Geoscience Canada

Facies Models 12. Subaqueous Evaporites

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Volume 5, Number 3, September 1978

URI: https://id.erudit.org/iderudit/geocan5_3art03

See table of contents

Publisher(s)

The Geological Association of Canada

ISSN

0315-0941 (print)
1911-4850 (digital)

Explore this journal

Cite this article

Kendall, A. C. (1978). Facies Models 12. Subaqueous Evaporites. *Geoscience Canada*, *5*(3), 124–139.

Facies Models 12. Subaqueous Evaporites

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Introduction

Most studies of marine evaporite deposits have focused attention upon facies that developed along supratidal margins of normal marine basins (see Kendall, 1978). But 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 and there are none comparable in magnitude with those of the past.

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 of 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 in depositional environments similar to those of the present time (in supratidal flats, lagoons and salinas; Shearmen, 1966, Friedman, 1972) whereas others consider that the great difference in scale between Recent and ancient deposits requires drastic departure 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 (Hsü *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 palaeogeography of evaporites, and because many evaporite rock characteristics have yet 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 in this paper.

Facies Models

Internal characteristics of evaporites alone can provide the necessary information about depositional environments and 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) are believed to identify a deeper environment but one that still resides within the photic zone; and 3) widespread evenly-laminated sediments (rhythmites) that lack evidence of current and algal activity (perhaps associated with gravity-displaced sediments) characterize the deep, subphotic environment.

Considerable difficulty exists in using 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 reduce 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.

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

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, annual 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. However, 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 (Kendall, *in prep.)*. Persistance of laminae up such slopes and the lack of associated lithologic change suggest deposition occurred from a brine body at least 40 m deep.

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

Sulphate mm-laminites (Fig. 1). Laminar 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-Bernburg, 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).

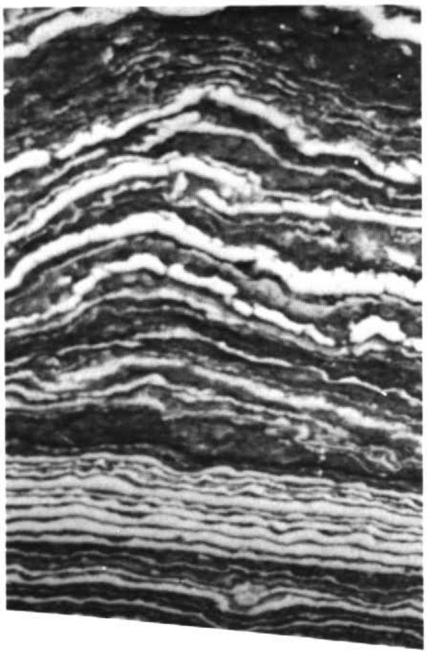

Figure 1

Interlaminated anhydrite (dark) and carbonate, affected by syn-sedimentary slumping. Only carbonate laminae are fractured. Middle Devonian Ratner Member (at base of Prairie Evaporite), Saskatchewan. Laminae such as these are traceable for many kilometres. Core is 8 cm across.

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 traceable over long distances (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 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 suphate 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.

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 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).

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, is interbedded with stringers of carbonate and anhydrite which drape over underlying halite crystals (Fig. 2). The clear character of 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 lower (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.

Figure 2

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.

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 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. 3), some exhibiting poorly-developed grading, associated with carbonate turbidites in flanking beds around Winnipegosis banks in Saskatchewan (Kendall, *in prep.*), 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 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.

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. 4). 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 buildups, 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).

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 five metres 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. 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.

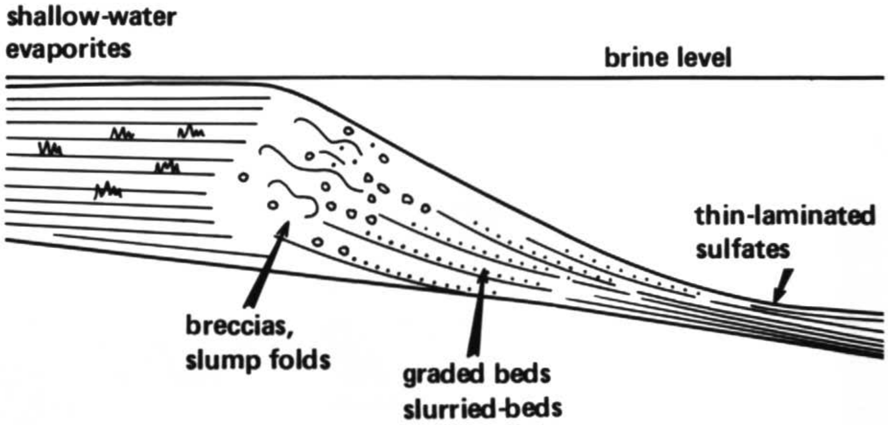

Figure 4
Schematic diagram of deep water and slope evaporite environments (after Schlager and Bolz, 1977).

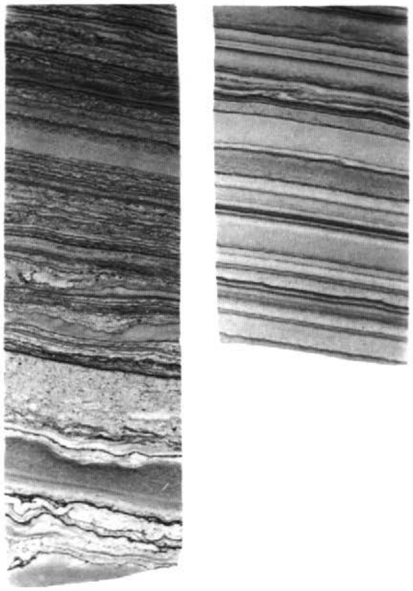

Figure 3
Carbonate and anhydrite turbidites from a facies that flanks M. Devonian (Winnipegosis Fm.) carbonate buildups; Saskatchewan. Graded carbonate turbidites at left are inserted within laminated carbonate and anhydrite. At right, poorly-graded anhydrite layers occur in association with thinner (autochthonous?) anhydrite laminae. Cores are 8.5 cm across.

Laminated sulphates 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. 5).

Cross-bedding, ripple-drift bedding (Fig. 6), basal scoured surfaces and rip-up breccias testify to environments with periodic high energy events, such as storms. Some small asymmetric ripplemarks 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 depositon is also shown by the occurrence of micritic, organic-rich stromatolites between, or within, some laminae; by bird or dinasour footprints, or by fossil brine shrimp.

Laminae are interpreted as storm deposits. Single laminae form during a storm when evaporitic tidal flats are flooded by sediment-charged water. Blue-green algal mats, which cover the 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 at 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 uppermost parts of laminae, or this feature may be of depositional origin. Upward segregation of coarser particles may have 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.

Shallow-water laminite units may be laterally persistent but typically contain fewer laminae than deep-water units and individual laminae cannot be traced for long distances. 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. 7) suggesting that they did not become lithified during early diagenesis.

Coarsely crystalline, selenitic gypsum 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. 8,9). Crystals are commonly euhedral and in aggregate define a vertical pallisade 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 twinning patterns and suffer crystal splitting to generate palmate to fan-shaped clusters of subparallel crystals (Fig. 10; for details see Schreiber, 1978).

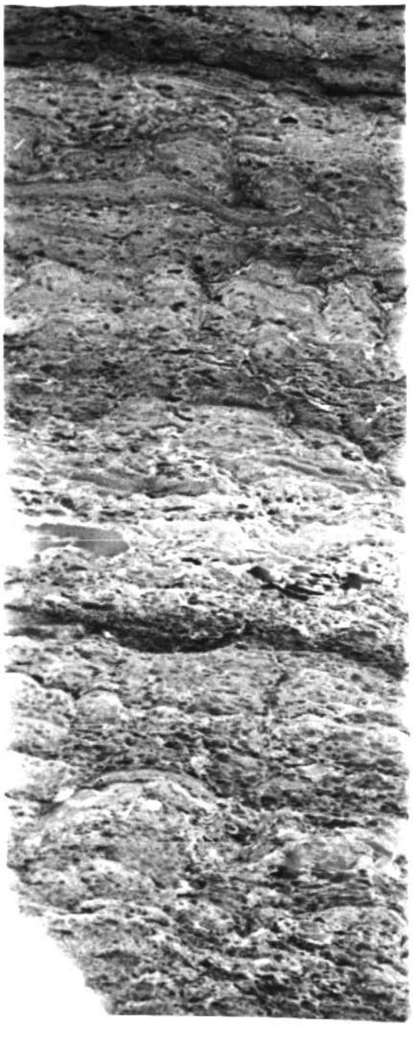

Figure 5
Anhydrite after displacive gypsum crystals which grew within mud-cracked stromatolitic carbonate. Each gypsum crystal is now represented by a small, angular anhydrite 'nodule'. Souris River Formation (U. Devonian, Saskatchewan), Core is 9 cm across.

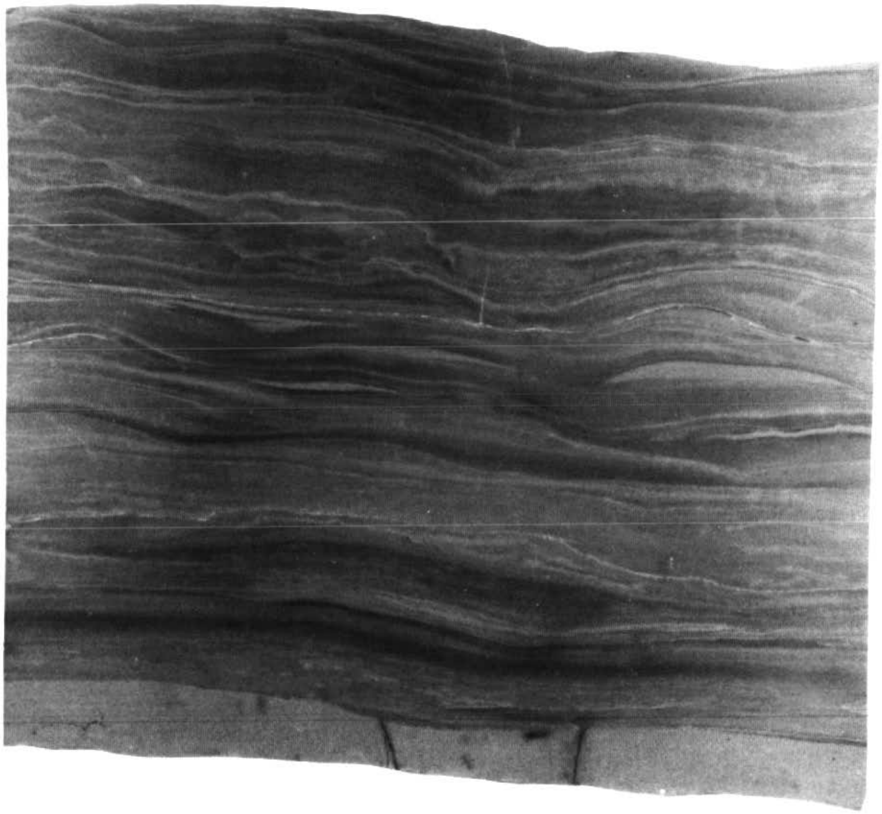

Figure 6
Laminated anhydrite containing minor amounts of disseminated dolomite that define lamination, ripples, minor cross-stratification and scoured surfaces. Poplar Beds (Mississippian) Saskatchewan. Core is 10.5 cm across.

Figure 7
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.

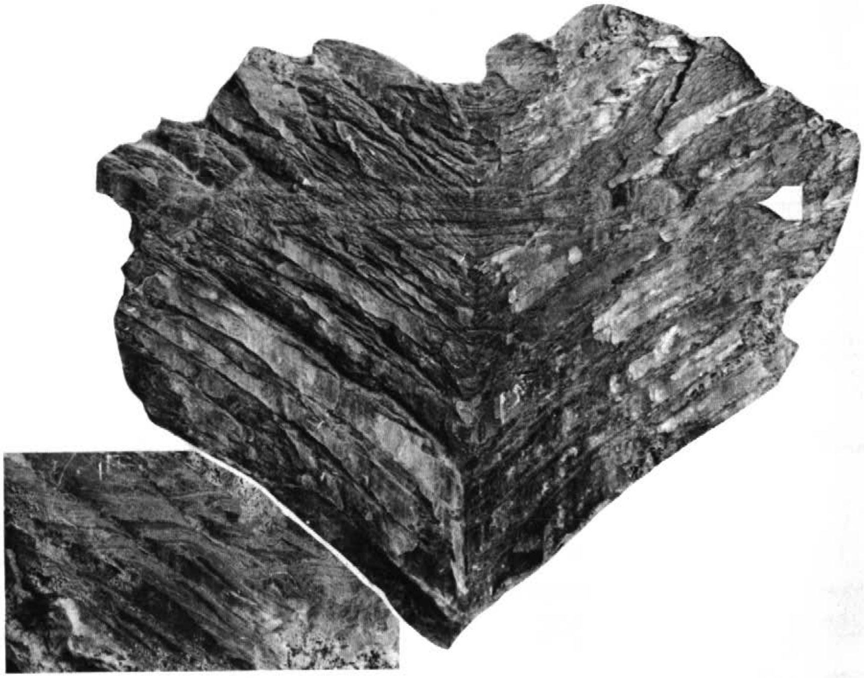

Figure 9
Swallow-tail twinned gypsum crystal (25 cm across) with dissolution surface at arrow. Inset is a cleavage plane surface of the same crystal revealing numerous inclusion-defined growth layers. Miocene of S. E. Spain. Photos courtesy B. C. Schreiber.

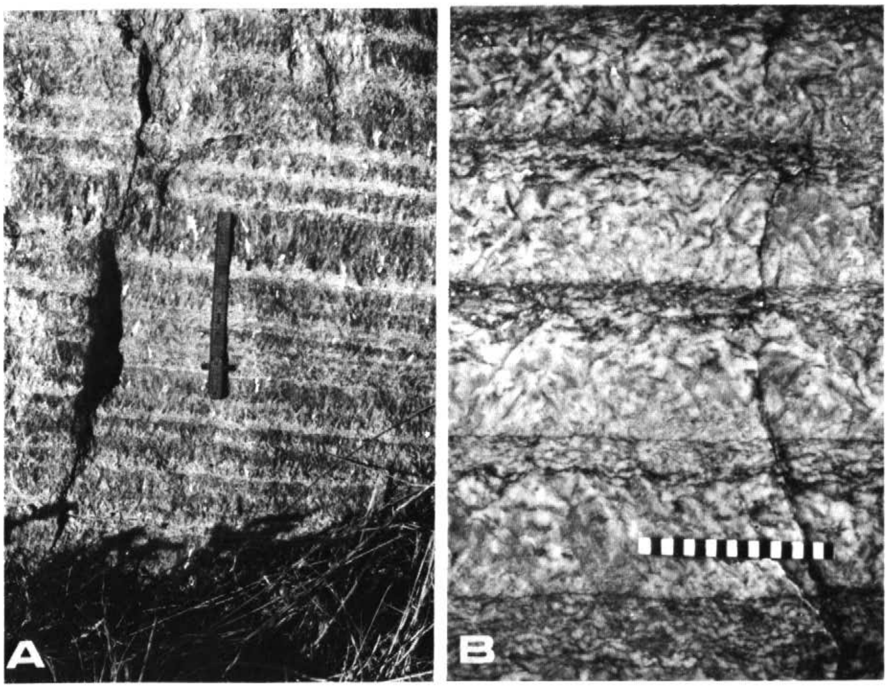

Figure 8
Coarsely crystalline, selenitic gypsum facies. A: Palisades of gypsum crystals, Miocene of Sicily. Photo courtesy B.C. Schreiber. B: Layered anhydrite with pseudomorphs after gypsum crystals, Otto Fiord Fm. (Pennsylvanian), Ellesmere Island. Photo courtesy N.C. Wardlaw. Scale divisions in cm.

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

The crystals contain faint lamination (Fig. 9), defined by carbonate and anhydrite inclusions, which passes through the crystalline beds, parallel to bedding. Inclusions lie parallel to crystal facies, recording successive positions of the growing crystal, or defining solution surfaces. Many crystals include algal filaments and appear to have invaded algal mats.

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. 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. 9). 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. 10). Much of the polyhalite from the Permian of New Mexico appears to have replaced and pseudomorphed selenitic gypsum (see Schaller and Henderson, 1932, pl. 29, 30).

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 penecontemporaneously disturbed and contain load cast or ball-and-pillow structures (Fig. 11). 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.

Figure 11
Parallel laminated, cross-stratified and load-casted gypsum sandstones (gypsarenites). Miocene of Sicily. Photo courtesy B.C. Schreiber. Penknife gives scale.

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 sheetfloods that carried selenite fragments. Progradation caused development of wide supratidal flats composed of this transported material and in this environment sabkha anhydrite was emplaced.

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 detrital carbonate, sulphate or terrigenous sediment) and identified as 'chevron halite' (Fig. 12 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, 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 result of halite precipitation) then allow slower and more perfect (inclusion-free) halite layers to be deposited. 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 (Kendall, 1978) 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)

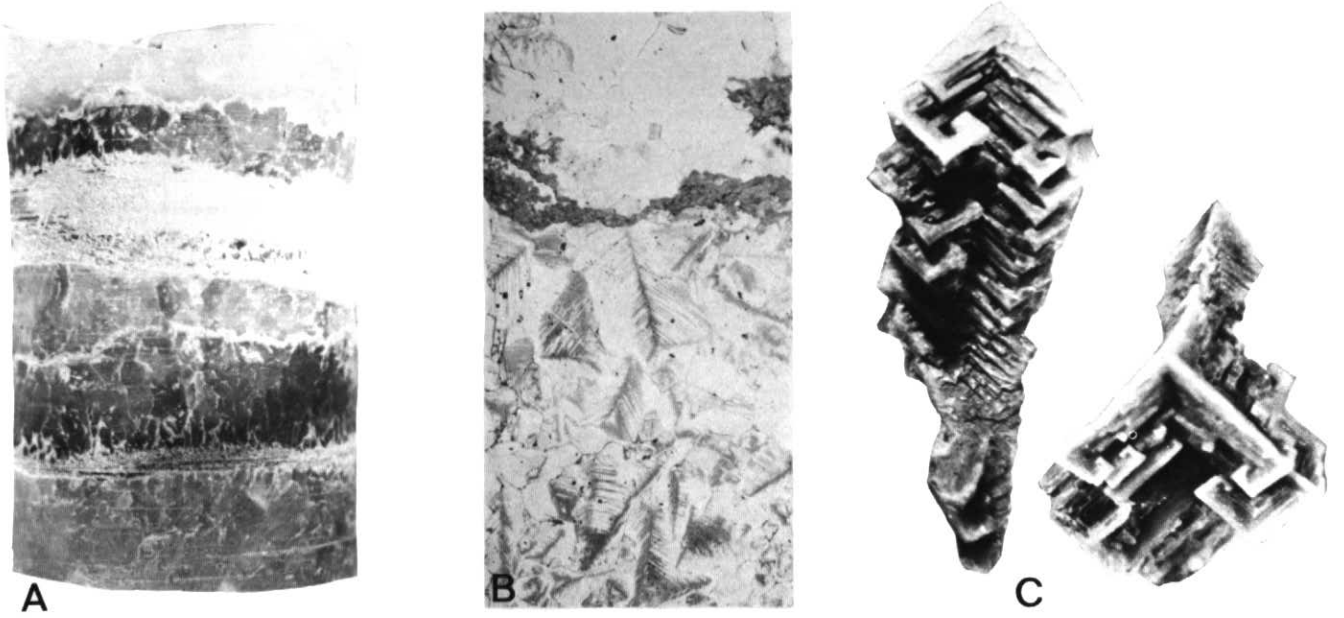

Figure 12
Chevron halite. A: Layers of chevron halite interbedded with laminated anhydrite, Souris River Fm. (U. Devonian) Saskatchewan. Core is 10 cm across. B: Thin-section through chevron halite layer containing cloudy inclusion-rich and clear void-filling crystals, the former truncated by an anhydrite lamina. Prairie Evaporite, Saskatchewan. (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.

cubes with hopper-like pyramidal hollows on each face (Fig. 13). 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 Prairies 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 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.

Wardlaw (1972) has described crusts of bottom-grown carnallite ($KC1$-$MgC1_2$-$6H_2O$) 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 unlithified and are capable of being deformed by slumping and differential loading. The occurrence of tachyhydrite ($CaC1_2.2MgC1_2.12H_2O$) in these evaporites, a mineral that cannot survive exposure to the atmosphere, also indicates evaporite deposition was entirely subaqueous.

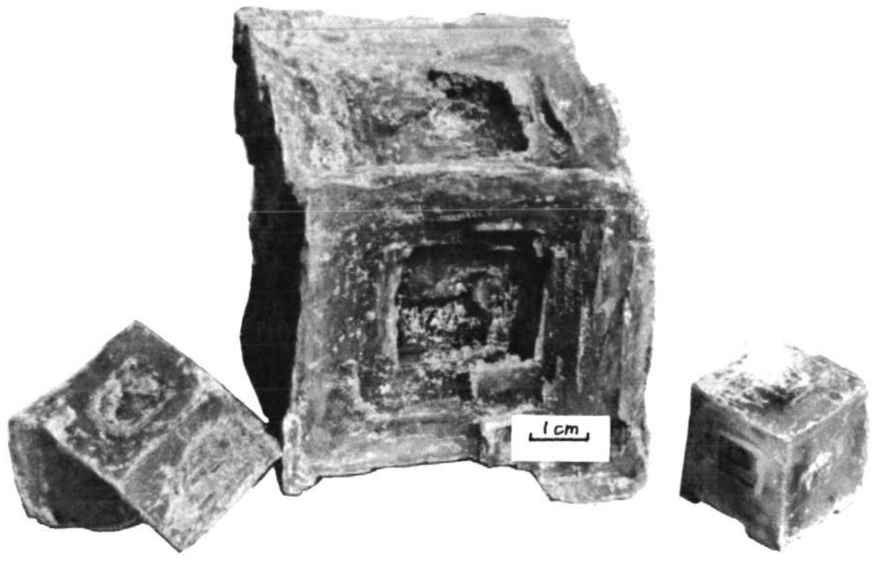

Figure 13
Displacive halite crystals (with 'hopper' - faces) that grew in micritic ooze at southern end of the Dead Sea (Photo courtesy B.C. Schreiber).

Shallow water models. Two models are proposed for shallow-water sulphates; both created for the Messinian evaporites of Italy (Fig. 14). 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. Gyp-

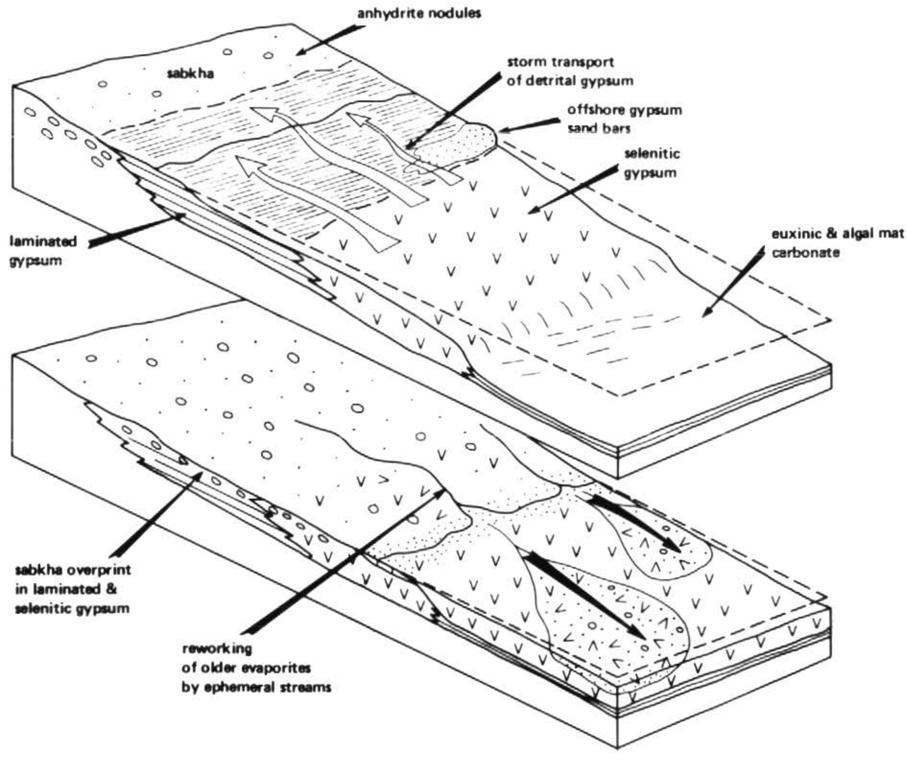

Figure 14
Models for deposition of shallow water sulphate evaporite facies. Above, after Hardie and Eugster (1970); below, Vai and Ricci Lucchi (1977).

sum 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 enchroached the basin. This cannibalistic model can be integrated with Hardie and Eugster's model to obtain a single, more dynamic 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.

Evaporite Sequences

Facies models are developed from the characters 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 desposition-al 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 that suffer lowering of the brine surface by evaporative downdraw, the thickness of cycles need not even record minimal water depths at the start of deposition. Unlike sea-level, which is usually 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 downdraw) 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. Downdraw 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. 15).

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 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. 16). By the time halite saturation is reached, the brine-level in

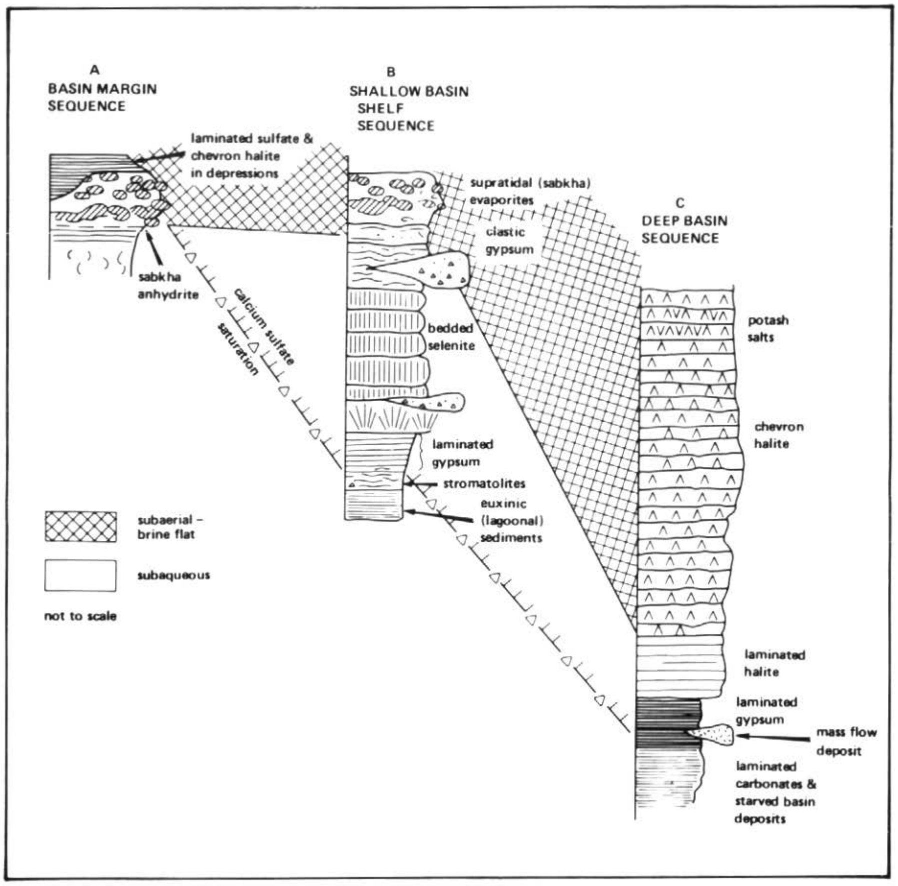

Figure 15
Hypothetical evaporite successions (not to scale) in different parts of evaporite basins.

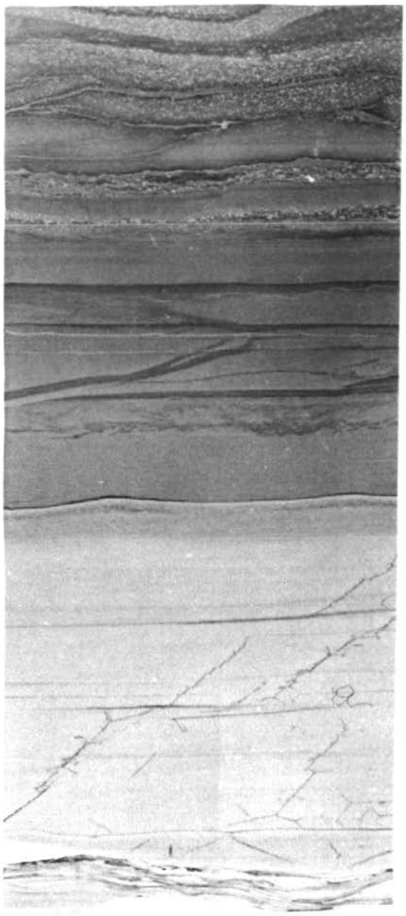

Figure 16
Part of Souris River Fm. (U. Devonian, Saskatchewan) evaporite cycle. Light coloured laminated carbonates at base pass up into pyritic-stained carbonates (marking episode when brines were gypsum saturated but gypsum failed to accumulate because of bacterial reduction in the sediment) and then 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.

the shallow basin or shelf environment has been lowered to such an extent that only shallow subaqueous or brine-pan salt is deposited.

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. 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 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), Hsü (1972), and Kirkland and Evans (1973) - attention is directed towards three currently accepted and competing depositional models (Fig. 17).

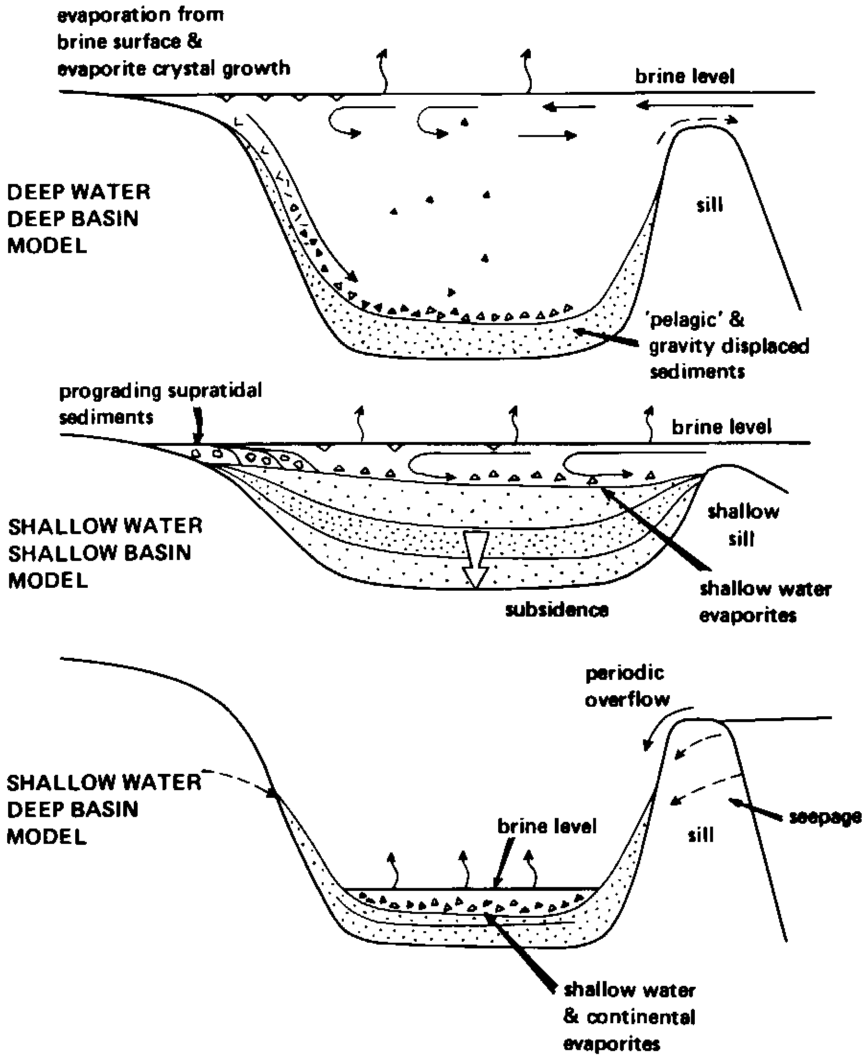

Figure 17
Depositional models for basin-central evaporites.

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 palaeogeographic 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 depositonal 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.

The shallow water, shallow basin model accounts for the sedimentalogic 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 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 of the concentrated brines The second, uplift of the barrier, would permit the basin to dry out and no further deposition 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

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 induce 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.

The shallow water, deep basin model was developed to account for preexisting 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 groundwater, sea-water springs or 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 complete desiccation.

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, 1977; re-interpreted by Shearman, 1970) testify to deposition of salt flats and imply basin desiccation. Most support for the shallow-water, deep basin model, however, comes from the DSDP program in the Mediterranean (Hsü *et al.*, 1973; Garrison *et al.*, in press) 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. Hsü (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. 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 and an earlier one in the facies model series (Kendall, 1978) have emphasized interpretations based upon evaporite fabrics and structures but have largely ignored geochemical evidence. Potash 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 and, probably more than any other paper in this series, this one will be outdated as soon as it is published. Evaporite sedimentology is in a considerable state of flux and probably will remain so for some years to come.

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.

Table I
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 are laterally impersistent.
		evidence of deposition by currents: clastic textures, ripple drift and X-bedding, rip-up breccias, reverse and normal grading.
		associated stromatolites, footprints.
	nodular anhydrite developed from laminated sulphates.	nodular anhydrite developed displacively in inter-inter- and supratidal sediments.
Clastic Sulphates	in form of gravity flows, slumps and turbidites.	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.	layers separated by terrigenous or carbonate-sulphate laminae.
		associated with potash salts.
	clear, inclusion-free halite cubes.	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.

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MS received May 25, 1978