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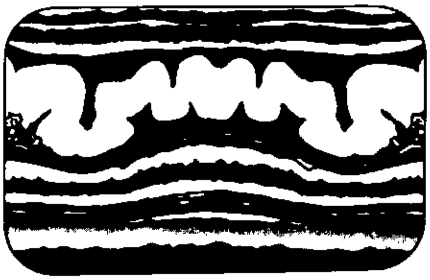

Facies Models 11. Continental and Supratidal (Sabkha) Evaporites

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Introduction

Evaporites are a group of rocks that form by precipitation from concentrated brines. Concentration necessary for 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. Many evaporites are not strictly primary precipitates, but are diagenetic precipitates, emplaced within non-evaporite sediments. Still others are diagenetic replacements of true primary precipitates.

Like iron formations (Dimroth, 1977), 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 (when they are controlled by depositional settings), the distinction between the two classes is blurred. This, and a succeeding paper discuss mainly sedimentary models but mention diagenetic changes when these are early or when a primary or late diagenetic origin is disputed.

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 as chemical precipitates. The initial success of the chemical approach caused this to dominate evaporite studies and only in the last decade have sedimentary aspects been stressed. For many evaporite deposits therefore, the basic data upon which facies models are based are 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.

2. Observations upon evaporites may be limited. Only rarely are unaltered evaporites exposed at outcrop. Most evaporite studies are confined to subsurface materials - cores or mine openings. 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. 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 extensive post-depositional change. The solubility of evaporite minerals, the tendency for metastable hydrates to be precipitated, and the susceptiblility 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 means 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. 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.

No single facies model can be applied to so heterogeneous a grouping of rocks as the evaporites. The dogma of the decade - supratidal (sabkha) evaporites - has become much too one-sided because there are other evaporite types that clearly are of subaqueous origin. It is probably true that, 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 consititute 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.

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 sulfates) (Fig. 1). Regimes grade into each other such that identification may depend more upon associated facies than upon internal characteristics. Continental sabkha deposits commonly are internally identical with coastal sabkha deposits, differing only in 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 is a somewhat academic exercise.

Three main environmental groupings are recognized, of which two, continental and coastal sabkha evaporites are considered in this paper. Subaqueous evaporites, whose facies are less clearly defined, are the subject of a succeeding paper in the facies models series.

Continental Evaporites
Evaporites formed exclusively from continental groundwaters are not common in rock record. Many evaporites that formed in continental settings were derived partly from marine input. It is difficult to identify the relative importance of continental and marine influences.

The rarity of continental evaporites also reflects the ephemeral nature of many evaporite minerals in the depositional environment. Many are recycled or move upwards at the same rate as sediment accretion and are thus non-accumulative. Their former presence may leave evidence in the form of crystal moulds 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 crusts (gypcrete) which form 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. Reference should be made to Cooke and Warren (1973) and Kulke (1974).

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 arid drainage basins - environments that are characterized by almost horizontal and largely vegetation-free surfaces of fine-grained sediments. These base-level plains are a distinctive feature of deserts and are given many different names (sabkha, sebkha, playa, salina, pan, chott, etc.). The name playa is employed here for these features (Fig. 2).

Alluvial fans at basin edges trap most coarse detritus so that only the finest material is carried into the basin. There it is periodically reworked into horizontally laminated sediments by sheetwash associated with storms. Apart from surface flow during storms, water circulation is generally confined to the subsurface.

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 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) are 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

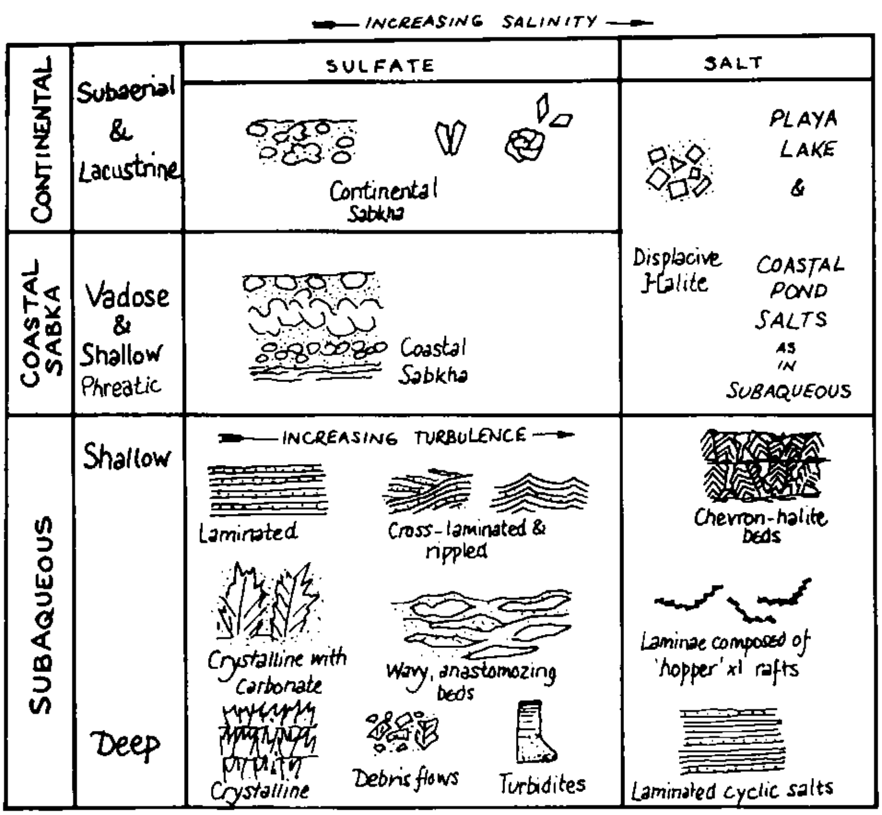


Figure 1
Summary of physical environments of evaporite deposition and the main facies present (modified from Schreiber et al., 1976).

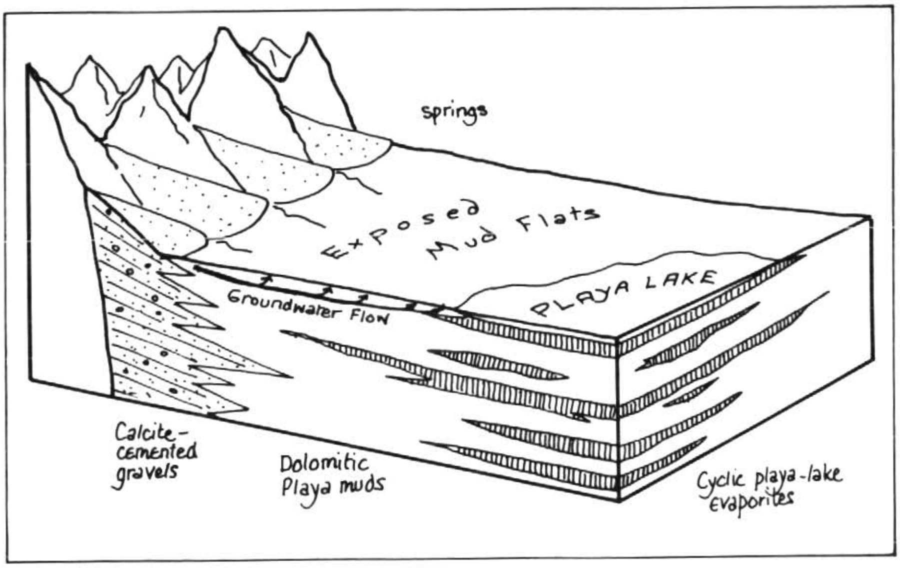


Figure 2
Schematic block-diagram showing depositional framework in the Playa Complex model (after Euster and Hardie, 1975).

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. 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 sheetflood which impart the laminated or cross-laminated structures. This lamination, however, is also continuously being disrupted and destroyed by further groundwater discharge (creating porous 'puffy-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.

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. In this manner monomineralic evaporite deposits are formed.

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.

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 these minerals to form concentrated brines that owe their highly modified compositons to this fractional dissolution. Ultimately these brines reach the basin centre.

Evaporite crusts may reach 30 or more centimetres 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 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, (Figs. 3 and 4), probably represent deposits of these evaporitic, but essentially non-evaporite preserving, environments.

Halite within playa sediments has not been specifically described from mod-

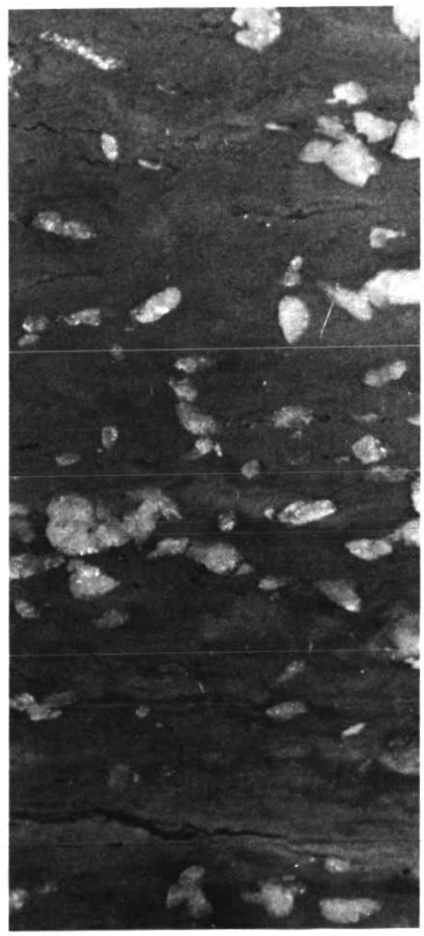


Figure 3
Red dolomitic mudstones with anhydrite pseudomorphs after gypsum crystals, Watrous Formation, Saskatchewan. Probable playa flat deposit. Core 10 cm across.

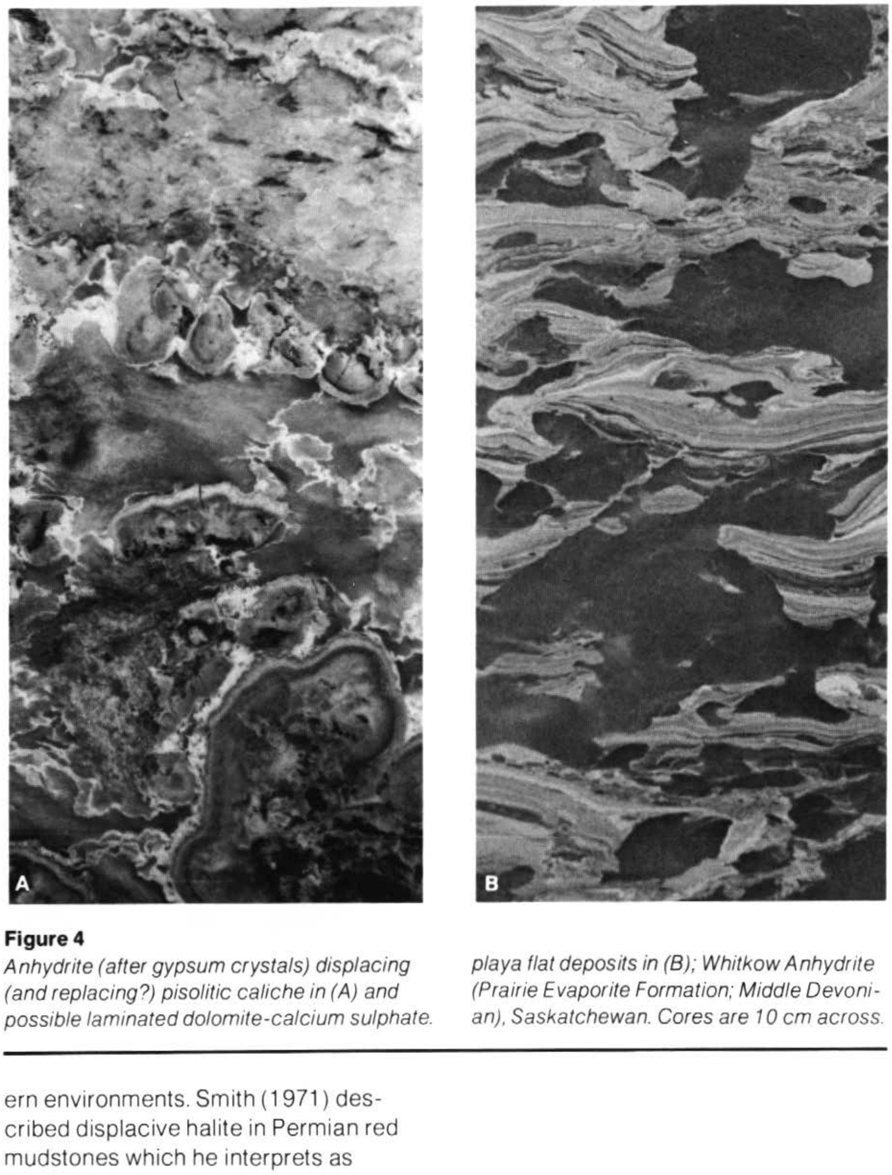


Figure 4
Anhydrite (after gypsum crystals) displacing (and replacing?) pisolitic caliche in (A) and possible laminated dolomite-calcium sulphate. playa flat deposits in (B); Whitkow Anhydrite (Prairie Evaporite Formation; Middle Devonian), Saskatchewan. Cores are 10 cm across.

ern environments. 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 disconinuous, then confined to isolated polyhedral pockets as the halite becomes a near-continuous interlocking mosaic. In more coherent sediments, however, halite occurs interstitially, as veneers around sand grains or as skeletal 'hopper' crystals (Fig. 5) - 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 dissolve 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 (see later article).

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' season 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' seasons 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; 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' 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 preceeding 'dry' seasons. Evaporation during the suceeding 'dry' season 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 seasonal 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,

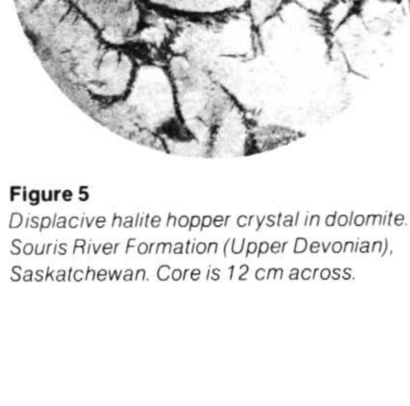


Figure 5
Displacive halite hopper crystal in dolomite. Souris River Formation (Upper Devonian), Saskatchewan. Core is 12 cm across.

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 salts; 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.

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.

Climate. Temperature influences evaporation rate but may also control the type and sequence of salt deposition more direclty. 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 ($Na_2SO_4 \cdot 10H_2O$) 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. 6) 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 is recorded by shrinkage of the lake area, a decrease in lake depth, and an increase in salinity ultimately leading to bedded evaporite deposition.

Climatic 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).

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 'bulls-eye' pattern of salt deposition (more saline salts in the centre; Fig. 7). 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.

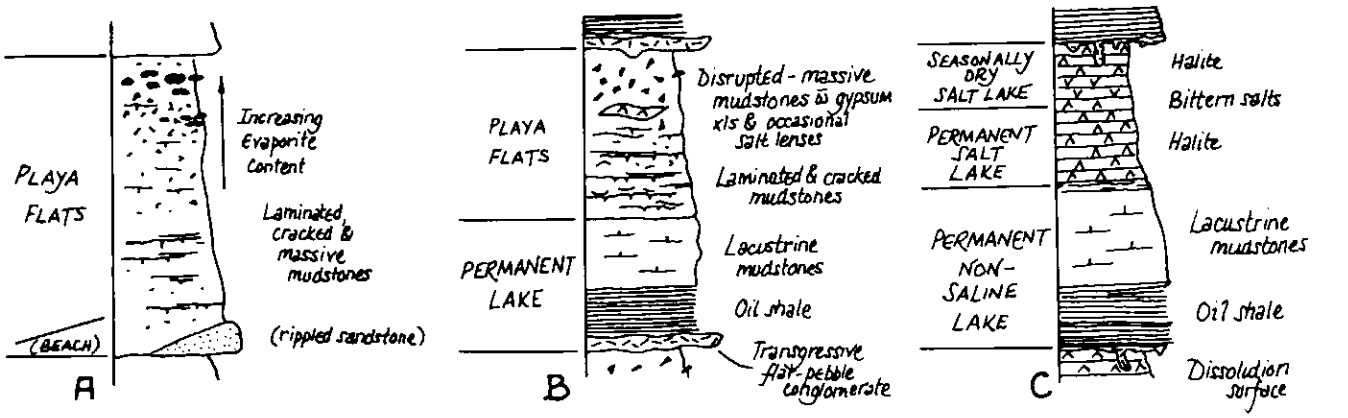


Figure 6
Hypothetical cycles reflecting increasing aridity. A: Distal playa flats. B: Playa flats marginal to playa lake. C: Playa lake

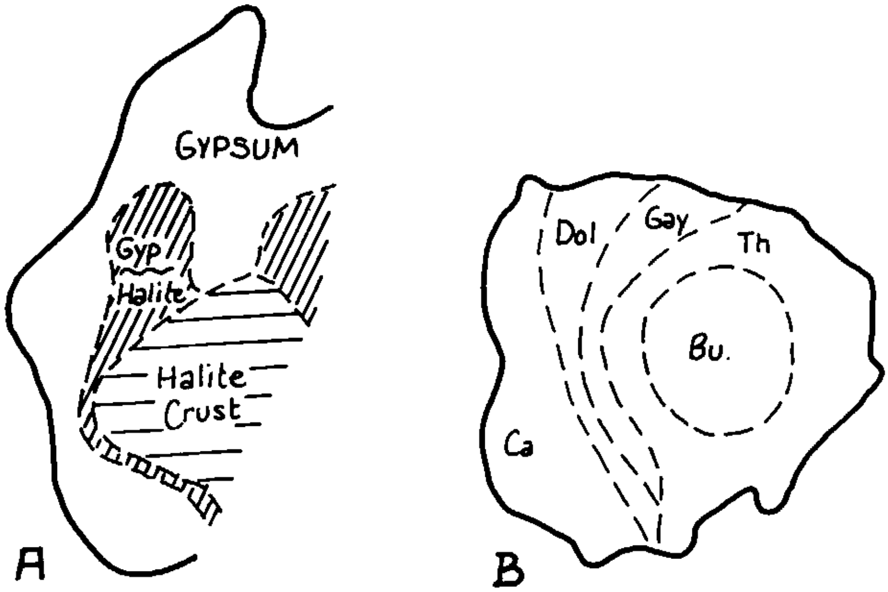


Figure 7
Saline mineral zonation in playas: A: Yotvata Sabkha (Israel) after Amiel and Friedman (1971); B: Deep Spring Lake, California, Ca = calcite/aragonite; Dol = Dolomite; Gay= gaylussite; Th=Thenardite; Bu= Burkeite (after Jones, 1965).

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.

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 affects the dominance of the same ions (Ca^{++}, Mg^{++}, Na^{+}, $CO_3{}^{II}$, $HCO^{I}{}_3$, $SO_3{}^{II}$, Cl^{I}), however, these 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 ($CaCO_3 \cdot Na_2CO_3 \cdot 2H_2O$), gaylussite ($CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$), and trona ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). When groundwaters are sulphate-rich then (dependent upon the dominant cations) glauberite ($CaSO_4 \cdot Na_2SO_4$), epsomite ($MgSO_4 \cdot 7H_2O$), bloedite ($MgSO_4 \cdot Na_2SO_4 \cdot 4H_2O$), thenardite ($Na_2SO_4$) and mirabilite ($Na_2SO_4 \cdot 10H_2O$) may be precipitated. Variation in playa and playa-like mineralogy constitutes a vast field of study, one that cannot be discussed here. Reference should be made to Reeves (1968) and Hardie and Eugster (1970).

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 in an earlier article in this facies model series under the heading of arid-zone variants of carbonate shallowing-upwards sequences (James, 1977). This style of shallowing-upward sequences (Fig. 8) 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. 9) and (3) nodular-mosaic anhydrite, commonly terminated by a sharp erosive contact (Fig. 10). These 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 (Shearman, 1966; Kinsman, 1969; Butler, 1970; Bush, 1973).

In areas of arid climate 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

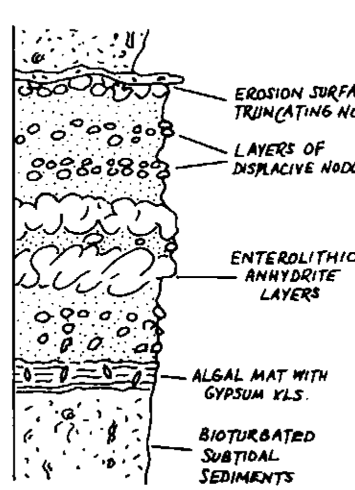
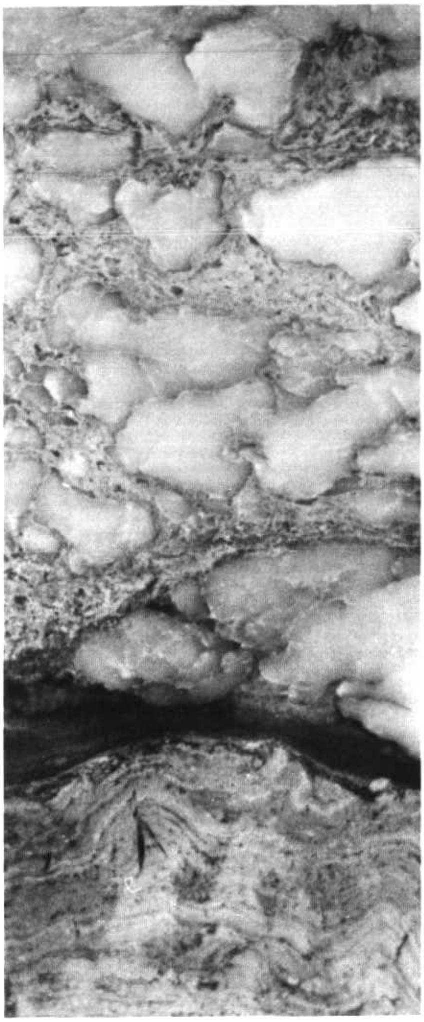


Figure 8
Characteristic features of coastal sabkha evaporites (after Shearman, 1966).



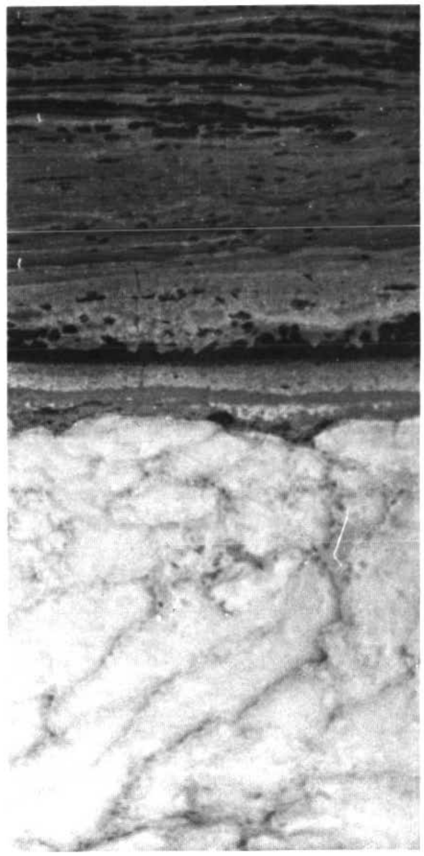


Figure 10
Upper part of sabkha cycle illustrated in Figure 9. Mosaic anhydrite cut across by erosion surface and surmounted by laminated micrites (with late-diagenetic anhydrite) of next lagoonal member. Frobisher Evaporite, Saskatchewan. Core is 11 cm across.

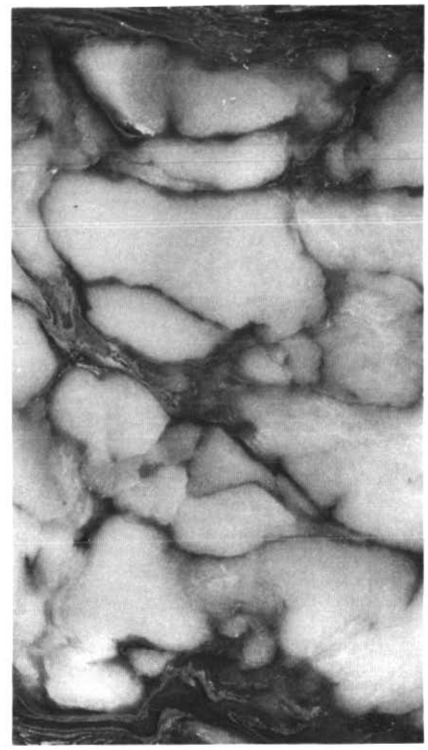


Figure 11
Mosaic anhydrite (displacing subaqeous laminated anhydrite) with individual nodules distorted against each other (a natural consequence of displacive growth). Ordovician Stonewall Evaporite, Saskatchewan. Core is 10 cm across.

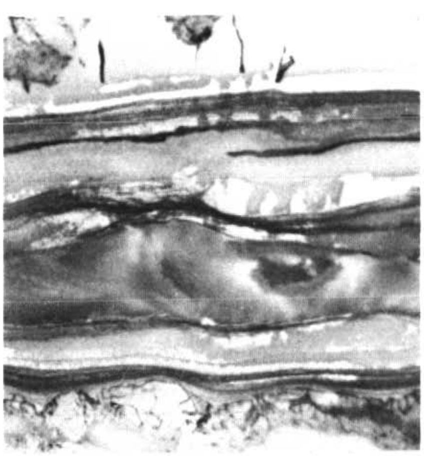


Figure 9
Laminated microdolomites (probably hypersaline lagoonal) overlain by algal mat, with gypsum pseudomorphed by anhydrite, and nodular and mosaic coastal sabkha anhydrite. Frobisher Evaporite (Mississippian) Saskatchewan. Core is 11 cm across.

of arid continental 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; Fig. 11). 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.

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 byproducts of diagenetic reactions and non-accumulating ions. These waters become progressively concentrated as 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. 12). 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.

The relative importance of the groundwater sources is dependent upon

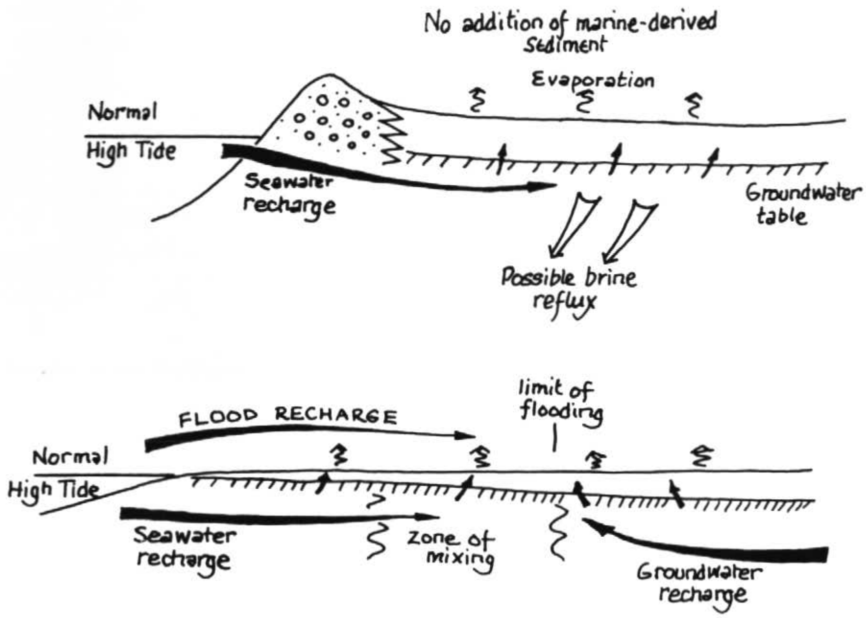


Figure 12
Contrasting water supply in sabkhas. Above, sabkha plain bordered by beach ridge. Seawater recharge is entirely intrasediment flow (based upon a Sinai coastal sabkha; Gavish, 1974). Below, sabkha groundwaters are replenished by flood recharge and seepage from seawater and continental reservoir (based upon Abu Dhabi sabkha).

local geomorphic conditions. Beach ridges seaward of the sabkha prevent inundation by marine floodwaters, whereas lack of hinterland relief will restrict continental groundwater inflow. 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 as products of reactions between groundwater 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 poikilitically 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. Dolomitization of aragonites releases strontium that is precipitated as celestite.

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. 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. 13). Some nodules are formed by alteration of earlier formed gypsum crystals (Butler, 1970). Pseudomorphs lose shape because of flowage

Figure 13
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 sulfate growth during reflux dolomitization, Frobisher Evaporite (Mississippian), Saskatchewan. Core is 11 cm across.

(adjustment during compaction) and the continued growth of primary anhydrite laths in and between pseudomorphs. Composite anhydrite nodules are remnants of gypsum crystal clusters and massive-appearing anhydrite forms from gypsum mush in former upper intertidal sediments. 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, then 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. Within fine grained sediments the displacive halite cubes assume a skeletal hopper form commonly to extreme degrees (Fig. 5). 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 the nature of the host sediment, the character of the offshore water body, the type of diastrophic control and the effects of differing local topography all may cause profound modifications from the 'norm', as represented by the Abu Dhabi sabkha (Fig. 14).

Nature of the host sediment. This determines the amount of drainage, the subsequent history of sabkha brines and the compactional history of the evaporate deposit.

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.

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

$$\underbrace{2CaSO_4{\cdot}2H_2O}_{\text{gypsum}} + \underbrace{2K + Mg + 2SO_4}_{\text{brine}} = \underbrace{K_2MgCa_2(SO_4)_4{\cdot}2H_2O}_{\text{polyhalite}} + 2H_2O$$

Reflux of brines capable of dolomitizing deeper-lying carbonates (well beneath the sabkha vadose zone) cause 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

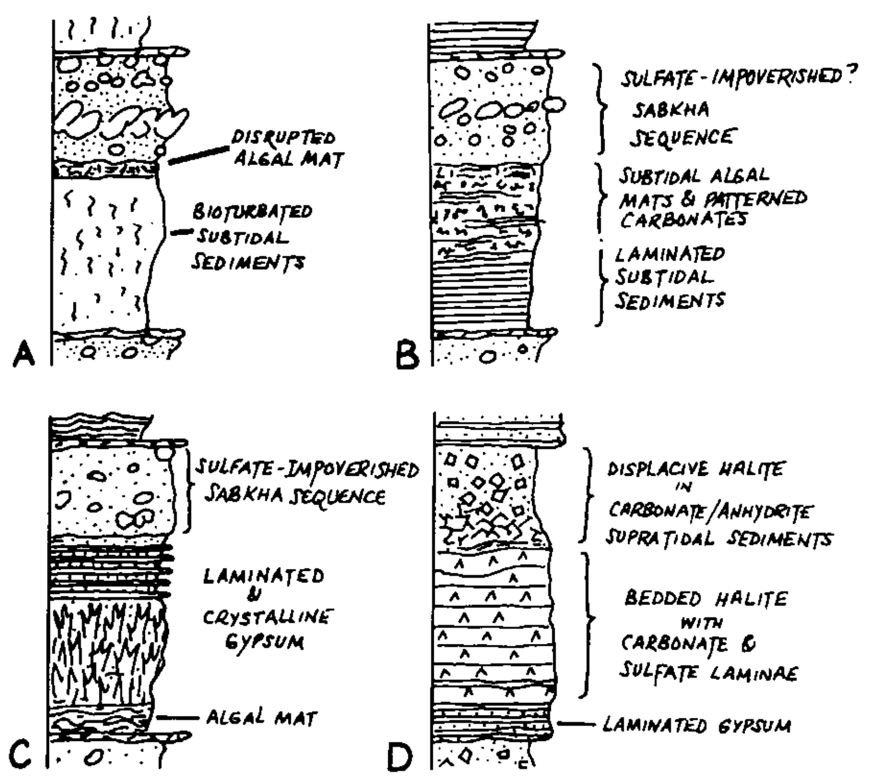


Figure 14
Hypothetical shoaling-upwards cycles: A. marginal to a normal marine to slightly hypersaline water body, B. marginal to a hypersaline water body within which sulphates are bacterially reduced, C. marginal water body precipitates and preserves gypsum, D. marginal water body is salt-precipitating, supratidal sequence largely composed of displacive (and replacive?) halite.

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.

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 sluggy or even laminar anhydrites (Shearman and Fuller, 1969). Mossop (1978) believes laminar anhydrites in the Ordovician Baumman Fiord Formation (Fig. 15) were originally nodular and have been drastically altered by early diagenetic compaction and flowage.

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-mat sediments (if present) are confined to upper intertidal to low supratidal environments (Fig. 14A) 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 subtidal environments where they may be preserved. When precipitated gypsum persists in the bottom sediment, the overlying sabkha sequence forms the uppermost member of a largely subaqueous evaporite sequence. However, the abundance of organic matter and dissolved sulphate in hypersaline waters normally induced reducing conditions within which sulphate-reducing bacteria thrive. Their activities cause reduction of gypsum; 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. 14B). Removal of calcium and sulphate from the offshore water body may severely restrict gypsum and anhydrite formation in adjacent sabkha environments (Fig. 14C).

Figure 15
Numerous superimposed sabkha cycles, Baumann Fiord Formation, Ellesmere Island (photo courtesy G. Mossop).

The atmosphere adjacent to large bodies of normal marine water is too humid for halite to persist in the subaerial environment (Kinsman, 1966). 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 (Fig. 14D). Such sediments form adjacent to halite-precipitating water bodies.

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 (1978) 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 downdraw). Criteria for distinguishing cycles that form from progradational events from those that reflect episodes of evaporative downdraw do not appear to have been sought.

When greater subsidence occurs towards the basin centre it is possible to recognize distal from proximal locations (Mossop, 1978). 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

Topographic control. The Abu Dhabi 'norm' is associated with a relatively simple progradational sediment wedge undissected by active channels, maritime lakes or ridges formed by former beach or offshore spit deposits (Fig. 16). 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 that does not appear to have been described from either the modern or the past. A humid subtropical equivalent, in which various alkaline earth carbonates are precipitating, occurs in the Coorong region of South Australia (von der Borch, 1977). Under slightly more arid conditions we might expect accumulation of gypsum and halite in the lakes and development of gypsum and anhydrite-bearing supratidal sediments in flats between the linear sand barriers.

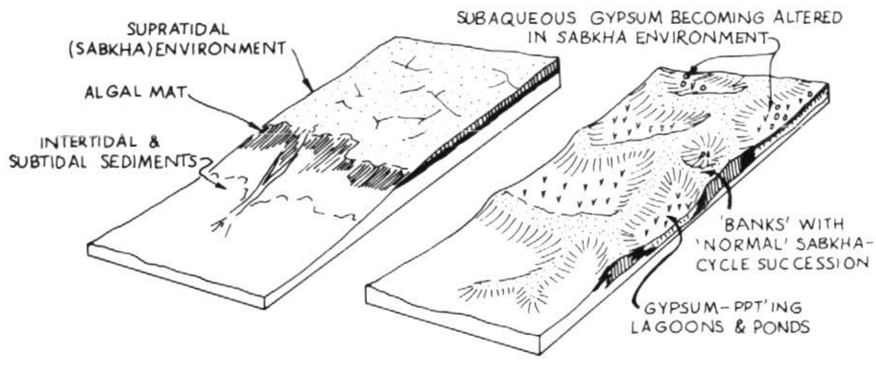


Figure 16
Contrasting patterns of supratidal sedimentation. A: simple sediment wedge, Recent Abu Dhabi sabkha; B: inferred environment for part of Frobisher Evaporite (Mississippian) in southeastern Saskatchewan - numerous shallow maritime lakes isolated by narrow strips of supratidal sabkha.

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 depressions will also attract groundwaters from beneath the surrounding sabkha and disrupt the more normal pattern of groundwater flow. The Sebkha el Melah (Busson and Perthuisot, 1977) was such a depression but has since been filled with evaporites including a halite sequence 30 metres 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 (Fig. 16) 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. 17) 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.

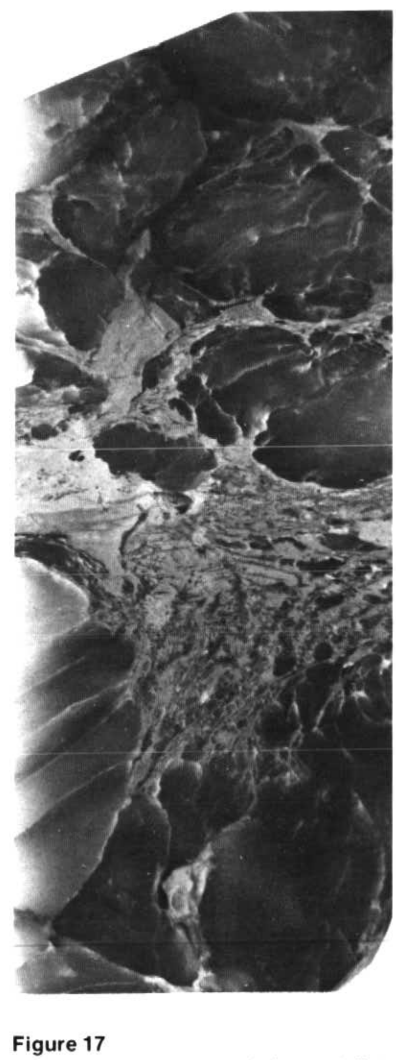


Figure 17
Displacive gypsum crystals (centre) distorted by growth of later but still early-diagenetic anhydrite nodules. Frobisher Evaporite, Saskatchewan. Core is 11 cm across.

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.

Acknowledgements
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There are numerous papers of merit dealing with evaporite sedimentology but unfortunately few deal with facies models or summarize earlier 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.

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Dean, W. E. and B. C. Schreiber, eds., 1978, Notes for a short course on marine evaporites: SEPM Short Course #4.
The most recent and comprehensive compilation of work upon the evaporites. The paper by Schreiber upon subaqueous sulphates is essential reading and the section upon halite fabrics by Shearman is clearly written and illustrated. Other papers concentrate upon environments, geochemistry and geophysical log evaluation of evaporites.

Busson, G., 1974, Sur les evaporites marines: sites actuels ou Recents de depots d'evaporites et leur transposition dans les series du Passe: Rev. Geog. phys. Geol. dynam., v. 16, p. 189-208.
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