments of intertidal or supratidal-lagoonal (marine or salina) settings with layering due to tide- or wind-induced influx of sediment or seawater.

Laminae are interpreted as storm deposits. Each lamina forms during a storm when evaporitic tidal flats are flooded by sediment-charged water. Blue-green algal mats, which cover the

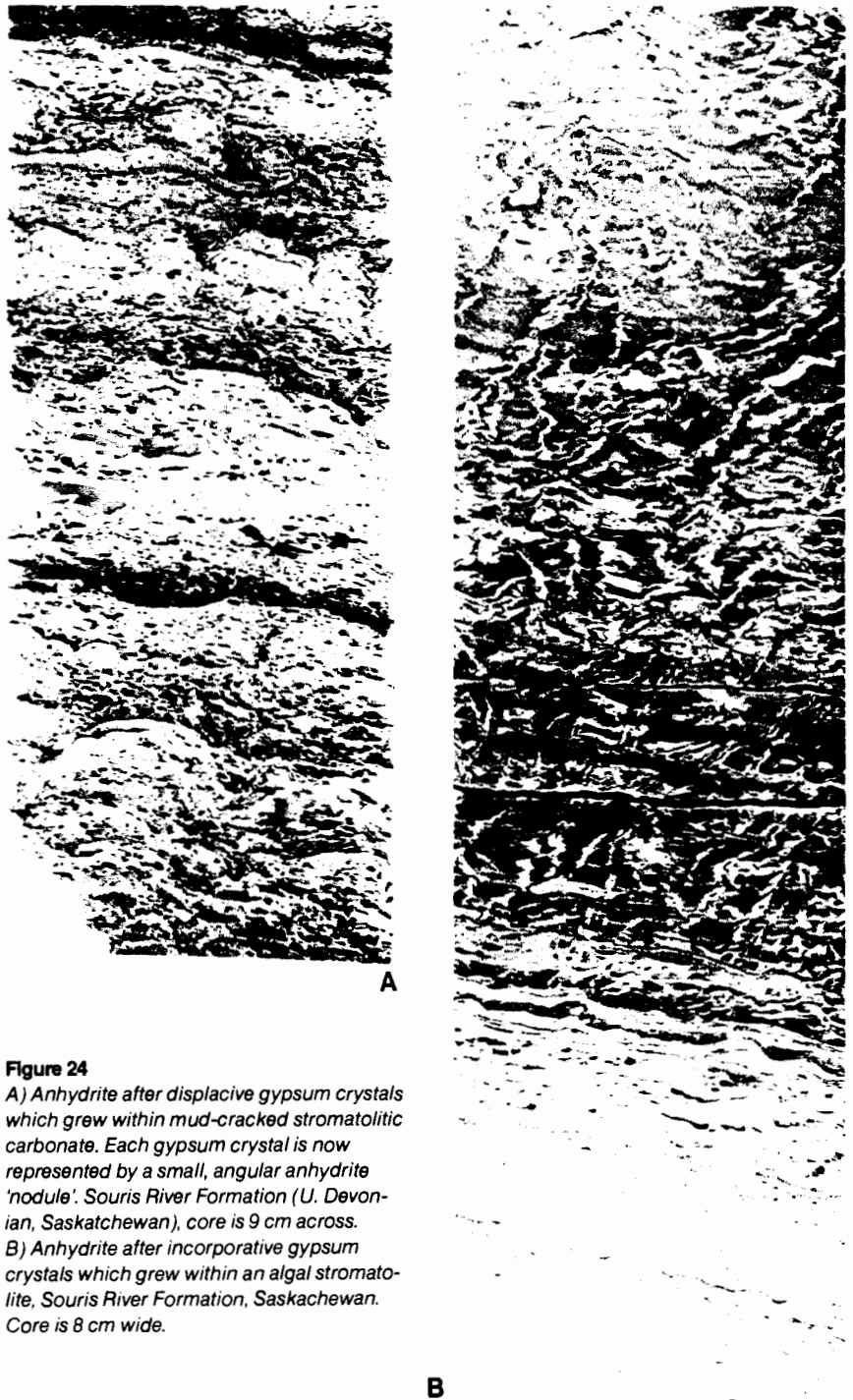


Figure 24

A) Anhydrite after displacive gypsum crystals which grew within mud-cracked stromatolitic carbonate. Each gypsum crystal is now represented by a small, angular anhydrite 'nodule'. *Souris River Formation (U. Devonian, Saskatchewan), core is 9 cm across.*

B) Anhydrite after incorporative gypsum crystals which grew within an algal stromatolite, *Souris River Formation, Saskatchewan. Core is 8 cm wide.*

flats, collect and bind evaporite sediment and, as the storm subsides, the coarser load is deposited as a traction layer or as a settle-out to produce a normally graded lamina. Algae grow through the new lamina, re-establish themselves on the surface and protect the underlying sediment from erosion. The analogy may be made with the

formation of storm laminae in other tidal-flat sediments.

Reverse-graded laminae are variously interpreted. They may record episodes of brine dilution that induce recrystallization of gypsum in the upper-most parts of laminae, or this feature may be of depositional origin. Upward segregation of coarser particles may have

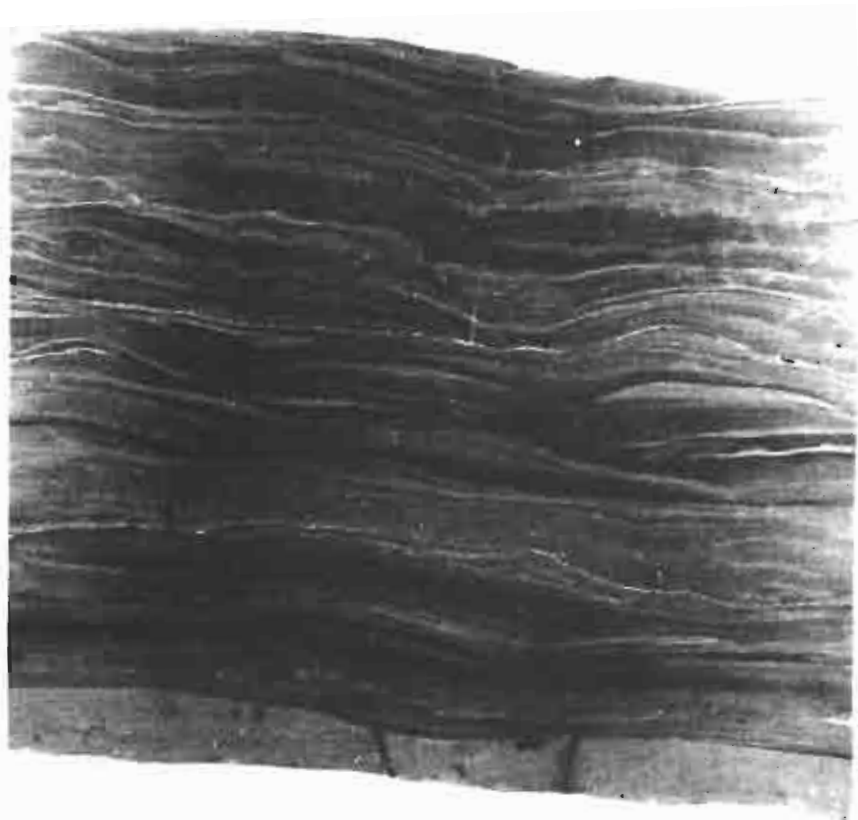


Figure 25
Laminated anhydrite containing minor amounts of disseminated dolomite that define lamination, ripples, minor cross-

stratification and scoured surfaces. Poplar Beds (Mississippian), Saskatchewan. Core is 10.5 cm across.

occurred within highly concentrated flowing sand sheets in very shallow waters upon tidal flats during storm surges. The reverse grading may then be emphasized by early diagenetic recrystallization and lithification during quiet periods between storms. Inversely graded layers, adhesion ripples, algal mats and early-diagenetic cementation of gypsum are recorded from evaporitic flats of the Laguna Mormona (Baja California; see Horodyski and Vonder Haar, 1975).

Gypsum laminites that have been altered to anhydrite rarely provide sufficient evidence for environmental reconstruction. Some laminites suffer pervasive recrystallization to coarse gypsum mosaics which transect all earlier fabric elements. If replaced by nodular anhydrite such crystals may yield rocks that superficially resemble sabkha anhydrite.

It was originally believed that although shallow-water laminite units could be laterally persistent they typically contained fewer laminae than deeper-water facies and that individual laminae could not be traced for long

distances. Now it is known that depositional environments that suffer widespread floods (salinas, some tidal flats) undergo periodic episodes of surface dissolution and reprecipitation as the floodwaters evaporate with the formation of a sedimentary sequence composed of laterally persistent thin beds or laminae - some of which are traceable over the whole environment or over the extent of the flooding.

Shallow-water laminites may also be distinguished by their association with other facies. Possibly the manner in which laminites deform provides evidence for different environments. Evaporitic flat sediments, which become emergent and suffer extensive early-diagenetic cementation, fracture and become incorporated into rip-up breccias. In contrast, some laminites interpreted as subaqueous, have suffered folding, slumping and plastic stretching (Fig. 26) suggesting that they did not become lithified during early diagenesis.

B) Coarsely Crystalline, Selenitic Gyp-

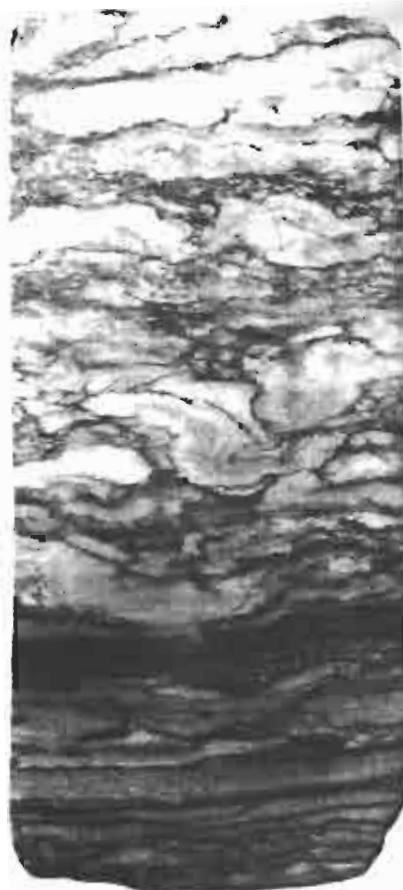


Figure 26
Deformed (slumped?) laminated to thin-bedded anhydrite which can easily be confused with displacive nodular anhydrite. Ordovician (Herald Fm.), Saskatchewan. Core is 10.5 cm across.

sum. This occurs as single crystals, clusters, crusts and as superimposed beds. This facies is best known from the Miocene of Italy but is also recognized in older sequences, now altered to anhydrite. Similar gypsum has been described from man-made salinas.

Beds of crystalline gypsum are mainly composed of orderly rows of vertically-standing, elongate and commonly swallow-tail twinned crystals that range from a few centimetres to a few metres in height (Figs. 27, 28, and 29). Crystals are commonly euhedral and in aggregate define a vertical pallasade fabric or may be arranged into radiating upwards conical clusters (cavoli). Individual crystals are separated from each other by micritic carbonate, fine-grained gypsum or gypsum sands; or secondary overgrowth produces an interlocking crystal mosaic. Other gypsum crystals exhibit more bizarre growth and twin-



Figure 27
Coarsely crystalline, selenitic gypsum facies.
 A) Palisades of gypsum crystals, Miocene of Sicily. Photo courtesy B.C. Schreiber.
 B) Layered anhydrite with pseudomorphs

after gypsum crystals, Otto Fiord Fm. (Pennsylvanian), Ellesmere Island. Photograph courtesy N.C. Wardlaw. Scale divisions in cm.



Figure 29
Swallow-tail gypsum crystals pseudomorphed by halite and anhydrite. Gypsum is unstable in contact with halite-saturated brines and dissolves to create molds that are subsequently plugged with halite. Clear Fork Formation (Permian) Texas. Photograph courtesy C.R. Handford. Core is 8 cm wide.



Figure 28
Swallow-tail twinned gypsum crystal (25 cm across) with dissolution surface at arrow. Inset is a cleavage plane surface of the same

crystal revealing numerous inclusion-defined growth layers. Miocene of S.E. Spain. Photograph courtesy B.C. Schreiber.

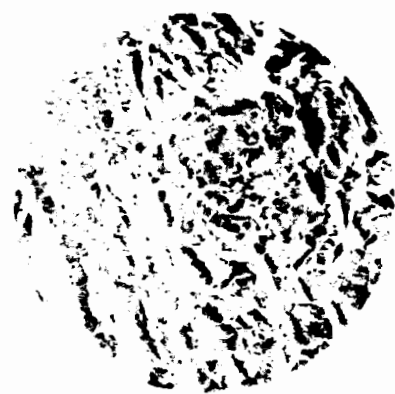


Figure 30
Anhydrite pseudomorphs of extensively twinned and split gypsum crystals within a dolomite matrix. Frobisher Evaporite (Mississippian), Saskatchewan. Cores are 10 cm across.

ning patterns and suffer crystal splitting to generate palmate to fan-shaped clusters of subparallel crystals (Fig. 30; for details see Schreiber, 1978; Orti-Cabo and Shearman, 1977). Twinning occurs at a variety of angles, probably as a consequence of the inclusion of organic matter along curved crystal faces (the greater the amount of impurity, the more obtuse the twinning angle). Other results of impurity absorption are that one twin arm may fail to grow or the crystals split into a wide and bizarre group of growth forms.

The crystals contain faint lamination (Fig. 28), defined by carbonate and anhydrite inclusions, which pass through the crystalline beds, parallel to bedding. Inclusions lie parallel to crystal faces, recording successive positions of the growing crystal, or defining solution surfaces. Many crystals include algal filaments and appear to have invaded algal mats (Fig. 24B).

Most authors now conclude that these gypsum crystals are primary and are mostly of very shallow-water origin. Schreiber (1978) notes that in salinas gypsum growth occurs mainly at depths shallower than five metres. Observations made in solar ponds reveal that the largest gypsum crystals form in environments of constant and active brine flow. The crystals record nucleation and slow incremental growth, presumably in quiet waters. The internal lamination and included algal mats indicate the crystals grew poikilitically, enclosing surficial veneers of sediment. Phases of slight undersaturation create minor dissolution surfaces that truncate the crystals. Renewed precipitation, however, commonly takes place upon

the etched surfaces, burying the surface within the crystal (Fig. 28). More severe interruptions may include: 1) a new phase of nucleation, producing a new bed of crystals, 2) lateral dissolution along crystal sides, perhaps with accumulation of residual impurities in the dissolution cavities, or 3) in extreme cases, crystals become disoriented and form residual gypsum breccias.

Beds originally composed of gypsum crystals may be difficult to identify when converted to anhydrite. Inclusions may define crystal faces within massive or mosaic anhydrite, but if the original crystals possessed numerous inclusions that defined laminae, the replacement can be mistaken for laminar sulphate. Gypsum crystals are most easily identified when the pseudomorphs are set within abundant carbonate matrix (Fig. 31). Much of the polyhalite from the Permian of New Mexico appears to have replaced and pseudomorphed selenitic gypsum (see Schaller and Henderson, 1932, Pls. 29 and 30).

Beds of gypsum crystals can become replaced during burial by mosaic anhydrite (Rouchy, 1976) which can closely resemble, and thus can be confused with, sabkha displacement-nodular anhydrite. Furthermore, if the gypsum-to-anhydrite transformation occurs in a low-permeability hostrock, the expelled water cannot easily escape. The sulphate becomes thixotropic and flows or fractures to nodular-anhydrite replacements of gypsum. I would interpret the peculiar anhydrite-structures in the Ferry Lake Anhydrite, describe by Loucks and Longman (1982), in this manner.



Figure 31
Parallel laminated, cross-stratified and load-casted gypsum sandstones (gypsarenites).

Miocene of Sicily. Photo courtesy B.C.Schreiber. Penknife gives scale.

C) Coarse Clastic Gypsum. Gypsum sands and pebbly sands, composed of worn gypsum cleavage fragments with variable amounts of carbonate and other materials, may be locally abundant but only rarely constitute major rock units. They do indicate, however, that gypsum may be transported and deposited in the same manner and environments as other clastic sediments, so long as the water body is gypsum-saturated. Such sands exhibit structures indicative of current or wave activity or may be penecemporaneously disturbed and contain load cast or ball-and-pillow structures (Fig 31). Clastic gypsum occurs as shoestring sands or in sand sheets; represents channel, beach, offshore shoal or spit deposits or may occur as intercalations between beds of laminar or selenitic gypsum.

Vai and Ricci Lucchi (1977) have interpreted wavy bedded and laminar gypsum (composed of mm-sized gypsum) with accompanying poorly-sorted, broken gypsum-crystal sands, as fluvial deposits that prograded into a basin. This facies first appears between beds of subaqueous selenite but increases in abundance upwards and includes selenitic nodules interpreted to have been supratidal anhydrite. It grades into a facies of disoriented large gypsum crystals and fragments in a clayey matrix

that represents deposits of subaerial debris-flows. Growth of subaqueous gypsum apparently became more and more interrupted by sheet-floods that carried selenite fragments. Progradation caused development of wide supratidal flats composed of this transported material and in this environment sabkha anhydrite was emplaced.

D) Halite. At least three main facies are present: detrital halite, halite crusts, and halite that grows displacively in pre-existing sediments. It is uncertain what controls which particular facies will be developed.

Halite crusts constitute the best understood facies – one for which there are detailed descriptions from the ancient (Wardlaw and Schwerdtner, 1966), from Recent salt pans (Shearman, 1970) and from experimental studies (Arthurton, 1973). Crusts form: 1) by the foundering of, and continued growth upon, rafts of halite crystals which nucleated on the brine surface; 2) by upward and lateral growth of floor-nucleated crystals; and 3) by accumulation of, and overgrowth upon, detrital halite particles. Various halite growth habits are observed but the most common is layered halite, formed by the superposition of crusts (each crust separated by films or thin beds of detri-

tal carbonate, sulphate or terrigenous sediment) and identified as 'chevron halite' (Fig. 32 A-C). Each halite layer is composed, in part, of vertically elongate crystals that contain abundant brine-filled inclusions. The crystal fabric results from an upward competitive crystal growth on the sea or lake floor such that crystals with coigns uppermost are the most favoured. Inclusions are concentrated in layers parallel to cube faces (100), so that in the elongate halite crystals with coigns uppermost, the zoning appears as chevrons with upwardly-directed apices. The upper surfaces of halite layers: 1) may exhibit crystal growth faces (interruption in growth caused by only temporary and slight brine undersaturation), 2) are truncation surfaces associated with cavities in the underlying halite crust (recording more extreme episodes of brine undersaturation and halite dissolution), or 3) are flat truncation surfaces (possible deflation surfaces cut during episodes of emergence). Each halite layer is usually composed of two types of halite; the zoned chevron halite and clear halite which fills former dissolution cavities made in the crust.

Inclusion-rich layers in zoned halite crystals form where brines are highly supersaturated and growth is rapid. Reduced brine concentrations (the

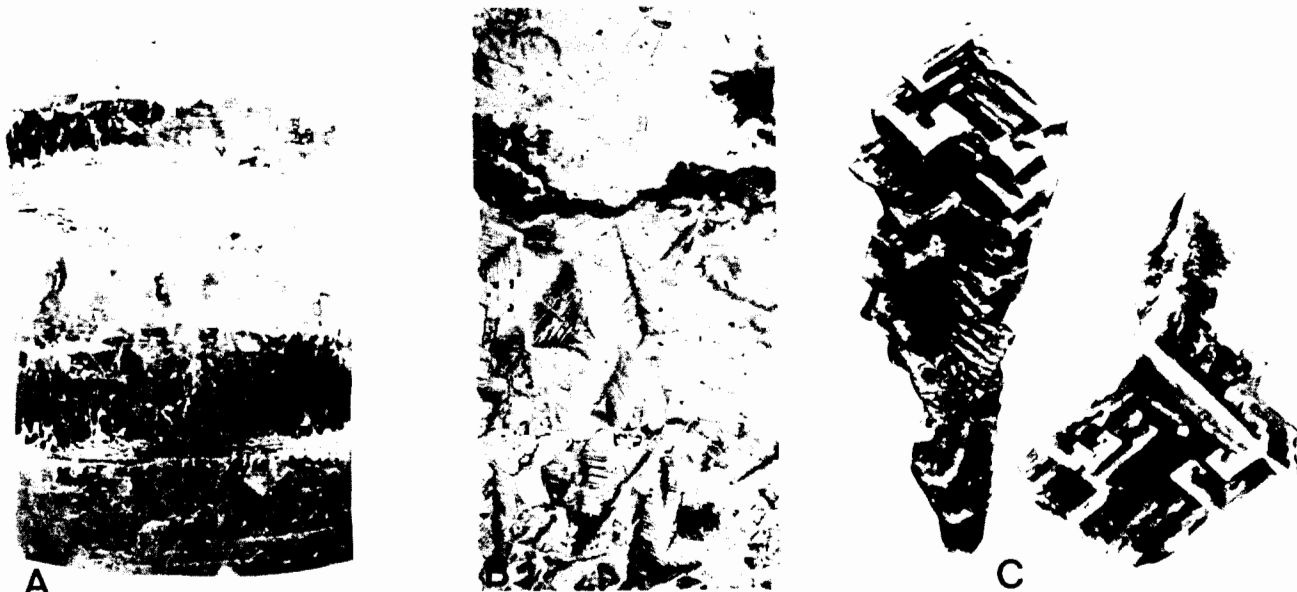


Figure 32
Chevron halite. A) Layers of chevron halite interbedded with laminated anhydrite, Souris River Fm. (U. Devonian), Saskatchewan. Core is 10 cm across. B) Thin-section

through chevron halite layer containing cloudy inclusion-rich and clear void-filling crystals, the former truncated by an anhydrite lamina. Prairie Evaporite, Saskatchewan.

wan. (Thin section loaned by N.C. Wardlaw). C) Isolated crystals from halite crust on bottom of brine pool in a Saskatchewan potash mine. Largest crystal is 3.5 cm long.

result of halite precipitation) then allow slower and more perfect (inclusion-free) halite layers to be deposited. Zonal laminae are 0.1 to 0.3 mm thick: thicknesses that could be expected to result from precipitation caused by diurnal fluctuations of evaporation rate and/or temperatures. Because brine reconcentration (necessary to cause deposition of succeeding inclusion-rich halite layers) can only occur by evaporation of the brine, the numerous alternations between inclusion-rich and inclusion-poor layers in chevron halite, indicate that rapid changes in brine concentration occurred. This can only be achieved in bodies of brine of small volume. The layering in chevron halite is thus indicative of shallow water precipitation and contrasts with the clear halite crystals of deep-water deposits.

Displacive halite has been described previously in connection with playa-flat and sabkha evaporites but may also be of subaqueous origin. It is recorded from the floor of the Dead Sea where it occurs as large (5 to 10 cm) cubes with hopper-like pyramidal hollows on each face (Fig. 33). Zoned inclusions of the enclosing sediment, parallel to all cube faces, indicate the crystal grew displacively within the mud. Sediments containing significant quantities of displacive halite cubes are termed Haselgebirge (see Arthurton, 1973) and rock units composed of displacive halite (with host sediment reduced to mere pockets or thin film between crystals) constitute the upper parts of the Prairie Evaporite and other Devonian halites in Saskatchewan.

Detrital halite is probably more important than published studies would suggest, perhaps because this facies seems particularly susceptible to recrystallization – so that depositional fabrics are lost. Detrital halite is composed of fragmentary surface-grown hopper crystals and small cubes that may represent overgrown hoppers, crystals precipitated during brine-mixing (Raup, 1970) or reworked material from bottom-growing crusts. Detrital halite is commonly ripple-marked and may exhibit cross-bedding and include other detrital material. Crystal growth may continue after deposition, by means of small-scale sediment displacement, and the detrital origin can become obscured.

Weiler *et al.* (1974) suggest that halite

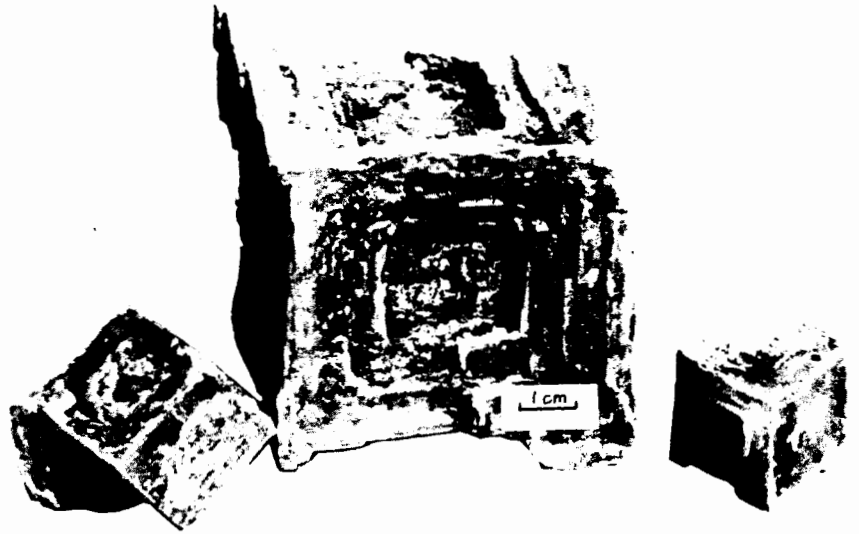


Figure 33
Displacive halite crystals (with hopper faces) that grew in micritic ooze at southern end of

the Dead Sea (Photo courtesy B.C. Schreiber).

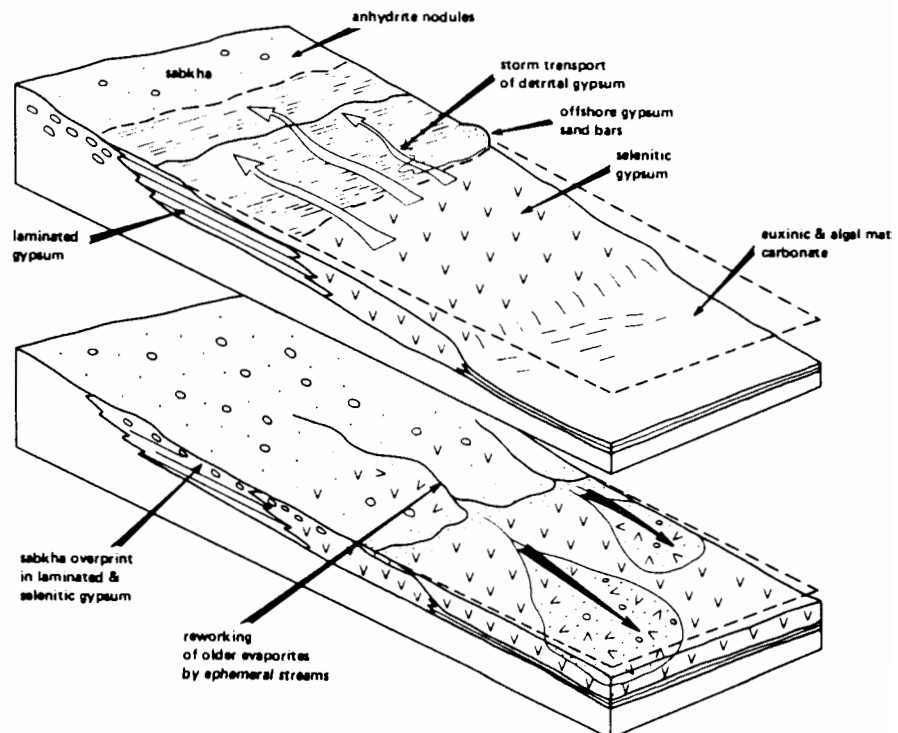


Figure 34
Models for deposition of shallow water sulphate evaporite facies. Above, after Hardie

and Eugster (1970); below Vai and Ricci Lucchi (1977).

crusts grow preferentially in shallow, quiet-water environments, whereas detrital halite, commonly ripple marked, dominates in higher energy environments because there the sunken surface-grown crystals are subject to bottom movement sufficient to prevent crust development.

Halite deposits may become consolidated early in their history by early diagenetic processes of crystallization and re-crystallization. Garrett (1970) concluded from studies of brine ponds, that in shallow-water deposits, much of the salt deposited in the evening redissolves during the day and subsequently recrystallizes. This tends to consolidate the deposit and with time and burial the porosity decreases progressively and rapidly (40% initially, 20% under 30cm of salt, 5 to 10% under 6 to 12 m of salt and to 0% with deeper burial). Not all salts, however, appear to follow this trend and the Holocene salt of Lake Macleod (Western Australia), up to 12 m thick, has porosities of 25% throughout its thickness and acts as an aquifer (Logan, pers. commun., 1982).

Much less is known about the textures and structures of potash-magnesia salts. Halite-sylvite in the Oligocene of the Rhine Valley exhibits varve-like banding (Baar and Kuhn, 1962). Because sylvite solubility is much more temperature-dependent than that of halite, the sylvite bands are interpreted to represent precipitation during periods of higher (summer) evaporation.

Most potash-magnesia salts, however, appear to be diagenetic replacements of, or additions to, earlier halite or sulphate deposits. All textures and structures may be diagenetic, but less-altered beds may still exhibit surprisingly well-preserved depositional features. Lowenstein (1982) describes primary textures in halite and anhydrite (after gypsum) from the potash ore beds of the Permian Salado Formation of West Texas-New Mexico.

Wardlaw (1972) has described crusts of bottom-grown carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$) interbedded with layers of detrital and surface-grown (?) halite. The salts are deformed by synsedimentary folds and by the displacive growth of large carnallite crystals within the sediment. Deformation of the sedimentary layering suggests that the salts were never subaerially exposed or lithified and that

subaqueous salts remain un lithified and are capable of being deformed by slumping and differential loading. The occurrence to tachyhydrite ($CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$) in these evaporites, a mineral that cannot survive exposure to the atmosphere, also indicates evaporite deposition was entirely subaqueous.

Shallow Water Evaporite Models

Two models are proposed for shallow-water sulphates; both created for the Messinian evaporites of Italy (Fig. 34). Hardie and Eugster (1971) invoke deposition of coarsely crystalline selenite in the quiet waters of a shallow lagoon or gulf, adjacent to a littoral belt of laminated gypsum. Gypsum in the laminites and in associated gypsum sand bodies (beach or offshore-shoal deposits) was derived from the area of selenite deposition and transported shorewards onto the marginal evaporitic flats during storms.

Vai and Ricci Lucchi (1977), on the other hand, working on a sequence that lacked gypsum laminites, suggest transport of gypsum toward the basin centre. Gypsum was reworked from older, emergent beds of selenitic gypsum by ephemeral slope-controlled agents (torrential streams and debris flows) which built up shallow alluvial cones that encroached the basin. This cannibalistic model can be integrated with Hardie and Eugster's model: Vai and Ricci Lucchi's interpretation applicable to times of regression, when older evaporites become exposed in marginal areas and subject to reworking, and Hardie and Eugster's interpretation appropriate to times of transgression or when the regression occurs entirely as a consequence of sediment outbuilding (when gradients will be low).

Whereas we possess a reasonable idea about details of the depositional environment of shallow-water halite (since we have a modern-day equivalent; Shearman, 1970), interpretation of the mechanism for depositing the enormous volumes of this material that occur in many evaporite formations remains problematical. As an example, the lower part of the Middle Devonian Prairie Evaporite consists almost entirely of chevron halite with carbonate-anhydrite laminae (Wardlaw and Schwerdtner, 1966) and represents deposition in shallow brine pools and salt flats. This environment apparently

stretched across Saskatchewan from Central Alberta and the source of the brine was from the northwest and would have had to have travelled more than 1600 km. It is difficult to imagine how this brine could have travelled across brine pools and salt flats without evaporating away before it had travelled for more than a small part of its journey. Interpretations of other large units of shallow-water halite would appear to be afflicted by the same problem.

DEEP WATER EVAPORITE FACIES

In this environment the brine is at or near saturation with respect to gypsum and/or halite. Crystal growth probably occurs mainly at the air-water interface and crystals settle through the water column as a pelagic rain. Regular interlamination of minerals of different solubilities (calcite and gypsum, with or without halite) reflect variations in brine influx, temperature or evaporation rate. Some calcium sulphate may grow within the upper layers of the bottom sediment and some salt may be precipitated during the mixing of brines in a stratified water body (Raup, 1970). Evaporite turbidites and mass-flow deposits, derived from shallower water carbonate and evaporite accumulations, may also be emplaced within this environment.

The depth of water in which "deep water" evaporites accumulate is difficult to determine. Where turbidites (composed of basin-marginal materials) occur at the basin centre, the centre to basin-margin distance combined with a minimal 1° slope suggests a minimum depth. Such a calculation for the Sicilian Basin during the Messinian (Upper Miocene) suggests depths exceeding 175 m (Schreiber *et al.*, 1976).

A minimum water depth can also be obtained by observing the relation of basinal evaporites to topographic elevations. Laminated evaporites at the base of the Muskeg-Prairie Evaporite Formations (Middle Devonian of the Elk Point Basin described by Wardlaw and Reinson, 1971; Davies and Ludlam, 1973) cover flanks of Winnipegosis - Keg River carbonate buildups to heights of at least 20 m. Persistence of laminae up such slopes and the lack of associated lithologic change suggest deposition occurred from a brine body at least 40 m deep.

Detailed log correlations across basin

margins can sometimes be used to identify the basin configuration and thus be used to determine the depths at which basin-central evaporites were deposited. Colter and Reed (1980) and Taylor (1980) have attempted this procedure for Zechstein (Permian) evaporites of the North Sea. They trace individual evaporite units from the basin up onto a pre-existing carbonate depositional shelf and this implies basinal evaporites were deposited in up to 200 metres of brine. Evaporite units identified as deepwater by this method include thick anhydrites, halites and halite-polyhalite which implies the presence of a deep basin filled with brine capable of precipitating bittern salts. Such an environment is not even remotely approached in the Recent.

Geochemical evidence can sometimes be employed to calculate water volume and, by implication, water depth. The smaller the volume of brine, the less the evaporative system is buffered and therefore the greater the possibility for larger variations in salinity and trace-element concentration.

Katz *et al.* (1977) have used the strontium content of aragonite laminae, some interlaminated with gypsum (Begin *et al.*, 1974), from the Pleistocene Lisan Formation of the Dead Sea region to establish a water depth of between 400 and 600 m.

A) Sulphate mm-Laminites (Figs. 35 and 36). Laminae sulphate (originally gypsum), either alone or in couplets or triplets with carbonate and/or organic matter, is probably the commonest deep-water evaporite facies and occurs in the Permian Castile Formation of Texas and New Mexico (Anderson and Kirkland, 1966; Anderson *et al.*, 1972), in the Permian Zechstein group of Germany (Richter-Bernurg, 1957; Anderson and Kirkland, 1966), in the Jurassic Todilto Formation of New Mexico (Anderson and Kirkland, 1966) and in the Middle Devonian Muskeg and Winnipegosis Formations of Western Canada (Davies and Ludlam, 1973; Wardlaw and Reinson, 1971).

Laminae are thin (1 to 10 mm thick) and although they are typically bounded by perfectly smooth, flat surfaces they may be uneven, crenulated or plastically disturbed. Over short sections, laminae are nearly of uniform thickness and individual laminae are



Figure 35
Cycles of varve-like laminated carbonate (light coloured) passing upward (in figure up and to the left) into interlaminated carbonate-anhydrite and into highly disturbed and distorted laminated anhydrite. Each cycle is

abruptly overlain by the lower carbonate laminae of the succeeding cycle. Ratner Member (basal Priarie Evaporite), Middle Devonian, central Saskatchewan. Top left is top of core, lower right is bottom of core: core is 8 cm wide.

margins can sometimes be used to identify the basin configuration and thus be used to determine the depths at which basin-central evaporites were deposited. Colter and Reed (1980) and Taylor (1980) have attempted this procedure for Zechstein (Permian) evaporites of the North Sea. They trace individual evaporite units from the basin up onto a pre-existing carbonate depositional shelf and this implies basinal evaporites were deposited in up to 200 metres of brine. Evaporite units identified as deepwater by this method include thick anhydrites, halites and halite-polyhalite which implies the presence of a deep basin filled with brine capable of precipitating bittern salts. Such an environment is not even remotely approached in the Recent.

Geochemical evidence can sometimes be employed to calculate water volume and, by implication, water depth. The smaller the volume of brine, the less the evaporative system is buffered and therefore the greater the possibility for larger variations in salinity and trace-element concentration.

Katz *et al.* (1977) have used the strontium content of aragonite laminae, some interlaminated with gypsum (Begin *et al.*, 1974), from the Pleistocene Lisan Formation of the Dead Sea region to establish a water depth of between 400 and 600 m.

A) Sulphate mm-Laminites (Figs. 35 and 36). Laminae sulphate (originally gypsum), either alone or in couplets or triplets with carbonate and/or organic matter, is probably the commonest deep-water evaporite facies and occurs in the Permian Castile Formation of Texas and New Mexico (Anderson and Kirkland, 1966; Anderson *et al.*, 1972), in the Permian Zechstein group of Germany (Richter-Bernurg, 1957; Anderson and Kirkland, 1966), in the Jurassic Todilto Formation of New Mexico (Anderson and Kirkland, 1966) and in the Middle Devonian Muskeg and Winnipegosis Formations of Western Canada (Davies and Ludlam, 1973; Wardlaw and Reinson, 1971).

Laminae are thin (1 to 10 mm thick) and although they are typically bounded by perfectly smooth, flat surfaces they may be uneven, crenulated or plastically disturbed. Over short sections, laminae are nearly of uniform thickness and individual laminae are



Figure 35
Cycles of varve-like laminated carbonate (light coloured) passing upward (in figure up and to the left) into interlaminated carbonate-anhydrite and into highly disturbed and distorted laminated anhydrite. Each cycle is

abruptly overlain by the lower carbonate laminae of the succeeding cycle. Ratner Member (basal Priarie Evaporite), Middle Devonian, central Saskatchewan. Top left is top of core, lower right is bottom of core: core is 8 cm wide.

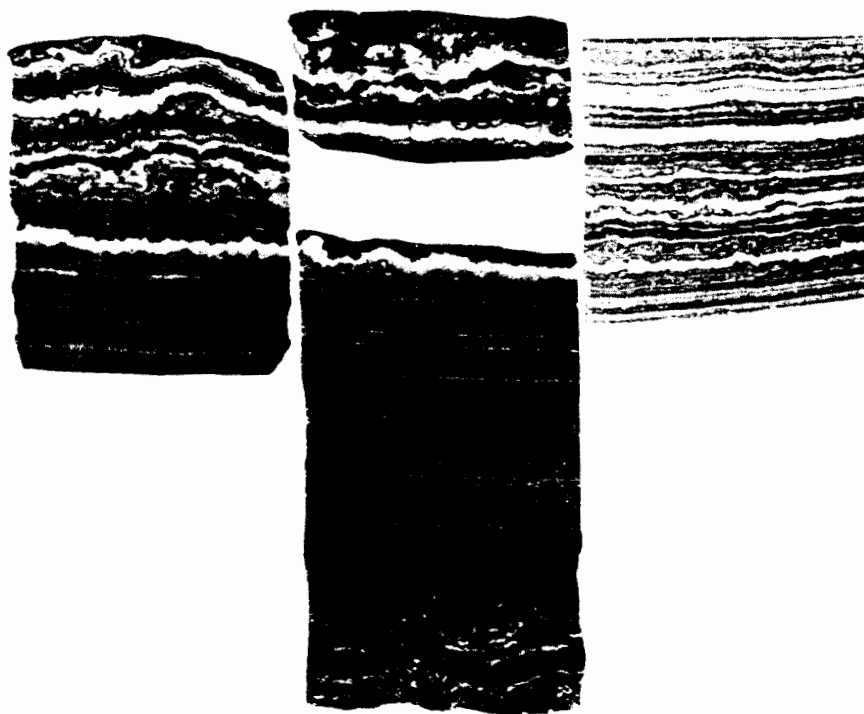


Figure 36
Lateral correlation of individual carbonate-anhydrite laminae within Ratner Member of

Saskatchewan. Cores are from wells located several kilometres apart: cores about 8 cm wide.

traceable over long distances (Fig. 36), (up to several hundred kilometres). The Castile - Lower Salado laminites are 440 m thick, comprise more than 250,000 anhydrite-carbonate couplets and some laminae have been traced laterally for more than 110 km (Anderson *et al.*, 1972).

Some anhydrite laminae exhibit evidence that they were originally composed of small lenticular gypsum crystals, arranged parallel to bedding (Shearman, 1971) and are similar to those in gypsum laminae from the Lisan Formation. Similar lenticular gypsum crystals precipitate from the water column (?) in shallow solar-salt ponds or grow displacively in algal sediments (Schreiber, 1978). Laminae that lack evidence of lenticular gypsum may have accumulated on the basin floor from a rain of fine gypsum or primary anhydrite needles precipitated at the air-water interface.

Nodular anhydrite intervals occur within the Castile Formation but are the result of a reorganization of pre-existing sulphate laminae, the nodular anhydrite rarely completely losing its laminated appearance. However, some intervals

do approach, in appearance, those formed in supratidal settings. Some authors (notably Friedman, 1972) would use the presence of nodular anhydrite to suggest that the entire Castile succession is shallow water in origin, whereas others (Dean *et al.*, 1975) conclude that this type of nodular anhydrite is not diagnostic of supratidal environments. The occurrence of nodular anhydrite at horizons where anhydrite laminae are thick or immediately beneath halite layers suggests nodule formation was associated with increased salinity.

Laminated sulphates record the precipitation and deposition of sediments in a water body whose bottom was unaffected by wave action and currents. Such stagnant, permanently stratified water bodies need not be particularly deep and carbonate laminae form in comparatively shallow waters of the Dead Sea (Neev and Emery, 1967) as a result of "whitings" at the brine surface. Lenticular and needle gypsum crystals precipitate in shallow brine ponds and also are non-diagnostic of water depth. The interpretation of some laminated sulphate deposits as deep-water thus rests primarily upon: 1) the wide-spread

occurrence of individual laminae, 2) the lack of other facies indicative of shallow water, 3) the size of the evaporite unit, and possibly 4) the presence of gravity-displaced sediments.

Unfortunately the utility of criterion 1 is questionable in that laminae of wide distribution are found in some shallow-water to subaerially exposed environments (see below). It has been held that shallow-water laminites are prone to current and wave reworking. Unfortunately abrupt brine stratification in the brine column can dampen wave motion at shallow depths, leading to a false impression of "depth".

B) Laminated Halite. Deep-water halite is difficult to recognize because many examples have suffered recrystallization, obliterating original characteristics. Even so, deep-water halite is invariably finely laminated and contains anhydrite-carbonate laminae (Jahresringe) similar to those of deep-water laminated sulphates (which commonly underlie or are interbedded with the halite). Lamination within the salt beds bounded by anhydrite-carbonate laminae is common and is defined by variations in inclusion content (liquid inclusions or very fine grained sulphate or pelitic material). Salt layers and laminae have been traced for many kilometres (Schreiber *et al.*, 1976; Richter-Bernburg, 1973; Anderson *et al.*, 1972).

Many halites are thus banded with alternations of clear translucent halite and dark grey to black halite. Dark colours are caused by light dispersion that is caused by anhydrite and/or talc inclusions. In some banded halite the dark layers contain clay or quartz silt and suggest episodes of clastic influx into the basin that alternated with periods of basin-floor halite growth.

The classic description of a subaqueous basin-central halite deposit is that of the Salina (Silurian of Michigan Basin) by Dellwig (1955) and Dellwig and Evans (1969). Salina salts exhibit a clear salt-cloudy salt banding (in 2 to 9 cm thick couplets) in addition to dolomite-anhydrite laminae. Banding is absent or only poorly developed in some basin-marginal locations where there is additional evidence for shallow-water conditions. Cloudy layers are inclusion-rich and are described by Dellwig as being composed of numerous pyramidal-shaped hopper crystals

that grew on the brine surface. When broken or disturbed, these skeletal crystals were swamped, sank and accumulated on the bottom as a sediment. They subsequently developed syntaxial inclusion-free overgrowths, and assumed cubic habits.

Cloudy and clear salt banding was interpreted by Dellwig (1955) as a product of variations in halite saturation on the basin floor. Sinking hopper crystals caused bottom brines to become saturated with respect to halite. A temperature rise in the bottom brines, however, caused undersaturation and some dissolution of previously accumulated hopper crystals. Subsequent cooling of the brine allowed the brine to become supersaturated and promoted growth of clear, inclusion-free halite as overgrowths of surviving bottom hopper crystals and as a new, clear, halite layer. Supply of new hopper crystals from the brine surface formed a new layer of cloudy halite on top of the clear layer. The early diagenetic origin of clear salt layers and of hopper overgrowths is shown where carbonate-anhydrite laminae drape over overgrowth crystal faces or when similar carbonate-anhydrite laminae overlie flat dissolution surfaces that cut across both hoppers and their overgrowths.

If Dellwig's interpretation of the clear halite is correct, then this may account for the recrystallized appearance of other deep-water halites. It is not known, however, whether a deep body of brine would suffer sufficient variation in bottom temperatures to promote this wholesale solution-reprecipitation.

Many of Dellwig's conclusions have been challenged by Nurmi and Friedman (1977). They identify much of the cloudy salt as having grown on the basin floor as crusts of upwardly-directed crystals and infer a shallow-water origin for it (see section on shallow-water halite). However, Dellwig categorically describes some halite crystals as being downwardly-directed so that both bottom-grown and surface-grown (hopper) halite may be present. Nurmi and Friedman also identify some clear halite crystals, interpreted as recrystallized halite by Dellwig, as primary. Such halite occurs as well-developed cubes and is interbedded with stringers of carbonate and anhydrite which drape over underlying halite crystals (Fig. 37). The clear character of



Figure 37

Deep-water halite layers, composed of cubic crystals, interbedded with laminated carbonate and anhydrite. Basal A-1 salt (Salina Group) Michigan basin. Vertical scale bar: 1 cm. Photo courtesy R.D. Nurmi.

these crystals reflects slow precipitation from a brine body that did not suffer rapid compositional changes. This, together with a restriction of this facies to the lower part of the lowest (A-1) Salina salt and to the basin centre, suggests deposition in somewhat deep-water environments. All other salt is reinterpreted to be of shallow-water origin.

C) Gravity-Displaced Evaporites. Clastic evaporite intervals, interbedded with deep-water laminated evaporites or with non-evaporite sediments, are interpreted as slump, mass-flow and turbidity-current deposits. Their presence is possibly the best indication of a large body of brine during deposition.

Gypsum or anhydrite turbidites are seemingly identical with non-evaporite equivalents. Sometimes the entire Bouma sequence is present (Schreiber *et al.*, 1976) but most beds are only composed of graded units or have poorly developed, parallel laminae in uppermost parts (Schlager and Bolz, 1977). Beds may be entirely evaporite in composition or contain carbonate and

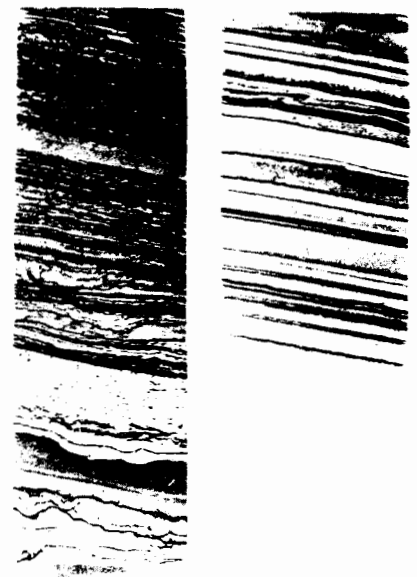


Figure 38

Carbonate and anhydrite turbidites from a facies that flanks M. Devonian (Winnipegosis Fm.) carbonate buildups: Saskatchewan. Graded carbonate turbidites at left are inserted within laminated carbonate and anhydrite. At right poorly-graded anhydrite layers occur in association with thinner (autochthonous?) anhydrite laminae. Cores are 8.5 cm across.

other types of clastic material. Gypsum-rich turbidites from the Miocene of the Periadriatic Basin (Parea and Ricci Lucchi, 1972) constitute a thin horizon within a thick siliciclastic flysch sequence, interpreted as a deep-sea fan deposit. Turbidites within some evaporite deposits are entirely carbonate in composition (Davies and Ludlam, 1973) indicating an entirely carbonate upslope source, or that evaporites at such locations contained no coarse-grained material. Centimetre-thick anhydrite beds (Fig. 38), some exhibiting poorly-developed grading, associated with carbonate turbidites in flanking beds around Winnipegosis banks in Saskatchewan, suggest that the deposits of turbidity currents which only carried fine-grained sulphate may be difficult to distinguish from "normal" basinal evaporites that are deposited as a pelagic rain.

Mass-flow deposits are represented by breccias composed of clasts of reworked sulphate, either alone or with carbonate fragments. They occur in well-defined beds; clasts are tightly packed and large fragments (up to a

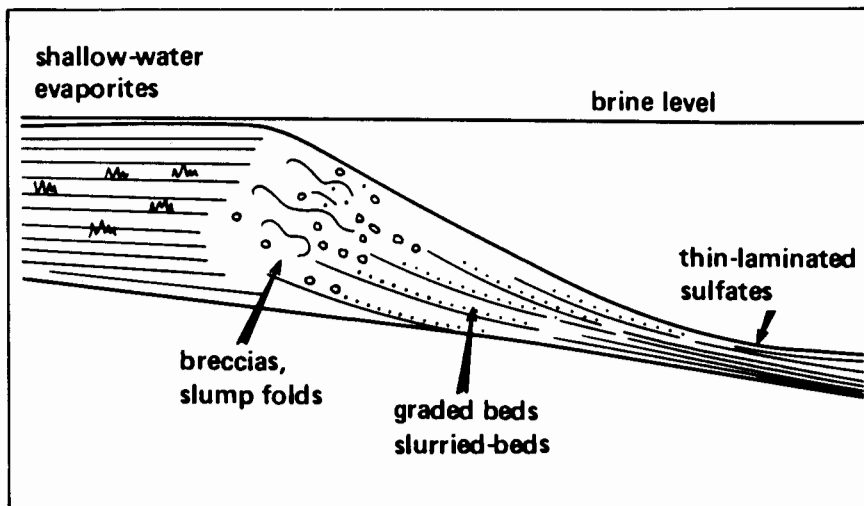


Figure 39
Schematic diagram of deep water and slope evaporite environments (after Schlager and Bolz, 1977).

metre in size) may be concentrated at the base of beds. They are commonly associated with beds affected by slump-folding. Confinement of deformation to certain horizons and possible truncation of deformed beds beneath undisturbed beds are indications that sediment transport down slope was penecontemporaneous.

Deep Water Evaporite Model

The deep-water evaporite model is only just beginning to be understood and to be recognized in ancient sulphate evaporites. When initial basin slopes are gentle, the basin periphery becomes the depositional site of thick shallow-water evaporites that build upwards and outwards into the basin and construct a ramp or platform (Schlager and Bolz, 1977) (Fig. 39).

In large part, this difference in sedimentation rate between basin centre and flanks is the result of the greater degree of evaporation that can occur in shallower waters. Additionally, deeper waters (below the photic zone) have little or no free oxygen, so that sulphate-reducing bacteria are able to prevent gypsum-precipitation or dissolve that which had been precipitated in shallower oxic waters. Deepwater sulphates must be transported to their final resting site from oxic waters either by settling from surface waters or by lateral displacement. Rate of sulphate supply must also exceed rates of removal by bacterial activities. Because evaporite

deposition at the deep basin centre is slower than upon the platform, steep depositional slopes develop at the platform edge. Upper parts of slopes are sites of slumping and mass flow, whereas lower parts of slopes contain graded beds that were emplaced by turbidity currents. Laminated sulphates (gypsum) are deposited on basin floors and slopes.

Not all deep-water evaporite basins are flanked by sulphate platforms. Basins flanked by lithified carbonate build-ups, for example, possess no source of evaporite detritus and are largely composed of laminites, possibly with minor carbonate turbidites at basin flanks.

Conversely, not all deep-water evaporites need have been emplaced under saturated waters. Some mass-flow deposits described by Parea and Ricci Lucchi (1972) were deposited after evaporites had ceased forming on the platform, and were presumably preserved in the undersaturated waters of their new environment by their fast mode of transport and burial beneath protective non-evaporite sediments.

Deep water halite accumulates in the same general environment as sulphate laminites but the brines became supersaturated with respect to halite. Periodic returns to sulphate precipitation, forming Jahresringe, suggest pulses of seawater entry into the basin – perhaps seasonally. Restriction of clear, cubic halite facies to central parts of the Michigan Basin suggest gradual desiccation of the basin occurred so that deep-water deposition became progressively restricted to the basin centre (Nurmi and Friedman, 1977).

Colter and Reed (1980) have shown that the same pattern of basin filling that occurs when calcium sulphates are deposited may occur during deposition of deeper-water halites and potash salts. Individual units are traceable from basin to depositional shelf and are arranged in a foresetting pattern with units exhibiting a thinning towards both the basin and shelf.

EVAPORITE SEQUENCES

Facies models are developed from the characteristics of individual facies and from the succession and arrangement of these facies. The thickness of many shoaling-upwards subaqueous sedimentary sequences also have commonly been used to estimate a minimum depth of water at the time deposition commenced. It is not possible to use this method for subaqueous-evaporite successions (although it has been attempted) because the upper depositional limit, the brine surface, is rarely static. Cycles in subaqueous evaporites can result as much from brine-level lowering (due to evaporation) as from any sedimentary upbuilding. Thus the "minimum" estimate of brine depth (for lower parts of the cycle) can be very much an underestimate. Conversely, because subaqueous evaporite deposition occurs in locations where the brine surface may be lowered by evaporative drawdown, the thickness of cycles need not even record minimal water depths at the start of deposition. Unlike sea-level, which is commonly a more or less static confining surface for marine sedimentation, the level of a brine surface may rise to offset the effect of sediment upbuilding, so maintaining a similar depth of water. In this way, shallow water evaporites may accumulate for many tens of metres without necessarily passing vertically into shallower facies. Shoaling-upwards cycles reflect a gradual decrease in brine depth but this need not occur at the same rate as sedimentary accretion.

It cannot be expected that brine depth will be stable over any great length of time. The very fact of evaporite precipitation means that the brine volume has been depleted by evaporation. In the absence of significant water input, precipitation of evaporites must be accompanied by dramatic lowering of the brine surface (evaporative drawdown) and even when water input

offsets this brine-loss it is most unlikely to balance the evaporation rate exactly and brine-level fluctuations will occur. Drowndraw and desiccation may cause shallow-water and supratidal sediments to be located only a short distance above those formed in deep water. Conversely, basin refill and dilution may cause episodes of non-evaporite deep-water sedimentation. Thus deep depositional basins may contain both deep and shallow-water deposits. Application of a single depositional model throughout the history of basin filling is unlikely.

Three types of vertical succession occur within marine evaporite sequences and each corresponds to deposition in a different part of a basin (Fig. 40).

Basin-marginal sequences (which in shallow basins may extend well into the basin) are characterized by sabkha deposits, with evaporites growing *within* the sediments. Calcium sulphate saturation is only achieved in upper intertidal-supratidal environments and shallow water evaporites are either absent or are confined: 1) to existing depressions on the sabkha surface, or 2) to brine-flats that develop if the rate at which the supratidal surface is raised by displacive evaporite growth falls below the rate of subsidence, and the former sabkha surfaces thus becomes flooded with brine. Leeder and Zeidan (1977) interpret laminar sulphates above nodular anhydrite as forming in this last-mentioned situation but, because the brines would have been derived from sabkha groundwaters (therefore calcium and sulphate depleted), salt-pan halite is more likely to be precipitated in such a situation. Halite in the Stettler Formation (Upper Devonian of Alberta; Fuller and Porter, 1969) may have been deposited in such supra-sabkha depressions.

In shallow basin or shelf sequences (which may also be located on the floors of partially desiccated deep basins) gypsum saturation is reached in the shallow subaqueous environment. Vertical variation is caused: 1) by sediment upbuilding, 2) by lowering of brine level by evaporation or drainage (commonly associated with cannibalism of earlier-formed evaporites), or 3) by changes in the rate of brine-recharge that occur as a result of brine-level rise toward the world sea-level, brought about by sediment upbuilding. Decreased recharge will result in desiccation and regressive sequences, whereas increased recharge

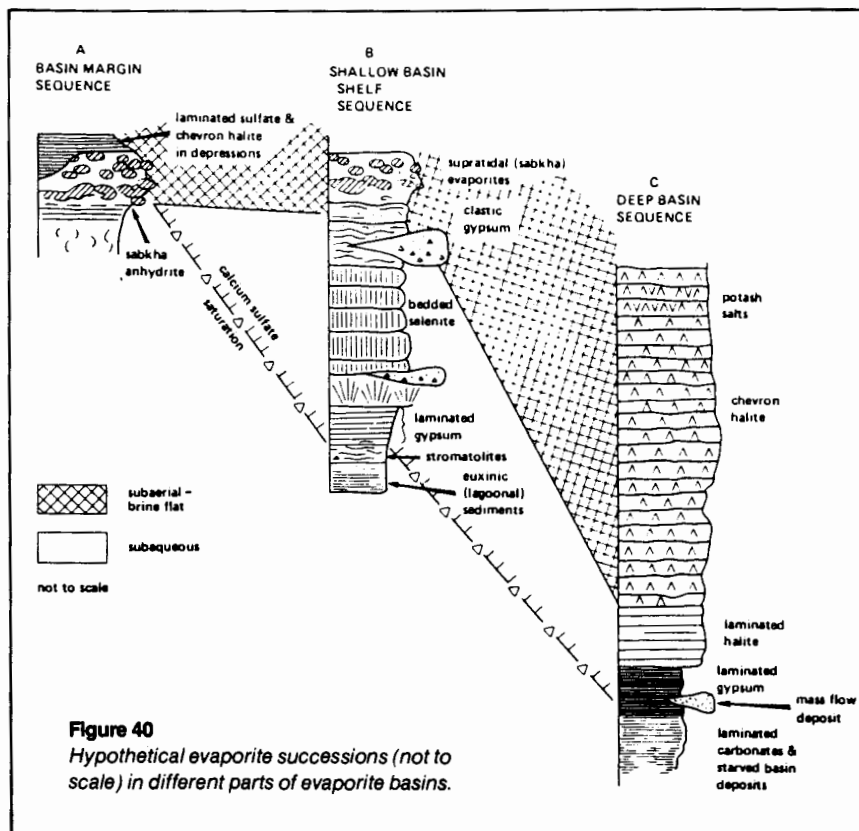


Figure 40
Hypothetical evaporite successions (not to scale) in different parts of evaporite basins.

will produce transgressive sequences. Changes in recharge will also affect the salinity of brines. Salinity increases are recorded by upward transitions from carbonates into sulphates, perhaps via patterned (or pyritic) carbonates that record sulphate precipitation and contemporaneous sulphate-reduction (Fig. 41). By the time halite saturation is reached, the brine-level in the shallow basin or shelf environment has been lowered to such an extent that only shallow subaqueous or brine-pan salt is deposited.

Lowenstein (1982) describes cycles of magnesite, anhydrite and halite (with diagenetic potash mineral overprints) from the Salado Formation of the Delaware Basin. They involve numerous (74 cycles in 160 m of core) passages from shallow lagoonal gypsum-carbonate deposits upwards into shallow lagoon-salt pan mud-free halites and, at the top, dry salt pan, displacive muddy halites. These sequences were compared with those described by Arakel (1980) from Hutt and Leeman Lagoons of Western Australia although the factors that caused these Holocene cycles (progressive restriction of the lagoons by growth of barrier beach and dune com-

plexes) are unlikely to be similar to the Permian examples.

A most valuable Holocene analog for interpreting sequences of shallow-water gypsum has been described by Warren (1982) (Figs. 42 and 43). From a comparison of the inferred hydrologic changes that have occurred in South Australian salinas and the depositional sequences present, Warren has been able to make sense of some of the depositional features. The salinas began as perennial brine lakes up to 10 m. deep. The volume for the brine pond was large and its waters were strongly density-stratified. Sediments were initially precipitated therefore from a stable, gypsum-saturated brine that was unaffected by seasonal input of meteoric waters that affected the shallow water-layers of the salina. This stable setting allowed continuous deposition of gypsum and aragonite in, and on, a surface covered by an algal mat. Gypsum crystals pushed aside the aragonite to form an interlocking mosaic of large gypsum crystals with an intercrystalline matrix.

Later, as the salina began to fill with sediment, the volume and depth of the brine ponds decreased and seasonal freshening of surface waters became

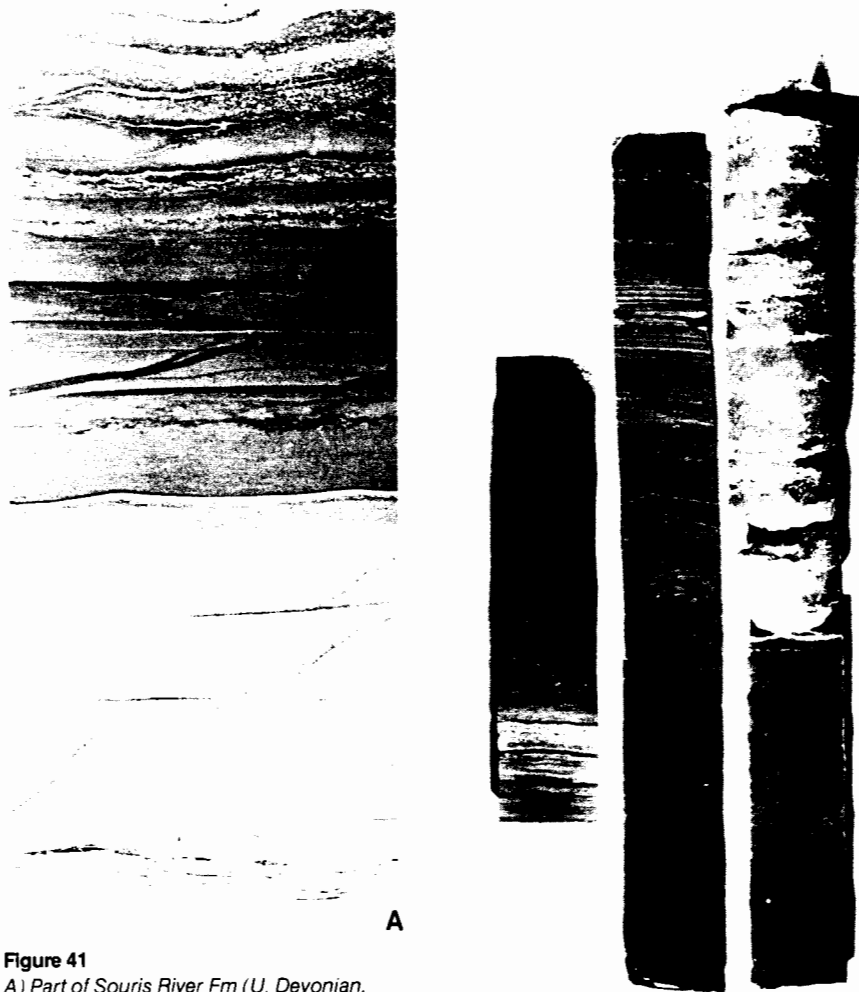


Figure 41

A) Part of Souris River Fm (U. Devonian, Saskatchewan) evaporite cycle. Light coloured laminated carbonates at base pass up into pyritic-stained carbonates (marking episode when brines were gypsum saturated but gypsum failed to accumulate because of bacterial reduction in the sediment) and then into laminated anhydrite (deposited when rate of gypsum precipitation exceeded the rate of its removal). A further salinity increase is revealed by the highly dendritic halite crystals that grew within the laminated carbonates. Core is 8 cm across. **B)** Evaporite cycle in Ratner Member (M. Devonian, south Saskatchewan) composed of varved

dolomite passing rapidly but gradationally into laminated and varved anhydrite (perhaps representing several cycles like those seen in Fig. 19), abruptly overlain by massive anhydrite (after gypsarenite?) and chevron, layered halite. Cycle represents a period of increasing salinity and decreasing water depth. It starts with subaqueous (deep?) calcium carbonate and sulphate and abruptly is overlain by shallow subaqueous to subaerial (salina) subphate and salt-pan halite.

progressively more important in controlling salina sedimentation. This induced a pronounced aragonite-layering within the gypsum crystals and poikilitic enclosure of some of the carbonate matrix. Initially carbonates were deposited upon the upturned crystal faces of the gypsum crystals (outlining them) but eventually the seasonal freshening caused the dissolution of the upper parts of the newly-precipitated gypsum

crystals to form truncation surfaces.

As the sediment surface approached sea-level, the brine-pond became ephemeral with rapid changes in salinity and saturation conditions. This promoted multiple gypsum-crystallite nucleation and gypsum precipitated as an annual crop of sand-sized crystals. Deposition changed from precipitation of large gypsum crystals (typical of more stable conditions) to a laminated

gypsarenite unit. During the transitional period, gypsarenite forms in the shallower margins of the salina and selenitic gypsum in the deeper, more central, parts. Similar sequences of gypsum to those which formed in the South Australian salinas have been described from the Miocene of Italy (Schreiber *et al.*, 1973; Vai and Ricci Lucchi, 1977; Fig. 42-4).

Calcium sulphate saturation is reached in the central deep-water parts of some basins and laminar sulphates overlie starved basin deposits. Some pyritic basal limestones may represent the by-product of subaqueous sulphate reduction (Friedman, 1972) and the change from carbonate to sulphate marks an increase in the rate of sulphate production so that some of the sulphate survives bacterial reduction. Halite saturation may be reached in shallow or deep-water environments but some basins seem to pass directly from deep-water sulphate laminites into brine-pan halite. The absence of deep-water halite from these basins presents a considerable problem. Upward sequences are produced: 1) by brine-level lowerings, caused by net evaporative loss, which causes precipitation of more saline and shallower water evaporites above deeper, less saline deposits; and 2) by flooding events that may cause deeper water, less saline deposits to abruptly overlie shallower, more saline evaporites. Taylor (1980) suggests that cycles in the Werraanhydrit of the North Sea (Fig. 42-5), which are composed of laminar carbonates that overlie laminar anhydrite and nodular anhydrite at the base, formed during conditions of progressively lower supersaturation and during episodes of transgression. To date this is the only transgressive evaporite deposit recognized. Most halite appears to have precipitated upon brine-flats, and thick sequences of chevron halite (the lower part of the Prairie Evaporite for example) must record sediment upbuilding coincident with a similar rise in brine-level on the floor of a fairly deep desiccated basin.

DEPOSITIONAL SETTINGS OF EVAPORITES (DEPOSITIONAL MODELS)

Rather than discuss the classic models that have been applied to subaqueous evaporites (such as the bar model of

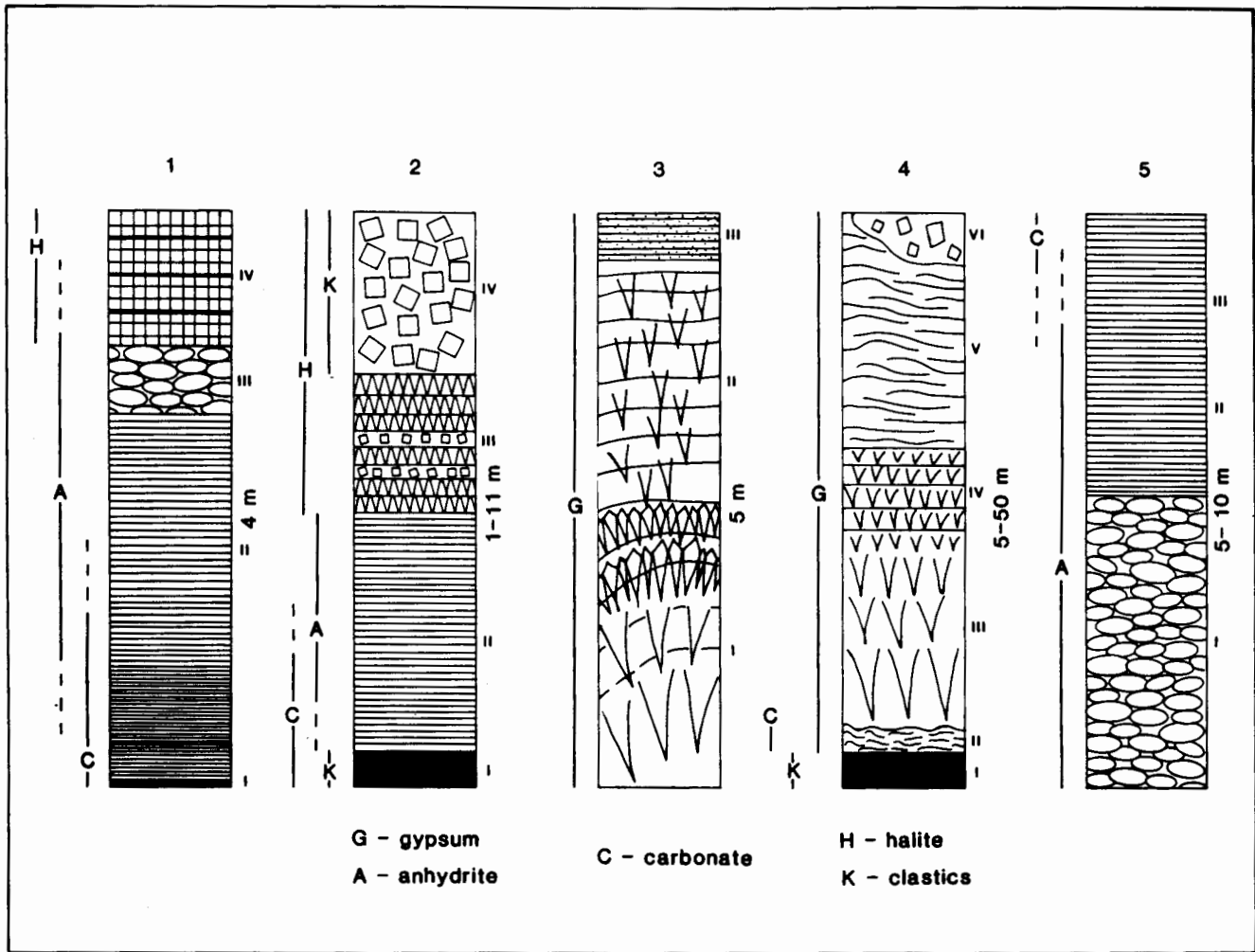


Figure 42
Evaporite cycles

1) Salinity cycle composed completely of deepwater laminites from the Castile Formation (Permian) of west Texas—New Mexico (after Dean, in Handford et al., 1982). Laminites are initially calcitic and very fine (i) but pass up, via calcite-anhydrite couplets into thicker laminites composed of anhydrite (ii) which at their top become nodular (iii). The cycle is terminated by thin-bedded halite containing anhydrite laminae (iv). Below the halite the carbonate-anhydrite laminite sequence closely resembles that seen in the Ratner Member of Saskatchewan (see Fig. 35) but there the deepwater anhydrites pass directly into salt-pan halite (Fig. 41B).

2) Lagoonal to salt-pan cycle from Salado Formation (Permian) of west Texas and New Mexico (after Lowenstein, 1982). (i) Mud containing magnesite is followed by alternations of anhydrite (after gypsum) and magnesite and then by anhydrite laminae after clastic and in-situ gypsum (ii) which represent shallow lagoon or hypersaline lake deposits. Mud-free halite with chevron and hopper structures (iii) were deposited in a perennial lagoon or lake that eventually dried

up, forming a dry salt pan or saline mud-flat within which chaotically-bedded muddy halite was deposited (iv). All parts of the Salado cycle may contain potash minerals that are diagenetic overprints. The cycle records the progressive increase in salinity and the desiccation of a lagoon or lake. It is the reverse of the sequence seen at the base of the Lotzberg Salt of northern Alberta (Fig. 8) which must illustrate the passage of a saline mud-flat into a halite-precipitating saline lake.

3) Salina cycle from New Lake, South Australia (after Warren, 1982). Selenite domes composed of coarsely-crystalline gypsum and with indistinct layering (i) pass transitionally upward into selenite with aragonitic laminae that drape over and define gypsum-crystal terminations. Overlying bedded, vertically-oriented gypsum crystals (ii) contain solutional surfaces overlain by aragonite laminae, all poikilolithically enclosed within the gypsum crystals. The uppermost part of the cycle is composed of laminated gypsarenites (iii). The cycle was formed by the progressive filling of a coastal salina, the sediments of which were progressively more affected by

seasonal freshening events.

4) Gypsum cycle from Messinian (Miocene) of Northern Apennines, Italy (after Vai and Ricci Lucchi (1977). (i) Bituminous shale is overlain by carbonate-gypsum algal laminite (ii) and massive selenite that has enclosed algal-mat sediment (iii). Upward the coarsely-crystalline gypsum becomes bedded and more finely-crystalline with the appearance of dissolution surfaces. The upper part of the cycle is composed of lenticular to laminated gypsum (iv) with beds of chaotic selenite (v) interpreted to be cannibalized parts of older gypsum deposits. The sequence of selenite types closely resembles that from South Australian salinas (Warren, 1982).

5) Anhydrite—carbonate cycle from Werranhydrit (Permian) of North Sea (after Taylor, 1980). Nodular to nodular-mosaic anhydrite (i) passes up into finely laminated anhydrite (ii) and carbonate (iii). This sequence is the reverse of that seen in the Castile Formation or the Ratner Member (Fig. 35) and has been interpreted to result from a progressive decrease in basin-water salinity, perhaps brought about by a slow transgression.

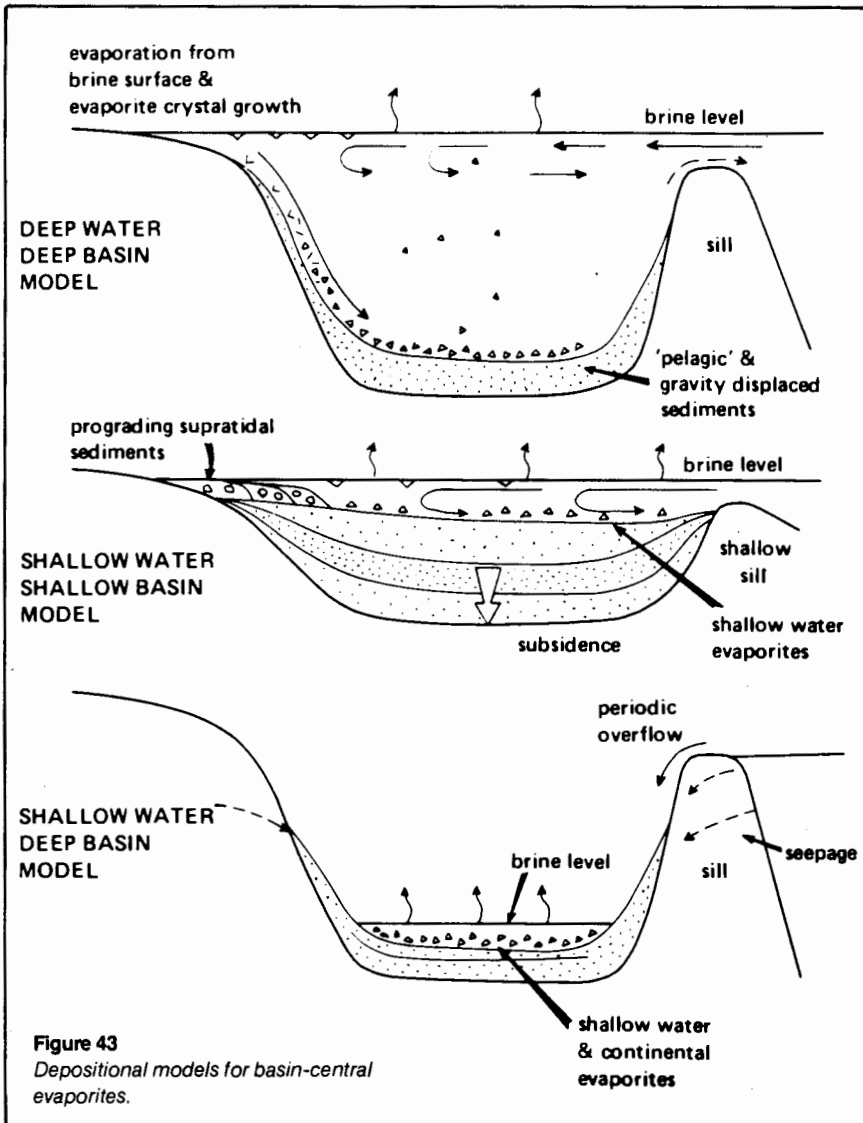


Figure 43
Depositional models for basin-central evaporites.

Ochsenius, the surface reflux model of King and the seepage reflux model developed by Adams and Rhodes) – models that are adequately described and discussed by Stewart (1963), Hsu (1972), and Kirkland and Evans (1973) – attention is directed towards three currently accepted and competing depositional models (Fig. 43). Deep- and shallow-water evaporites are also contrasted in Table 2.

Deep Water Deep Basin Model

The deep water, deep basin model is founded upon evidence that giant evaporite basins were deep topographic depressions. Evidence of this comes from: 1) the rate of evaporite deposition compared to possible rates of basin-floor subsidence, and 2) from paleogeographic reconstructions.

The Zechstein (Permian) of Germany locally contains almost 2,000 m of evaporites which accumulated at an average rate, based upon varve measurements (assumed to be annual), of 10 mm/year. Even if the Zechstein basin subsided at rates comparable with those of geosynclines (0.1 mm/year), a postulate for which there is no confirming evidence, the initial depth of the Zechstein basin could not have been less than 1,165 m (Schmalz, 1969). The depositional rate may be disputed because the annual nature of the evaporite varves is uncertain (see Shearman, 1970). Other evidence, however, indicates that evaporite depositional rates can be very high. More than two km of salt in the Messinian of the Mediterranean accumulated in less than two million years and more than 300 m of

evaporites in the Muskeg-Prairie Evaporite Formations of the Elk Point Basin (western Canada) were deposited in the time interval corresponding to a fraction of a conodont zone – possibly only 500,000 years. Such rates require that deposition was initiated within a pre-existing deep basin.

Carbonate buildups (reefs or mud-mound complexes) are commonly associated with basin-central evaporites and occur in marginal or basin-central locations. They accumulated either before evaporite deposition was initiated or are (in part) contemporaneous with evaporite deposition. The height of pre-evaporite portions of the buildups can be used to determine depth for the basin and such evidence commonly indicates pre-evaporite basins were at least hundreds of metres deep.

Evaporite deposits also commonly include intercalations of euxinic sediments, such as black shales. These are considered, by some, as evidence for deep-water deposition (Schmalz, 1969).

There is thus considerable evidence for the postulate that many evaporites were deposited on the floors of deep basins. Unfortunately, most of these criteria identify the basin depth but not the depth of water in which the evaporites formed. Many evaporites and genetically related sediments exhibit evidence for shallow-water or subaerial deposition. Nevertheless, there are some evaporite deposits whose internal characteristics strongly suggest deep water deposition and, as will be seen, the shallow water, deep basin model must progress through a deep water, deep basin stage in its development.

Shallow Water Shallow Basin Model

The shallow water, shallow basin model accounts for the sedimentologic and geochemical evidence for shallow water and/or subaerial depositional environments for basin-central evaporites; evidence that commonly is overwhelming. The main argument against the applicability of the shallow water, shallow basin model is the structural and stratigraphic evidence that deposition occurred within pre-existing deep topographic depressions – depressions that, from the evidence of the evaporite facies themselves, must have been only partially filled with brine. There are also difficulties in generating thick evaporite

Table 2
Sedimentary Aspects of Deep-Water and Shallow-Water Evaporite Deposits.

Mineralogy	Deep Water	Shallow Water
Sulphate Laminites	thin, traceable over long distances.	thicker than in deep water, individual laminae may be laterally impersistent. evidence of deposition by currents: clastic textures, ripple drift and X-bedding, rip-up breccias, reverse and normal grading. associated stromatolites, footprints.
Clastic Sulphates	nodular anhydrite developed from laminated sulphates. in form of gravity flows, slumps and turbidites.	nodular anhydrite developed displacively in inter- and supratidal sediments. in form of offshore bar, channel, beach and sand spit deposits and as intercalations between other facies.
Selenitic Gypsum		layers of swallow-tail twinned crystals.
Halite	finely laminated with carbonate-sulphate laminae. Inclusion-defined laminae traceable over long distances. clear, inclusion-free halite cubes.	layers separated by terrigenous or carbonate-sulphate laminae. associated with potash salts. inclusion-rich 'chevron' halite with clear cavity-filling halite. detrital halite, ripple-marked and cross-bedded. emersion surfaces, salt-thrust polygons.

Note that recrystallization and other diagenetic changes commonly destroy the evidence necessary to place evaporites into environmental settings. No single criterion is diagnostic.

deposits by this model because it must be assumed that the basin floor subsides at approximately the same rate as the evaporites were deposited – unlikely in most tectonic environments. Furthermore, it is also necessary to postulate that the barrier zone, which controls ingress of oceanic water (needed to account for the volume of evaporites precipitated) and egress of refluxing brines (required to prevent isochemical successions from being formed), remains at approximately the same altitude. The barrier can neither subside (as does the basin) nor rise. The first would permit entry of fresh sea-water, which would dissolve previously deposited salts, and reflux out of the basin the concentrated brines. The second, uplift

of the barrier, would permit the basin to dry out and no further deposition of marine derived salts would occur. Because the rates of evaporation and corresponding rates of salt deposition are high in arid climates, the rates of basin subsidence would have to be both rapid and constant. Estimated rates of evaporite deposition thus do not support theories of shallow-water deposition with contemporaneous subsidence for the formation of vast bodies of salt. On the other hand, the shallow water, shallow basin model is certainly applicable to evaporite formation in satellite basins and to formation of thin evaporite deposits in basin-central locations. The latter occur at the top of sedimentary cycles which can be numerous and

superimposed such that, in aggregate, the evaporites constitute a major proportion of the sedimentary sequence. Examples of such sequences in the Williston Basin occur within the Ordovician (Kendall, 1976), the Upper Devonian (Wilson, 1967; Dunn, 1975) and the Poplar Beds of the Mississippian, although the subaqueous nature of much of these evaporites has not been previously recognized or is disputed.

Basins bound by active faults are locations where rates of subsidence could be fast enough to keep pace with evaporite deposition. Rates of isostatic readjustment deduced from the Lake Bonneville (Utah) area indicate that such movements can be both rapid and responsive to very small differences in load – in this instance, the weight of water in Pleistocene Lake Bonneville. This leads to an interesting possibility (so far unexplored) that varying climatic conditions control the volume of brine in some basins and the weight of these brines induces isostatic subsidence or uplift with the formation of sedimentary cycles that appear to be of purely tectonic origin. Windsor (Mississippian) evaporites of the Maritimes accumulated in graben (Evans, 1970) and could theoretically, have been deposited in shallow water, shallow basin environments that suffered continuous subsidence.

Shallow Water Deep Basin Model

The shallow water, deep basin model was developed to account for pre-existing deep basins that become filled by evaporites with internal evidence for shallow water and/or subaerial depositional environments.

Calculations made by Lucia (1972) on the degree of basin restriction required to promote gypsum and halite precipitation suggest that the barrier between the open sea and the hypersaline basin must be almost complete. Sea-water-supplying channels into gypsum-precipitating basins can only be of very small dimensions and salt deposition implies complete surface disconnection from the ocean. The source for the halite is from episodic flooding over the barrier. A corollary to Lucia's argument is that when a deep basin undergoes restriction and loses connection with the world ocean (a requirement needed before evaporites can be precipitated) there may be little to prevent desicca-

tion or a pronounced depression of the brine level in the basin well below sea level.

The shallow water deep basin model was developed largely to account for two major evaporite deposits – the Middle Devonian Elk Point evaporites of western Canada (Muskeg and Prairie Evaporite Formations) and the Miocene Messinian evaporites of the Mediterranean. Fuller and Porter (1969) and Shearman and Fuller (1969) identified laminated dolomites and anhydrites at the base of the Prairie Evaporite, located between carbonate buildups, as algal mat and sabkha deposits and so postulated desiccation of the Elk Point Basin. The laminated beds are now interpreted as subaqueous deposits (Wardlaw and Reinson, 1971; Davies and Ludlam, 1973) but immediately overlying halites (described by Wardlaw and Schwerdtner, 1966; re-interpreted by Shearman, 1970) testify to deposition of salt flats and imply basin desiccation. Most support of the shallow-water deep basin model, however, comes from the DSDP program in the Mediterranean (Hsü *et al.*, 1978). During the Late Miocene the Mediterranean basins were covered by deep marine waters when evaporites were not being formed, but the evaporites were deposited in shallow waters, brine-flats or subaerially on the floor of the basins, thousands of metres below sea level.

Evaporation of the entire Mediterranean Sea would yield only enough salts to reach 60 m in thickness locally. Part of the Messinian evaporites may have been derived from the salt content of waters that drained into the desiccated Mediterranean, but Hsü *et al.* (1973) estimated that at least 11 flooding-desiccation events would have been required to generate the Messinian evaporite sequence. In this calculation no attention was paid to groundwater contribution. Deep basins must intersect the groundwater pattern of neighbouring areas and, if deep enough, would constitute a major sink for groundwater flow. Much shallow water, deep basin evaporite may thus be derived from groundwaters. The low bromine halite of the Lower Elk Point in Alberta may have been entirely derived from such a groundwater source (Holser *et al.*, 1972).

During basin desiccation and after basin isolation from the world ocean the

desiccating sea must pass through a deep water, deep basin stage within which deep water sulphates and halite are precipitated. Hsu (1972) calculates that the Mediterranean would have reached saturation with respect to gypsum while still more than a thousand metres deep. Friedman (1972), however, argues that deep water sulphates will not be preserved because organic matter in the brine promotes bacterial reduction of dissolved sulphate or of already precipitated gypsum. This argument assumes that the rate at which sulphate is bacterially reduced will always exceed the rate at which sulphates are precipitated, itself dependent upon the evaporation rate. The assumption is clearly incorrect in locations where subaqueous sulphates are being precipitated today, like the brine ponds described by Schreiber *et al.* (1977) and Schreiber and Kinsman (1975).

Upon complete desiccation the floors of basins in which major bodies of evaporite formed (such as the Mediterranean and Zechstein basins) must have lain one or more kilometres below sea level. Such large depressions would provide conditions that are unlike any now present on the earth's surface. Air temperatures would be high (perhaps exceeding 60°C), brine temperatures even higher (80°C or more) and humidities would be very low because of the extreme continentality of basin floors and because of reduced vapour pressures, caused by the high temperatures. Such conditions should markedly influence the type of evaporite minerals formed and it is possible that primary subaqueous anhydrite might have been able to form during the extreme desiccation stages of the Mediterranean.

SUMMARY

This paper has emphasized interpretations based upon evaporite fabrics and structures but has largely ignored geochemical evidence. Postash and similar evaporites have also been little mentioned because few sedimentologic studies have been attempted for these rocks. In part, this sparsity reflects the major changes imposed by diagenesis causing few dispositional characters to survive. The treatment given to other evaporites has also been subject to considerable personal bias. Interpretation of evaporites is still very much an

art and many stratigraphic units have been interpreted in very different ways. Important new interpretations seem to appear each year.

ACKNOWLEDGEMENTS

Noel P. James read an earlier version of this manuscript and suggested many worthwhile changes. The paper was partially written when the author was a member of the Saskatchewan Geological Survey and an employee of Amoco Canada.

BIBLIOGRAPHY

Of the numerous papers dealing with the sedimentology, few deal with facies models or summarize previous work. Many facies were first, or are best, described from Canadian deposits but others have yet to be adequately described from Canada. Canadian sources are thus not listed separately but are identified by asterisks.

INTRODUCTORY READING

Busson, G., 1974. Sur les évaporites marines sites actuels on Recents de dépôts d'évaporites et leur transposition dans les séries du Passé. *Revue de Géographie Physique et de Géologie Dynamique* (2), v. XVI, p. 189-208.

Dean, W.E., and Schreiber, B.C., eds., 1978. Notes for a short course on marine evaporites. Society of Economic Paleontologists and Mineralogists Short Course No. 4. A comprehensive, but uneven, compilation of work upon evaporites. The paper by Schreiber upon subaqueous sulphates remains essential reading and the section upon halite fabrics by Shearman is clearly written and illustrated. Other papers deal with environments, geochemistry and geophysical-log evaluation of evaporites.

Handford, C.R., Loucks, R.G., and Davies, G.R., eds., 1982. Depositional and diagenetic spectra of evaporites – a core workshop. Society of Economic Paleontologists and Mineralogists Core Workshop No. 3, Calgary, Canada, 395 p. A beautifully illustrated collection of papers concerned with both Recent and ancient evaporites. Provides an interesting contrast to Kirkland and Evans (1973) in that subaqueous evaporites are perhaps over-represented. Includes a useful summary paper by Schreiber, Roth and Helman.

Hosler, W.T., 1976. Mineralogy of evaporites. In Burns, R.G., ed., *Mineralogical Society of America Short Course Notes*, v. 6 Marine Minerals. Washington, Mineralogical Society of America, p. 211-294.

Kirkland, D.W., and Evans, R., 1973. Marine evaporites: origin, diagenesis and geo-

- chemistry. Benchmark Papers in Geology. Stroudsburg, Penn., Dowden, Hutchinson and Ross.
- Probably the best starting point, particularly the introductions to the papers written by the editors. A carefully selected collection of papers, but now outdated in that subaqueous evaporites are under-represented. This failing is filled by Dean and Schreiber, eds., 1978.
- Perthuisot, J.-P., 1980. Sites et processus de la formation d'évaporites dans la nature actuelle. Bulletin Centre Recherche Exploration Production Elf Aquitaine, v. 4 p. 207-233.
- Two critical reviews of Recent evaporite environments.
- Strakhov, N.M., 1970. Principles of lithogenesis v. 3. New York, Oliver and Boyd, 557 p.
- A survey of Soviet ideas on arid-zone sedimentation, concentrating upon evaporites. Particularly good in its use of evidence from Recent salt lakes and ancient deposits.
- MODERN CONTINENTAL EVAPORITES**
- Amiel, A.J., and Friedman, G.M., 1971. Continental sabkha in Arava Valley between Dead Sea and Red Sea: significance for origin of evaporites. American Association of Petroleum Geologists Bulletin, v. 55, p. 581-592.
- Cook, R.U., and Warren, A., 1973. Geomorphology in deserts. London, B.T. Batsford Ltd.
- Parts 2 upon desert surface conditions, 2 and 3.5 on playa systems provide an excellent geomorphic background to continental evaporites. Also see: Glennie, K.W., 1970. Desert sedimentary environments. Developments in sedimentology 14. Amsterdam, Elsevier, 222 p.
- Eugster, H.P., and Hardie, L.A., 1978. Saline lakes. In Lerman, A., ed., Chemistry, geology and physics of lakes. New York, Springer-Verlag, p. 237-293.
- Handford, C.R., 1982. Sedimentology and evaporite genesis in a Holocene continental - sabkha playa basin - Bristol Dry Lake, California. Sedimentology, v. 29, p. 239-253.
- Hardie, L.A., and Eugster, H.P., 1970. The evolution of closed-basin brines. Mineralogical Society of America, Special Publication 3, p. 273-290.
- Hardie, L.A., Smoot, J.P., and Eugster, H.P., 1978. Saline lakes and their deposits: a sedimentological approach. In Matter, A., and Tucker, M.E., eds. Modern and ancient lake sediments. Special Publication 2. International Association of Sedimentologists. Blackwell Scientific Publications, p. 7-41.
- Excellent summary papers dealing with the sedimentology and brine-geochemistry of saline lakes and surrounding environments.
- Jones, B.F., 1965. The hydrology and mineralogy of Deep Springs Lake. Inyo County, California. United States Geological Survey, Professional Paper 502-A, 56 p.
- Describes concentric zonation of carbonate-sulphate evaporite minerals in a small playa lake.
- Kinsman, D.J.J., 1969. Modes of formation, sedimentary associations and diagnostic features of shallow-water and supratidal evaporites. American Association of Petroleum Geologists Bulletin, v. 53, p. 830-840.
- Neal, J.T., ed., 1965. Geology, mineralogy and hydrology of U.S. playas. United States Air Force, Cambridge Research Laboratory, Environmental Research Paper 96, 104 p.
- Valyashko, M.G., 1972. Playa lakes - a necessary stage in the development of a salt-bearing basin. In Richter-Bernburg, G., ed., Geology of saline deposits. Proceedings of the Hanover Symposium 1968, UNESCO, Paris, p. 41-51.
- Watson, A., 1979. Gypsum crusts in deserts. Journal of Arid Environments, v. 2, p. 3-20.
- ANCIENT CONTINENTAL EVAPORITES**
- No detailed studies appear to have been made of possible continental evaporites and associated evaporitic sediments in Canada. They occur in the basal Mississippian of the Maritimes, parts of Arctic Canada and in the Juro-Triassic Watrous-Amaranth Formations of Saskatchewan and Manitoba.
- Arthurton, R.S., 1980. Rhythmic sedimentary sequences in the Triassic Keuper Marl (Mercia Mudstone Group) of Cheshire, northwest England. Geological Journal, v. 15, p. 43-58.
- Deardorff, D.L., and Mannion, L.E., 1971. Wyoming trona deposits. University of Wyoming Contributions to Geology, v. 10, p. 25-37.
- Dyni, J.R., Hite, R.J., and Raup, O.B., 1970. Lacustrine deposits of bromine-bearing halite, Green River Formation, northwestern Colorado. In Rau, J.L., and Dellwig, L.F., eds., Third Symposium on Salt. Northern Ohio Geological Society, p. 166-180.
- Eugster, H.P., 1980. Lake Magadi, Kenya, and its precursors. In Nissenbaum, A., ed., Hypersaline brines and evaporitic environments. Amsterdam, Elsevier, p. 195-232.
- Eugster, H.P., and Hardie, L.A., 1975. Sedimentation in an ancient playa-lake complex. The Wilkins Peak Member of the Green River Formation of Wyoming. Geological Society of America Bulletin, v. 85, p. 319-334.
- Although not dealing primarily with evaporites, contains an excellent summary of the playa environment which was used as the basis for the section upon continental evaporites in this paper.
- VanHouten, F.B., 1965. Crystal casts in Upper Triassic Lockatong and Brunswick Formations. Sedimentology, v. 4, p. 301-313.
- Wills, L.J., 1970. The Triassic succession in the central Midlands in its regional setting. Quarterly Journal of the Geological Society of London, v. 126, p. 225-285.
- MODERN COASTAL SABKHAS AND SALT-FLATS**
- Amdurer, M., and Land, L.S., 1982. Geochemistry, hydrology and mineralogy of the Sand Buge area, Laguna Madre Flats, south Texas. Journal of Sedimentary Petrology, v. 52, p. 703-716.
- Bush, P.R., 1973. Some aspects of the diagenetic history of the sabkha in Abu Dhabi, Persian Gulf. In Purser, B.H., ed., The Persian Gulf. Berlin, Springer-Verlag, p. 395-407.
- Butler, G.P., 1970. Holocene gypsum and anhydrite of the Abu Dhabi Sabkha, Trucial Coast: an alternative explanation of origin. In Rau, J.L., and Dellwig, L.F., eds., Third Symposium on Salt. Northern Ohio Geological Society, p. 120-152.
- Gavish, E., 1974. Geochemistry and mineralogy of a recent sabkha along the coast of Sinai, Gulf of Suez. Sedimentology, v. 21, p. 397-414.
- Holser, W.T., 1966. Diagenetic polyhalite in Recent salt from Baja California. American Mineralogist, v. 51, p. 99-109.
- Kinsman, D.J.J., 1966. Gypsum and anhydrite of Recent age, Trucial Coast, Persian Gulf. In Rau, J.L., ed., Second Symposium of Salt. Northern Ohio Geological Society, p. 302-326.
- Matthews, R.K., 1974. Dynamic stratigraphy. Englewood Cliffs, N.J., Prentice-Hall, 370 p.
- McKenzie, J.A., Hsu, K.J., and Schneider, J.F., 1980. Movement of subsurface waters under the sabkha, Abu Dhabi, UAE, and its relation to evaporative dolomite genesis. Society of Economic Paleontologists and Mineralogists, Special Publication 28, p. 11-30.
- Patterson, R.J., and Kinsman, D.J.J., 1976. Marine and continental ground-water sources in a Persian Gulf coastal sabkha. In Frost, S.J., Weiss, M.P., and Saunders, J.B., eds., Reefs and related carbonates - ecology and sedimentology, p. 381-399.
- Patterson, R.J., and Kinsman, D.J.J., 1981. Hydrologic framework of 2 sabkhas

- along the Arabian Gulf. American Association of Petroleum Geologists Bulletin, v. 65, p. 1457-1475.
- Phleger, F.B., 1969. A modern evaporite deposit in Mexico. American Association of Petroleum Geologists Bulletin, v. 53, p. 824-829.
- Picha, F., 1978. Depositional and diagenetic history of Pleistocene and Holocene oolitic sediments and sabkhas in Kuwait, Persian Gulf. *Sedimentology*, v. 25, p. 427-449.
- Shearman, D.J., 1970. Recent halite rock, Baja California, Mexico. Transactions of the Institute of Mining and Metallurgy, v. 79B, p. 155-162.
- West, I.M., Ali, Y.A., and Hilmy, M.E., 1979. Primary gypsum nodules in 2 modern sabkhas on the Mediterranean coast of Egypt. *Geology*, v. 7, p. 354-358.
- ANCIENT COASTAL SABKHAS AND SALT-FLAT DEPOSITS.**
- Bosellini, A., and Hardie, L.A., 1973. Depositional theme of a marginal marine evaporite. *Sedimentology*, v. 20, p. 5-27.
- Handford, C.R., 1981. Coastal sabkha and salt-pan deposition of the lower Clear Fork Formation (Permian), Texas. *Journal of Sedimentary Petrology*, v. 51, p. 761-778.
- *Jansa, L.F., and Fischbuch, N.R., 1974. Evolution of a Middle and Upper Devonian sequence from a clastic coastal plain - deltaic complex into overlying carbonate reef complexes and banks. Sturgeon - Mitsue area, Alberta. *Geological Survey of Canada, Bulletin 234*, 105 p.
- Kerr, S.D., and Thomson, A., 1963. Origin of nodular and bedded anhydrite in Permian shelf sediments, Texas and New Mexico. *American Association of Petroleum Geologists Bulletin*, v. 47, p. 1726-1732.
- *Mossop, G.D., 1974. The evaporites of the Baumann Fiord Formation, Ellesmere Island, Arctic Canada. *Geological Survey of Canada Bulletin 298*, 52 p.
- Renfro, A.R., 1974. Genesis of evaporite-associated stratiform metalliferous deposits - a sabkha process. *Economic Geology*, v. 69, p. 33-45.
- *Schenk, P.E., 1969. Carbonate-sulphate-redbed facies and cyclic sedimentation of the Windsorian Stage (Middle Carboniferous), Maritime Provinces. *Canadian Journal of Earth Sciences*, v. 6, p. 1037-1066.
- Smith, D.B., 1971. Possible displacive halite in the Permian Upper Evaporite Group of northeast Yorkshire. *Sedimentology*, v. 17, p. 221-232.
- Smith, D.B., 1973. The origin of the Permian middle and upper Potash deposits of Yorkshire: an alternative hypotheses. *Proceedings of the Yorkshire Geological Society*, v. 39, p. 327-346.
- Wood, G.V., and Wolfe, M.J., 1969. Sabkha cycles in the Arab/Darb Formation off the Trucial Coast of Arabia. *Sedimentology*, v. 12, p. 165-191.
- SUBAQUEOUS EVAPORITES - GENERAL**
- *Bebout, D.G., and Maiklem, W.R., 1973. Ancient anhydrite facies and environments, Middle Devonian Elk Point Basin, Alberta. *Bulletin of Canadian Petroleum Geology*, v. 21, p. 287-343.
- Schreiber, B.C., Friedman, G.M., Decima, A., and Schrieber, E., 1973. Depositional environments of the Upper Miocene (Messinian) evaporite deposits of the Sicilian Basin. *Sedimentology*, v. 23, p. 729-760.
- Schreiber, B.C., Roth, M.S., and Helman, M.L., 1982. Recognition of primary facies characteristics of evaporites and the differentiation of these forms from diagenetic overprints. *Society of Economic Paleontologists and Mineralogists Core Workshop 3*, p. 1-32.
- Three recent studies that stress the range of subaqueous evaporite environments.
- DEEP WATER EVAPORITES**
- Anderson, R.Y., Dean, W.E., Kirkland, D.W., and Snider, H.I., 1972. Permian Castile varved evaporite sequence. West Texas and New Mexico. *Geological Society of America Bulletin*, v. 83, p. 59-86.
- Anderson, R.Y., and Kirkland, D.W., 1966. Intra-basin varve correlation. *Geological Society of America Bulletin*, v. 77, p. 241-256.
- Begin, Z.B., Ehrlich, A., and Nathan, Y., 1974. Lake Lisan, the Pleistocene precursor of the Dead Sea. *Geological Survey of Israel Bulletin*, v. 63, 30 p.
- Colter, V.S., and Reed, G.E., 1980. Zechstein 2 Forden Evaporites of the Atwick No. 1 borehole, surrounding areas of N.E. England and the adjacent southern North Sea. *Contributions to Sedimentology*, v. 9, p. 115-129.
- *Davies, G.R., and Ludlam, S.D., 1973. Origin of laminated and graded sediments. Middle Devonian of western Canada. *Geological Society of America Bulletin*, v. 84, p. 3527-3546. For a contrary view see Shearman and Fuller, 1969.
- *Dean, W.E., Davies, G.R., and Anderson, R.Y., 1975. Sedimentological significance of nodular and laminated anhydrite. *Geology*, v. 3, p. 367-372.
- Dellwig, L.F., 1955. Origin of the Salina Salt of Michigan. *Journal of Sedimentary Petrology*, v. 25, p. 83-110.
- Nurmi, R.D., and Friedman, G.M., 1977. Sedimentology and depositional environments of basin-center evaporites, Lower Salina Group (Upper Silurian), Michigan Basin. *In Fisher, J.H., ed. Reefs and evaporites - concepts and depositional models. American Association of Petroleum Geologists, Studies in Geology 5*, p. 23-52.
- Parea, G.C. and Ricci Lucchi, F., 1972. Resedimented evaporites in the Periadriatic Trough. *Israel Journal of Earth Science*, v. 21, p. 125-141.
- Schlager, W., and Bolz, H., 1977. Clastic accumulation of sulphate evaporites in deep-water. *Journal of Sedimentary Petrology*, v. 47, p. 600-609.
- *Shearman, D.J., and Fuller, J.G., 1969. Anhydrite diagenesis, calcitization, and organic laminites, Winnipegosis Formation, Middle Devonian, Saskatchewan. *Bulletin of Canadian Petroleum Geology*, v. 17, p. 496-525.
- Presents contrary view to that of Davies and Ludlam, 1973.
- Taylor, J.C.M., 1980. Origin of the Werraanhydrit in the U.K. southern North Sea - a reappraisal. *Contributions to Sedimentology*, v. 9.
- *Wardlaw, N.C. and Reinson, G.E., 1971. Carbonate and evaporite deposition and diagenesis, Middle Devonian Winnipegosis and Prairie Evaporite Formations of Saskatchewan. *American Association of Petroleum Geologists Bulletin*, v. 55, p. 1759-1786.
- RECENT SHALLOW WATER EVAPORITES**
- Arakel, A.V., 1980. Genesis and diagenesis of Holocene evaporitic sediments in Hutt and Leeman lagoons, Western Australia. *Journal of Sedimentary Petrology*, v. 50, p. 1305-1326.
- Horodyski, R.J., and VonderHaar, S.P., 1975. Recent calcareous stromatolites from Laguna Mormona (Baja California) Mexico. *Journal of Sedimentary Petrology*, v. 45, p. 894-906.
- Kushnir, J., 1981. Formation and early diagenesis of varved evaporitic sediments in a coastal hypersaline pool. *Journal of Sedimentary Petrology*, v. 51, p. 1193-1203.
- Neev, D., and Emery, K.O., 1967. The Dead Sea - depositional processes and environment of evaporites. *Geological Survey of Israel, Bulletin 41*, 147 p.
- Schreiber, B.C., Catalano, R., and Schreiber, E., 1977. An evaporitic lithofacies continuum: the latest Miocene (Messinian) deposits of the Salerni Basin (Sicily) and a modern analog. *In Fisher, J.H., ed. Reefs and evaporites - concepts and depositional models. American Association of Petroleum Geologists, Studies in Geology 5* p. 196-180.

- Schreiber, B.C., and Kinsman, D.J.J., 1975. New observations on the Pleistocene evaporites of Montalegno, Sicily and modern analog. *Journal of Sedimentary Petrology*, v. 45, p. 469-479.
- Shearman, D.J., 1970. Recent halite rock, Baja California, Mexico. *Institute of Mining and Metallurgy Transaction*, v. 79B, p. 155-162.
- Warren, J.K., 1982. The hydrological setting, occurrence and significance of gypsum in late Quaternary salt lakes in South Australia. *Sedimentology*, v. 29, p. 609-637.
- Weiler, Y., Sass, E., and Zak, I., 1974. Halite oolites and ripples in the Dead Sea, Israel. *Sedimentology*, v. 21, p. 623-632.
- ANCIENT SHALLOW WATER EVAPORITES**
- Arthurton, R.S., 1971. The Permian evaporites of the Langwathly Borehole, Cumberland. Report of the Institute of Geological Sciences U.K. 71-17, 18 p.
- Arthurton, R.S., 1973. Experimentally produced halite compared with Triassic layered halite-rock from Cheshire, England. *Sedimentology*, v. 20, p. 145-160. Possibly the best illustrated paper written upon evaporites and one that reveals the potential of detailed fabric and experimental studies for environmental interpretation.
- Dellwig, L.F., 1968. Significant features of deposition in the Hutchinson Salt, Kansas and their interpretation. *In* Mattox, R.B., ed., *Saline deposits*. Geological Society of America Special Paper 88, p. 421-426.
- Dellwig, L.F. and Evans, R., 1969. Depositional processes in Salina Salt of Michigan, Ohio and New York. *American Association of Petroleum Geologists Bulletin*, v. 53, p. 949-956. See also Dellwig, 1955.
- Garrison, R., Schreiber, B.C., Bernoulli, D., Fabricius, F.H., Kidd, R.B., and Melieres, F., 1978. Sedimentary petrology and structures of Messinian evaporitic sediments in the Mediterranean Sea. Leg 42A. Deep Sea Drilling Project. *In* Hsu, K.J., and Montaderi, L., et al., *Initial Reports of the Deep Sea Drilling Project* v. 42, p. 571-611. Washington, D.C., United States Government Printing Office. See also Schreiber et al., 1976; and Schreiber et al., 1977.
- Hardie, L.A., and Eugster, H.P., 1971. The depositional environment of marine evaporites: a case for shallow, clastic accumulation. *Sedimentology*, v. 16, p. 187-220.
- *Kendall, A.C., 1976. The Ordovician carbonate succession (Bighorn Group) of southeastern Saskatchewan. Saskatchewan Department of Mineral Resources Report 180, 185 p.
- Lowenstein, T., 1982. Primary features in a potash evaporite deposit, the Permian Salado Formation of West Texas and New Mexico. *Society of Economic Paleontologists and Mineralogists, Core Workshop 3*, p. 276-304.
- *Nassichuk, W.W., and Davies, G.R., 1980. Stratigraphy and sedimentation of the Otto Fiord Formation - a major Mississippian - Pennsylvanian evaporite of subaqueous origin in the Canadian Arctic Archipelago. *Geological Survey of Canada Bulletin* 286, 87 p.
- Orti-Cabo, F., and Shearman, D.J., 1977. Estructuras y fabricas deposicionales en las evaporitas del Mioceno superior (Messiniense) de San Miguel de Salinas (Alicante, Espana). *Inst. Investigaciones Geologicas Diputacion Provincial Universidad de Barcelone*, v. 32, p. 5-54.
- Richter-Berburg, G., 1973. Facies and paleogeography of Messinian evaporites in Sicily. *In* Drooger, C.W., ed., *Messinian events in the Mediterranean*. Amsterdam, North Holland, p. 124-141.
- Vai, G.B., and Ricci Lucchi, F., 1977. Algal crests, autochthonous and clastic gypsum in a cannibalistic evaporite basin: a case history from the Messinian of Northern Apennines. *Sedimentology*, v. 24, p. 211-244.
- Wardlaw, N.C., and Schwerdtner, W.M., 1966. Halite-anhydrite seasonal layers in Middle Devonian Prairie Evaporite Formation, Saskatchewan, Canada. *Geological Society of America Bulletin*, v. 77, p. 331-342.
- DEPOSITIONAL MODELS**
- Hite, R.J., 1970. Shelf carbonate sedimentation controlled by salinity in the Paradox Basin, southeast Utah. 4th symposium on salt. *Northern Ohio Geological Society*, p. 48-66.
- Hsu, K.J., 1972. Origin of saline giants: a critical review after the discovery of the Mediterranean evaporite. *Earth Science Reviews*, v. 8, p. 371-396.
- Hsu, K.J., Cita, M.B., and Ryan, W.B.F., 1973. The origin of the Mediterranean evaporites. *In* Ryan, W.B.F., Hsu, K.J., et al., *Initial Reports of the Dead Sea Drilling Project*, v. 13. Washington, United States Government Printing Office, p. 1203-1231. The deep basin, shallow-water model applied to Miocene evaporites from the Mediterranean. Hsu's paper contains a useful review of other depositional models.
- Kinsman, D.J.J., 1976. Evaporites: relative humidity control of primary mineral facies. *Journal of Sedimentary Petrology*, v. 46, p. 273-279.
- Lucia, F.J., 1972. Recognition of evaporite-carbonate shoreline sedimentation. *In* Rigby, J.K. and Hamblin, W.K., eds., *Recognition of ancient sedimentary environments*. Society of Economic Paleontologists and Mineralogists, Special Publication 16, p. 160-191. Includes calculation of the degree of restriction required for subaqueous evaporite deposition.
- Matthews, R.D., and Egleson, G.C., 1974. Origin and implications of a mid-basin potash facies in the Saline Salt of Michigan. 4th symposium on salt. *Northern Ohio Geological Society*, p. 15-34. Discusses aspects of the deep-basin deep-water model.
- Schmalz, R.F., 1969. Deep-water evaporite deposition: a genetic model. *American Association of Petroleum Geologists Bulletin*, v. 53, p. 798-823. Discusses aspects of the deep-basin, deep-water model.
- Shaw, A.B., 1977. A review of some aspects of evaporite deposition. *Mountain Geologist*, v. 14, p. 1-16. A thought-provoking analysis of deep-water evaporite models which should command more attention than it has.
- REFERENCES CITED IN TEXT**
- Baar, A., and Kühn, R., 1962. *Der Werdegang der Kalisalz-lagerstätten am Oberrhein*. Neues Jahrbuch fuer Mineralogie, Abhandlungen, v. 97, p. 289-336.
- Busson, G., and Pethuisot, J.P., 1977. Interêt de la Sebka el Nelah (sud-tunisien) pour l'interpretation de series evaporitiques anciennes. *Sedimentary Geology*, v. 19, p. 139-164.
- de Groot, K., 1973. Geochemistry of tidal-flat brines at Umm Said, S.W. Qatar, Persian Gulf. *In* Purser, B.J., ed., *The Persian Gulf*. Berlin, Springer-Verlag, p. 377-394.
- Dixon, J., 1976. Patterned carbonate - a diagenetic feature. *Bulletin of Canadian Petroleum Geology*, v. 24, p. 450-456.
- *Dunn, C.E., 1975. The Upper Devonian Duperow Formation in southeastern Saskatchewan. Saskatchewan Department of Mineral Resources, Report 197, 151 p.
- *Evans, R., 1970. Sedimentation of the Mississippian evaporites of the Maritimes: an alternative model. *Canadian Journal of Earth Sciences*, v. 7, p. 1349-1351.
- Friedman, G.M., 1972. Significance of Red Sea in problem of evaporites and basinal limestones. *American Association of Petroleum Geologists Bulletin*, v. 56, p. 1072-1086.
- *Fuller, J.G.C.M., and Porter, J.W., 1969. Evaporite formations with petroleum

- reservoirs in Devonian and Mississippian of Alberta, Saskatchewan, and North Dakota. *American Association of Petroleum Geologists Bulletin*, v. 53, p. 909-926.
- Garrett, D.E., 1970. The chemistry and origin of potash salts. *In* Rau, J.L., and Dellwig, L.F., eds., 3rd symposium on salt. *Northern Ohio Geological Society*, v. 1, p. 211-222.
- *Holser, W.T., Wardlaw, N.C., and Watson, D.W., 1972. Bromide in salt rocks: extraordinarily low content in the Lower Elk Point salt, Canada. *In* Richter-Bernburg, G., ed., *Geology of saline deposits*. Paris, UNESCO, p. 69-75.
- Katz, A., Kolodny, Y., and Nissenbaum, A., 1977. The geochemical evolution of the Pleistocene Lake Lisan-Dead Sea system. *Geochimica et Cosmochimica Acta*, v. 41, p. 1609-1626.
- Kendall, A.C., 1977. Patterned carbonate – a diagenetic feature (by James Dixon): Discussion. *Bulletin of Canadian Petroleum Geology*, v. 25, p. 695-697.
- Leeder, M.R., and Zeidan, R., 1977. Giant late Jurassic sabkhas of Arabian Tethys. *Nature*, v. 268, p. 42-44.
- Loucks, R.G., and Longman, M.W., 1982. Lower Cretaceous Ferry Lake Anhydrite, Fariway Field, East Texas: product of shallow-subtidal deposition. *Society of Economic Paleontologists and Mineralogists, Core Workshop 3*, p. 130-173.
- Mueller, G., 1960. The theory of formation of north Chilean nitrate deposits through capillary concentration. *Report of the 19th International Geological Congress, Norden 1960. Part 1*, p. 76-86.
- Raup, O.B., 1970. Brine mixing: an additional mechanism for formation of basin evaporites. *American Association of Petroleum Geologists Bulletin*, v. 54, p. 2246-2259.
- Richter-Berburg, G., 1957. Isochrone Warven in Anhydrite des Zechstein. *Geol. Jahrb.*, v. 74, p. 601-610.
- Rouchy, J.M., 1976. Sur la genèse de deux principaux types de gypse (finement lité et en chevrons) du Miocène terminal de Sicile et d'Espagne méridionale. *Revue de Géographie Physique et de Géologie Dynamique (2)*, v. 18, p. 347-364.
- Schaller, W.T. and Henderson, E.P., 1932. Mineralogy of drill cores from the potash field of New Mexico and Texas. *United States Geological Survey Bulletin 833*, 124 p.
- Schreiber, B.C., Friedman, G.M., Decima, A., and Schreiber, E., 1976. Depositional environments of Upper Miocene (Messinian) evaporite deposits of the Sicilian basin. *Sedimentology*, v. 23, p. 729-760.
- Shearman, D.J., 1971. Marine evaporites: the calcium sulphate facies. *American Association of Petroleum Geologists, Seminar, University of Calgary*, 65 p.
- *Shearman, D.J., and Fuller, J.G., 1969. Anhydrite diagenesis, calcitization and organic laminites, Winnipegosis Formation Middle Devonian, Saskatchewan. *Bulletin of Canadian Petroleum Geology* v. 17, p. 496-525.
- Stewart, F.J., 1963. *Data of Geochemistry*, 6th Edition, Chapter Y. *United States Geological Survey Professional Paper 440-Y*, 52 p.
- von der Borch, C.C., 1977. Stratigraphy and formation of Holocene dolomitic carbonate deposits of the Coorong area, South Australia. *Journal of Sedimentary Petrology*, v. 46, p. 952-966.
- Wardlaw, N.C., 1972. Syn-sedimentary folds and associated structures in Cretaceous salt deposits of Sergipe, Brazil. *Journal of Sedimentary Petrology*, v. 42, p. 572-577.
- *Wilson, J.L., 1967. Carbonate-evaporite cycles in Lower Duperow Formation of Williston Basin. *Bulletin of Canadian Petroleum Geology*, v. 15, p. 230-312.