

# The Problem of Distinguishing Between Primary and Secondary Features in Evaporites

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## ABSTRACT

Because saline minerals are readily altered even on shallow burial, a full confrontation of the critical problem of distinguishing syndepositional (= primary) from post-burial (= secondary) features should be an absolute prerequisite to any study of an ancient evaporite. Toward resolution of this problem we offer the following criteria:

- **Syndepositional Features**—1) sedimentary structures, e.g., lamination, ripple marks, etc., 2) detrital framework textures, both traction and settle-out, e.g., cumulates, 3) "open-space" crystal growth textures, e.g., vertical competitive growth of chevrons, etc., identified using the cement criteria of Bathurst (1975), 4) dissolution-reprecipitation features, such as rounding and syntaxial rebuilding of euhedra, etc., 5) fluid inclusions that show low homogenization temperatures, shrinkage bubbles as opposed to vapor under pressure, and banding that records systematic changes in salinity from core to rim, and 6) absence of high temperature salts.

- **Post Burial Features**—1) massive crystalline mosaics without bedding, 2) crystalline mosaic patches that cross cut bedding, 3) sutured mosaic textures, identified using the neomorphic spur criteria of Bathurst (1975), 4) polygonal mosaic textures with 120° triple junctions, e.g., "foam" structures due to annealing recrystallization, 5) solid inclusions, etc., purged to grain boundaries during recrystallization, 6) high temperature salts, as mosaics, euhedra, nodules or pseudomorphous replacements, 7) fluid inclusions that show high homogenization temperatures, vapor bubbles under pressure, and no systematic salinity changes from core to rim, 8) deformation features such as folds, veins, foliation, stylolites, slip bands, etc.
- **Ambiguous Features**—minerals with wide temperature stability ranges that occur as 1) pseudomorphous replacements, 2) intrasediment growths as euhedra or nodules, 3) void-filling cements.

## INTRODUCTION

Evaporites carry an importance in the geological record that is out of proportion to their relatively limited abundance. Apart from their economic value, evaporites are significant indicators of paleoclimate and of rift-valley tectonic settings. In addition, they are major sources of solutes for deep-circulating hydrothermal brines and sedimentary basin formation waters, and in terms of the global chemical budget, they are massive subsurface "warehouses" for storage of the soluble by-products of chemical weathering of the crust. Most significantly, of all deposits in the sedimentary record, evaporites are the premier recorders of the chemistry of ancient sea waters,

lake waters and other surface waters. If we are to properly exploit these special assets of evaporites, particularly those involving paleochemistry and paleoenvironments, it is absolutely essential to be able to separate those minerals, textures and structures that are of primary depositional origin from those that are due to secondary alteration on burial.

It has long been recognized that evaporite minerals are easily altered on burial by even modest increases in temperature. As a consequence much attention in the past was given to such burial metamorphism (see Stewart, 1963, pp. 42-43; Borchert and Muir, 1964, pp. 93-147, 158-179, 237-254; Braitsch, 1971, pp. 108-130, 173-195), but unfortunately little agreement emerged as to

which features were due to burial alteration and which were depositional features. However, in recent years there has been considerable progress in the recognition of primary and early diagenetic features through studies of modern evaporite environments. It seemed worthwhile, therefore, to attempt to compile and evaluate an up-to-date set of working criteria for distinguishing between syndepositional and later burial features in evaporites, despite the fact that a number of longstanding questions about alteration remain unresolved at the present time. In our compilation we offer no unequivocal solutions to the complex problem of primary versus secondary features. Our objective is really to open a dialogue, to refocus attention on a critically important but rather neglected aspect of evaporites. Most of the criteria we discuss are best examined in this section, and it is a further hope of ours that we can encourage a return to the kind of petrographic work so splendidly carried out by Schaller and Henderson (1932) on the Salado evaporites.

Finally, our examples are very heavily biased toward gypsum, anhydrite and halite deposits. This is due to the overwhelming weight of published observations on such deposits and the paucity of appropriate descriptions on potash, alkali sulfates, alkali carbonates and other evaporite minerals. We hope the present paper will stimulate evaporitologists to correct this imbalance.

#### PRIMARY VERSUS SECONDARY FEATURES: DEFINITIONS

There is no real consensus on the meanings of the terms primary and secondary as applied to evaporites. At the 1962 International Conference on Saline Deposits (where this problem was considered as a priority by the deposition and geochemistry work sessions group) primary minerals were defined as those "precipitated directly from the solution" and secondary minerals as those "formed later than the primary ones" (Ingerson, 1968, p. 671). Stewart held similar views in that he dealt with both "penecontemporaneous changes" and "postconsolidation changes" under secondary changes (Stewart, 1963, p. 42). Braitsch (1971, p. 92), on the other hand, included early diagenetic alteration in his definition of "primary precipitation." These differences are in one sense merely semantic, since all acknowledge that initial precipitates may be altered soon after deposition, so it becomes a matter of preference as to whether to include early alteration under primary (as does Braitsch) or under secondary (as does Stewart). On the other hand, the distinction between early diagenetic changes and later burial changes is a truly pivotal decision and we need terms that explicitly acknowledge the timing of such changes. In terms of timing, a mineral, mineral assemblage, texture, fabric, fluid inclusion or structure could be

1. depositional, i.e., formed at the time of deposition of a sedimentation unit or deposited in its existing form
2. post-depositional but pre-burial, i.e., formed diagenetically soon after deposition by processes controlled by the existing depositional environment or
3. post-burial, i.e., formed by late diagenetic or metamorphic-metasomatic processes controlled by the subsurface burial environment.

The first two classes, one primary (depositional) and the other secondary (diagenetic), both depend on processes operating in the depositional environment. They both house valuable information about primary environmental parameters and for this reason we have grouped them together under *syndepositional* features, as distinguished from *post-burial* features. In a depositional context, then, we could regard all syndepositional features including early diagenetic (penecontemporaneous) alteration as "primary." Post-burial features would be "secondary." However, we prefer to emphasize the timing aspect of the problem and so in compiling criteria we have followed the syndepositional versus post-burial classification.

But there remains a class of features that are equivocal in that there are no decisive criteria that point to their time of origin. We have grouped these under *ambiguous* features.

To complicate matters it is not uncommon to find extensive secondary changes in mineralogy with no change in the primary texture (e.g., pseudomorphous replacement by halite of vertically oriented gypsum euhedra, Lowenstein, 1982, Figure 4) or alteration of texture that does not entirely obliterate the original depositional structure (e.g., Dellwig, 1955, Figure 2; Hardie and Eugster, 1971, Figure 11A). Despite the alteration overprints, we regard such recognizable primary textures and structures as syndepositional features because they carry legible information about depositional processes and environments.

Finally, the terms primary and secondary are not easily applied to evaporite deposits as a whole because so many deposits carry both syndepositional and secondary alteration features (and often in the same bed or crystal, as just discussed above). Should the need arise to use such terms for the overall deposits, then we suggest "primary evaporite" might be used to describe those deposits not sufficiently altered to obscure the primary syndepositional features. Or perhaps "modified primary evaporite" might be better where alteration is extensive but where it has still been possible to "read through" the alteration. Secondary evaporites would be those deposits so thoroughly altered on burial that few if any syndepositional features can be unambiguously identified.

## CRITERIA FOR SYNDEPOSITIONAL FEATURES

Criteria for syndepositional features basically comprise (a) mechanical sedimentary structures and detrital textures and fabrics produced during traction and suspension load deposition of chemical sediment particles; (b) crystalline textures and fabrics produced as chemically precipitated minerals grew in place on and within bottom sediment; and (c) features indicative of contemporaneous cementation, dissolution and reprecipitation of salts. Additional criteria come from fluid inclusions and mineral stability ranges.

### Sedimentary Structures

It is well documented that mechanical sedimentary structures typical of clastic deposition are common in evaporite deposits, particularly those involving gypsum-anhydrite and, to a lesser extent, halite (Dellwig, 1968; Dellwig and Evans, 1969; Hardie and Eugster, 1971; Parea and Ricci-Lucchi, 1972; Ricci-Lucchi, 1973; Schreiber et al., 1976; Schlager and Bolz, 1977; Schreiber and Hsu, 1980). These are essentially stratification and bed form structures, but other primary structures such as slump folding (Schlager and Bolz, 1977, p. 602), sole markings (Parea and Ricci-Lucchi, 1972, Figure 24), mudcracks and flat pebble conglomerates (Hardie and Eugster, 1971, Figure 20) have been reported.

Stratification in evaporites is expressed as both textural and mineralogical variations from layer to layer. Traction load deposition is recorded in ripple cross-lamination and other cross-stratification structures (Hardie and Eugster, 1971, Figure 13; Schreiber and Hsu, 1980, Figures 18 and 19; Lowenstein, 1982, Figure 5A) and in flat laminated coarse grainstones (Hardie and Eugster, 1971, Figures 14 and 16). Settle-out from suspension is recorded in graded bedding (Schlager and Bolz, 1977, Figure 6; Schreiber et al., 1982, Figure 7A) and in the repetitious interlamination of clay or carbonate mud with saline mineral crystal mud (Lowenstein, 1982, Figure 4A and 5D). Stratification types may be organized into Bouma sequences, as have been described from several  $\text{CaSO}_4$  deposits (Schreiber et al., 1976, Figure 4; Parea and Ricci-Lucchi, 1972, Figure 23), and into other simpler fining-upward sequences (Schlager and Bolz, 1977, Figures 4 and 5). Bed forms reported from evaporites are typically wave ripple marks (Kaufman and Slawson, 1950; Weiler et al., 1974, Figure 2; Nurmi and Friedman, 1977, Figure 14; Schreiber et al., 1982, Figure 7C) and are found capping both gypsum and halite grainstone layers.

The preservation of all these structures in evaporite sedimentation units not only testifies against pervasive destructive recrystallization, replacement and deformation of the deposit but it allows valuable interpretations to be made about depositional processes and the environ-

ments in which they operated. This follows, of course, because these sedimentary structures carry the same genetic messages as their siliciclastic and carbonate counterparts, about which much has been written (e.g., Collinson and Thompson, 1982). However, as with many carbonate rocks, close examination of layered evaporites may show that both mineralogy and textures have been altered by recrystallization or replacement without destruction of the primary macro-structures (Figure 6). As long as the structures survive the alteration then there should be no serious loss of information about primary depositional processes (see Lowenstein, 1982, pp. 286-289).

In contrast, one should be on guard against misidentification of deformational flow banding as primary depositional lamination or as primary soft sediment slump folding.

### Detrital Framework Textures

As with other sedimentary rocks, the classic criterion of a framework of grains with point contacts should firmly establish a primary detrital texture in evaporites. For example, in gypsum grainstones the detrital framework may be made up of abraded fragments of selenite single crystals (e.g., Hardie and Eugster, 1971, Figures 15 and 16) or of stacks of gypsum needle euhedra oriented parallel to foreset laminae (Figure 1; Lowenstein, 1982, Figure 5A).

Halite detrital textures are subtle features easily overlooked. Such textures may be of two types: (a) mechanical accumulations of cubes that precipitated in the water column and settled to the bottom; and (b) frameworks of abraded crystals sorted by bottom currents. Crystallization of halite from an evaporating brine begins at the air-brine interface as hopper-shaped nuclei (Dellwig, 1955). Individual hopper cubes and laterally-linked "rafts" of hopper cubes will grow on these nuclei at the surface until their weight overcomes the surface tension. They then founder and sink to the bottom where they accumulate as a framework of small cubic grains (mm-scale) and flat, elongated sheets of connected cubes ("rafts"), a behaviour observed in modern salt pans and readily reproduced in laboratory experiments (Arthurton, 1973). Our own observations on natural and artificial salt pans and on laboratory experiments indicate that the foundered cubes have cloudy, inclusion-rich cores (representing rapid initial growth of skeletal hoppers) and clear, inclusion-poor rims (representing slower syntaxial infilling of hollow hopper faces). In shallow unstratified brine pools typical of salt pans the foundered cubes act as nuclei for extensive and continued syntaxial growth on the bottom which soon modifies the initial detrital texture and replaces it with competitive-growth crystalline fabrics as discussed in the next section. In contrast, in the absence of bottom growth the foundered cubes and rafts will simply continue to pile up as mechanical accumulates. The

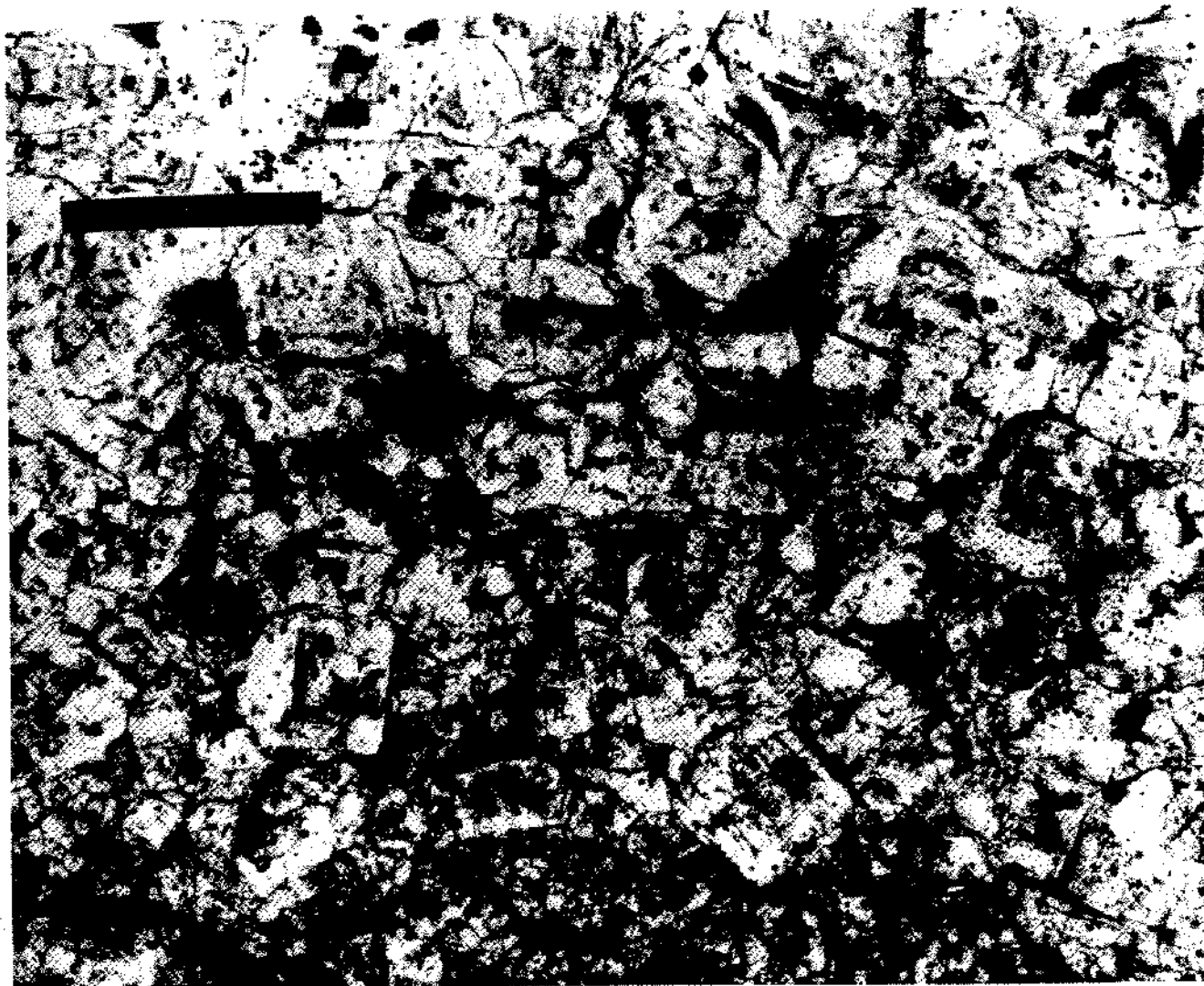


**Figure 1.** Thin section photograph of part of a wave ripple composed of prismatic gypsum pseudomorphs, viewed perpendicular to the strike of the ripple crest. Clear crystal fragments with gypsum morphologies but now composed of halite, are aligned along foresets. Dark surrounding sediment is microcrystalline anhydrite and polyhalite. Vertically oriented prismatic gypsum pseudomorphs (bottom), composed of halite and some sylvite (arrow, lower right), are the same size and shape as the gypsum pseudomorphs comprising the wave ripples. Sample from Salado Fm. laminated anhydrite/polyhalite rock. Scale bar is 5 mm long.

"cumulate" texture of such mechanical settle-out is well-preserved in certain beds in the Permian Salado formation of New Mexico (Figures 2 and 3; see also Lowenstein, 1982, Figure 7). Beds of halite with detrital cumulate textures signify, we believe, either (1) periods of rapid nucleation of hoppers on the surface of shallow unstratified salt-pan brines where settling rates were faster than syntaxial bottom growth (see next section), or (2) accumulation of settled hopper cubes on the bottom of a *stratified* brine body. We experimented with two layer stratified systems in which the bottom brine stratum was saturated with respect to halite and isolated from the atmosphere by a less dense surface brine stratum. Many months of continued operation failed to produce syntaxial enlargement of bottom seed crystals either as overgrowths or as crusts of "chevron" and "cornet" halite, testifying to the difficulty of supersaturating the bottom layer of such stably stratified brines. On the other hand, as soon as we

destroyed the brine stratification either surface nucleation of hoppers dominated (when evaporation rate was rapid) or bottom growth of chevrons and cornets took over (when evaporation was slow). We suggest, therefore, that cumulate textures not only indicate primary detrital deposition but also signify either settling in a stratified brine system or very rapid evaporation in an unstratified system. It is also possible that deep water favors cumulate deposition because rates of surface evaporation may be faster than rates of transportation of supersaturated brine to the bottom, but this is very speculative. Cumulate textures formed in any of these ways may also exhibit reverse grading (Figure 4), the upward crystal size increase perhaps due to longer and longer surface residence times as the surface brine density progressively increased with progressive evaporation.

Where bottom currents are strong enough to agitate the foundered halite cubes and work them into bed



**Figure 2.** Thin section photograph of randomly oriented, mm-scale, detrital halite cubes with cumulate texture. Dark clots and bands in halite cube cores are fluid inclusions. Dark material interstitial to halite is microcrystalline polyhalite. Sample from Salado Fm. mud-free halite rock. Scale bar is 2.5 mm long.

forms, a framework texture of abraded and sorted halite grains results. This is, of course, most likely to happen in moderately shallow wave-agitated brine pools, as for example, has been reported by Weiler et al. (1974) along the shores of the 6m deep South Basin of the Dead Sea. Here, in the foreshore zone a fine sand of halite crystals is beautifully wave-rippled (Weiler et al., 1974, Figure 2) while the beach berm of the backshore is built of spectacular sand- to granule-size halite ooids abraded by storm-wave transport (Weiler et al., 1974, Figures 3-6).

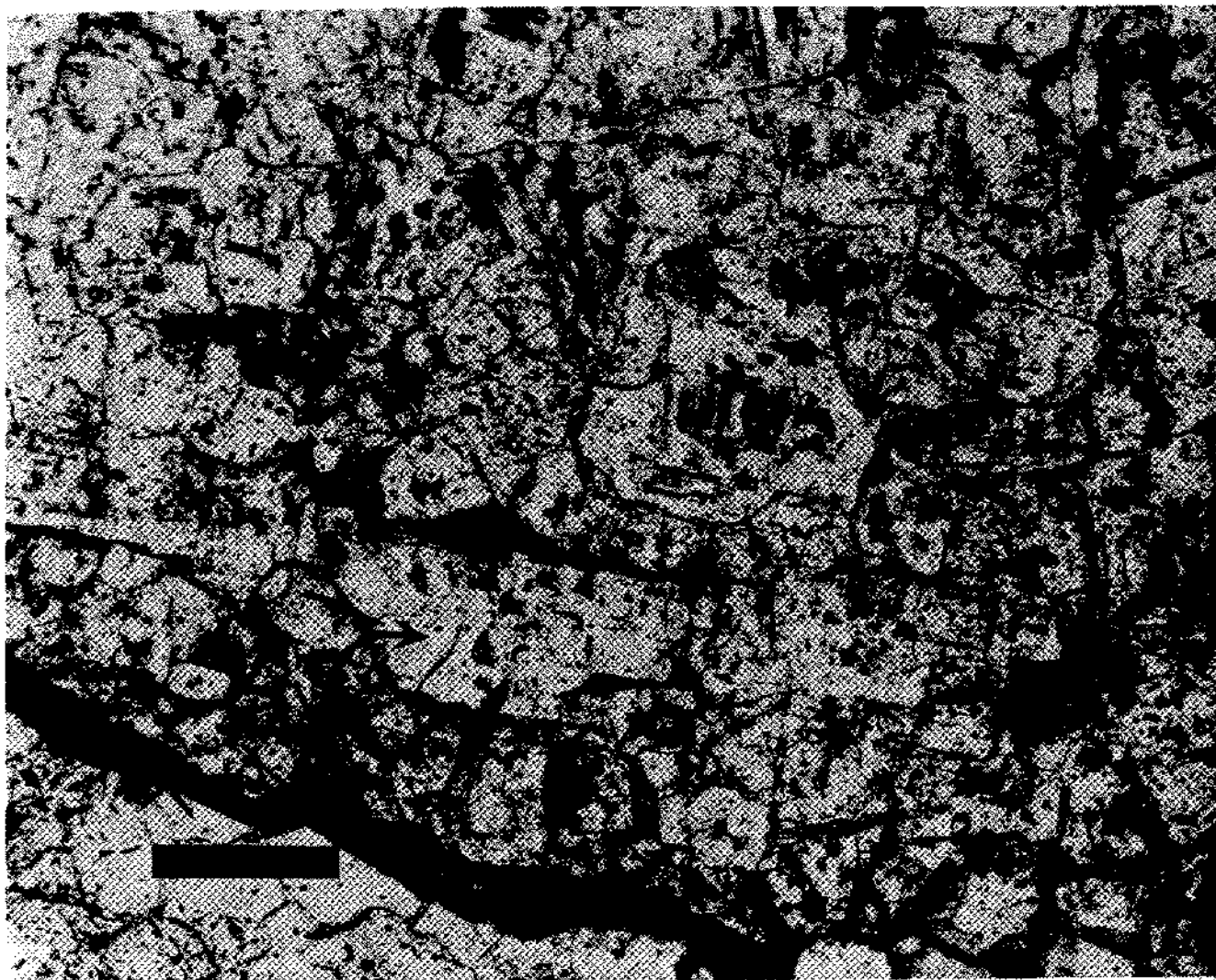
#### Crystalline Framework Fabrics

Fabrics diagnostic of in situ, open space crystal growth on the bottom of brine pools are commonly preserved in modern and ancient evaporites, particularly for gypsum and halite (Schaller and Henderson, 1932; Stewart, 1949,

1951; Hardie and Eugster, 1971; Schreiber and Kinsman, 1975; Caldwell, 1976; Schreiber and Schreiber, 1977; Arakel, 1980; Warren, 1982; Lowenstein, 1982, 1983, for gypsum, and Gottesmann, 1963; Jones, 1965; Wardlaw and Schwerdtner, 1966; Shearman, 1970; Arthurthron, 1973; Handford, 1981; Lowenstein, 1982, 1983, for halite). Such fabrics for other salts have been reported (see Eugster, 1970, for trona, and Wardlaw, 1972, for sylvite), but, unfortunately, there are no complete descriptions.

The dominant fabric of open space precipitation is a layered, syntaxially-grown crystalline framework consisting of vertically-oriented and vertically-elongated crystals. In essence, this fabric represents competitive crystal growth upward into a free-standing, saturated brine, a process identical in style to void-filling cement crystalli-





**Figure 3.** Thin section photograph of a laterally elongated sheet of connected halite crystals ("sunken hopper raft"—arrow) surrounded by randomly oriented detrital halite cubes ("cumulates"). The dark lamina at the base is microcrystalline polyhalite. Sample from Salado Fm. mud-free halite rock. Scale bar is 2 mm long.

zation. Therefore, the cement criteria carefully documented by carbonate petrographers (see Bathurst, 1975, pp. 416–425) serve as guides to the recognition of open space bottom growth of a crystalline framework fabric in evaporites. When specifically applied to the evaporite minerals gypsum and halite as viewed in thin section, the basic fabric criteria for syndepositional bottom growth are as follows:

1. for gypsum, vertically oriented prisms with euhedral terminations (commonly "swallow-tail" twins), and for halite, vertically directed "chevrons" (syntaxial overgrowths on upward facing cube coigns) and "cornets" (syntaxial overgrowths on upward facing cube faces) with euhedral terminations and

fluid inclusion banding parallel to crystal growth faces (Figure 5)

2. upward coarsening and widening of crystals (Figure 6; Hardie and Eugster, 1971, Figure 21; Arakel, 1980, Figure 9) where, during competitive growth, crystal bottoms abut the substrate and sides of crystals abut one another along compromise boundaries (Shearman, 1970; Bathurst, 1975, pp. 421–425 and Figure 303). Crystal growth is therefore most rapid on upward-directed faces. For example, for halite, the upward-facing cube faces and coigns of foundered hoppers that settled randomly on the bottom become the dominant growth directions, producing "cornets" and "chevrons" respectively.



**Figure 4.** Thin section photograph of reverse grading within a halite crystal cumulate layer. Halite cubes, with dark fluid inclusion banding in crystal cores, increase in size upward. Dark gray layer at the base is microcrystalline polyhalite. Sample from Salado Fm. mud-free halite rock. Scale bar is 5 mm long.

Additional textural evidence that supports a syndepositional origin of vertically oriented crystal fabrics is

3. growth originating from a common, laterally continuous substrate, particularly where the basal zones of the growth layer consists of detrital seed-crystals
4. mud drapes or crystal cumulates immediately above vertically oriented crystal layers thicken in depressions and thin over tops of the framework crystals. This demonstrates that vertically directed growth must have occurred before deposition of overlying layers (e.g., Hardie and Eugster, 1971, Figure 21A).
5. dissolution or erosion surfaces that truncate vertical crystals and act as substrates for growth of a new crystalline layer (see next section).

Crystalline framework fabrics produced by syndepositional open space growth on the bottom of a brine body preserve a wealth of information on primary environmental conditions. For these frameworks to grow the physical conditions must be such that continuous supplies of supersaturated brines must be allowed to come into direct contact with the bottom growing crystals. Our experi-

ments with stratified and unstratified brine systems showed that these conditions are difficult if not impossible to achieve in a stably stratified brine (cf. previous section) but are readily met in very shallow, freely mixed brine sheets. We believe, therefore, that syntaxially-grown crystalline frameworks are not only primary features but strong evidence for shallow unstratified evaporite environments. The presence of dissolution-reprecipitation features (see next section) provide additional confirmation of this view because such features require either ephemeral conditions or shallow enough brines to allow significant brine dilution by undersaturated flood water influxes. The abundance of crystalline frameworks showing dissolution features in modern salt pans (Lowenstein and Hardie, 1982) amply support this contention. Finally, the fluid inclusions that outline growth layering in halite crystalline frameworks, for example, can add significant information about the physicochemical conditions during primary growth (see later).

#### Dissolution-Reprecipitation Features

Syndeponitional dissolution-reprecipitation features in gypsum-anhydrite (e.g., Hardie and Eugster, 1971, Figure 21; Schreiber and Kinsman, 1975, Figure 7; Warren, 1982, Figure 12, 15B) and halite deposits (e.g., Dellwig, 1955, Figure 11; Wardlaw and Schwerdtner, 1966, Plate 3, Figure 4; Shearman, 1970, Figure 6; Arthurton, 1973, Figure 9; Lowenstein, 1982, Figure 6D) indicate dramatic fluctuations in solution composition during crystal growth and layer accumulation.

Unequivocal evidence of syndepositional dissolution is basically of two types:

1. sharp but smooth truncations parallel to bedding of vertically oriented crystal frameworks overlain in turn by layers of detrital mud, crystal cumulates or vertically oriented crystals (e.g., Figure 7; see also Wardlaw and Schwerdtner, 1966, Plate 3, Figure 4; Arthurton, 1973, Figure 9)
2. rounding of euhedral terminations of single crystals followed by syntaxial rehealing (Figure 8). For example, large selenite crystals have been found with rounded terminations draped by thin mud laminae and rehealed by renewed syntaxial growth that preserves both the rounded faces and the mud laminae within the vertically grown crystals (Hardie and Eugster, 1971, Figure 21; Schreiber and Kinsman, 1975, Figure 7).

More complex dissolution and reprecipitation features accompany the above phenomena in modern ephemeral salt pans where halite crystalline frameworks are forming. Ephemeral salt pans go through a repeating three-stage cycle of events: (1) an initial flooding stage when undersaturated floodwaters inundate the pan after a storm, (2) a saline

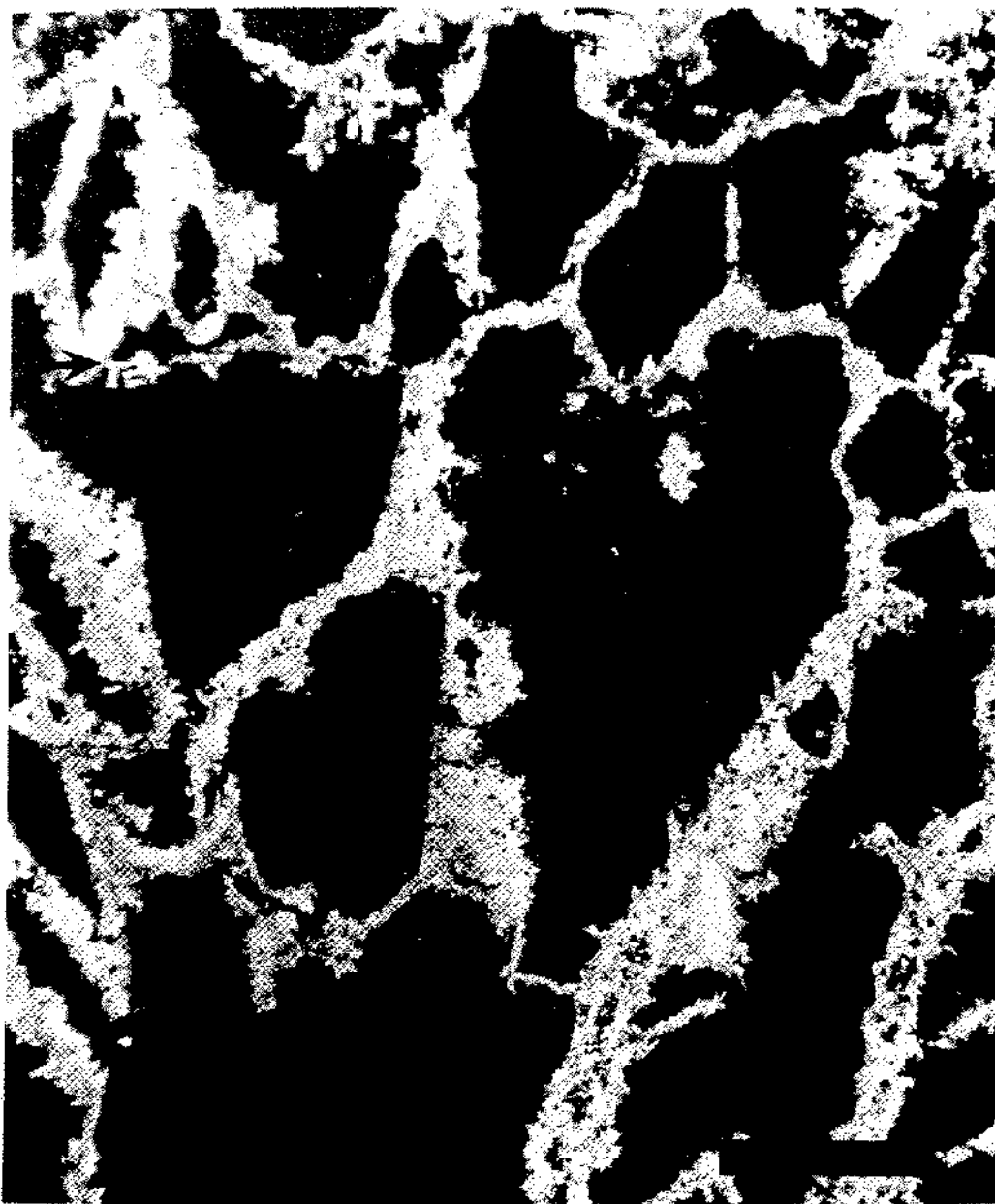


**Figure 5.** Thin section photograph of vertically oriented halite chevrons (upward directed edges and corners) and corners (upward directed cube faces). Within single crystals, dark bands rich in fluid inclusions alternate with lighter bands containing few fluid inclusions. White areas are clear inclusion-poor halite, usually present as rims on chevrons and corners. Sample from Salado Fm. mud-free halite. Scale bar is 3 mm long.

lake stage when evaporative concentration leads to growth of a crystalline framework layer, (3) a desiccation stage when the pan surface dries up and only subsurface, intracrystal brines remain (Lowenstein and Hardie, 1982). The initial flood stage, in addition to producing dissolutional truncation of the framework and rounding of individual halite crystals, causes extensive tubular networks of vertical and horizontal dissolution cavities that follow grain boundaries between vertically oriented crystals and

along bedding planes. Subsequent evaporative concentration of the floodwaters results in halite saturated brines and renewed crystal growth. Dissolution cavities become lined with inward growing clear halite crystal cements and rounded and dissolved euhedra will be rehealed by syntaxial growth. At the desiccation stage the brine sinks below the pan surface and the voids in the upper halite crust become partly filled with a cement of clear halite (Lowenstein and Hardie, 1982). All these features





**Figure 6.** Thin section photograph (crossed nicols) of upward coarsening and widening halite crystals (black) outlined by gray microcrystalline polyhalite. Halite cornets (center), with upward facing cube faces, are flat-topped (arrow) and overlain by smaller vertically oriented crystals. Sample from Salado Fm. mud-free halite rock. Scale bar is 2 mm long.

are syndepositional, formed concurrently with deposition of the halite framework layers, but they may not be easy to distinguish from some burial dissolution-precipitation features in ancient evaporites. Burial dissolution, cementation and recrystallization could give rise to rounded voids filled with clear halite cements as well as to patches of clear halite mosaics. Care must be taken to look for other evidence of the timing of dissolution and cements-

tion, such as internal sediment overlying cement, truncation of void fills by primary layering, etc.

#### Fluid Inclusions

We present here a brief discussion of the criteria for recognizing syndepositional evaporite minerals on the basis of fluid inclusions. We refer the reader to the Appendix for terminology and a summary of techniques of heating, freezing and crushing of inclusions.



**Figure 7.** Thin section photograph of fluid inclusion-banded halite crystal with a sharply truncated upper surface. Light halite lamina (1 cm thick) is overlain by gray microcrystalline polyhalite. Sample from Salado Fm. mud-free halite rock.

Primary evaporite brines are considered to be brines at or near the earth's surface. These brines therefore should be at temperatures found in modern evaporite basins or salt pans, temperatures typically much less than 100°C. The brines should be connected to the atmosphere and therefore be at or near atmospheric pressure. In deep water settings the composition of the brine increases slowly during salt precipitation, while in shallow water settings or salt pans brine composition increases rapidly during salt precipitation. Modern evaporitic brines are almost all multicomponent systems. The heating, freezing and crushing behavior of such systems may now be developed.

Syn depositional evaporite inclusions should contain "normal shrinkage bubbles" or vapor which does not change on cracking, as determined by crushing stage tests. It may be possible to develop vapor under pressure in inclusions due to organic decomposition; however, formation at higher T, P conditions in a system with a solvus is more likely. Only homogenization or melting temperature data obtained from inclusions with "normal shrinkage bubbles" should be considered reliable for syn depositional evaporite inclusions regardless of the petrographic interpretation.

Those syn depositional evaporite inclusions with "normal shrinkage bubbles" should homogenize at tempera-

tures much less than about 100°C. Inclusions that formed near 25°C or lower may have to be chilled in order to nucleate bubbles (to as low as -25°C in some cases). Studies of inclusions of halite, which appear on petrographic evidence to be syn depositional (e.g., "rafts" and "chevrons") from the Permian Salado Formation, New Mexico (Roedder and Belkin, 1979) show homogenization temperatures within this range. Roedder and Belkin (1979) report on more than 300 inclusions, the majority of which homogenized between 20°C and 50°C.

Although the homogenization temperatures are within the range of modern evaporite basins and salt pans, there is some question as to the reliability of the results. Roedder and Belkin (1979) discuss the tendency of halite inclusions to "stretch" during heating, and for inclusions heated to temperatures greater than the homogenization temperature to homogenize at higher temperatures during subsequent runs. This is probably due to solid-fluid metastability. The solubility of most salts is temperature dependent, and therefore as a crystal is heated the contained inclusions may grow so that upon cooling a super-saturated brine (denser than the original brine) may persist in the "expanded" inclusion. An inclusion volume change of about one percent results in a homogenization temperature increase of nearly 20°C. A great deal of caution needs to be exercised during sample preparation of halite; these samples should not be heated. As a result of the tendency for inclusions in halite to "expand" (especially above 50°C), homogenization temperatures taken from a grain of salt should also be taken with a grain of salt.

Syn depositional evaporite inclusions should begin melting around -50 to -60°C (although this may be difficult to observe) due to the multicomponent nature of evaporating brines. Final melting is dependent on the concentration of species in solution; for inclusions in halite or more soluble salts the final melting phase will usually be a hydrate and not ice. A systematic change in first melt behavior and final melting temperature may be observed from core to rim (especially in shallow water evaporites) due to compositional variation in the fluids. The case of sea water evaporation during halite formation (Figure 9) will be used as an example of changing fluid composition and melting behavior. The fluid composition remains in the same system ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ ) throughout. The fluid, as halite begins to precipitate, contains a large proportion of  $\text{Na}^+$  and  $\text{Cl}^-$ . Although melting begins at the six component eutectic ( $\sim -57^\circ\text{C}$ ), relatively little melt will form. As evaporitic concentration continues  $\text{Na}^+$  and  $\text{Cl}^-$  are buffered in solution by halite precipitation, while  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$  and  $\text{K}^+$  increase in concentration. Melting will still begin at the six component eutectic; however, a larger proportion of melt will form at lower temperatures due to the increased concentration of  $\text{Mg}^{2+}$ ,  $\text{SO}_4^{2-}$  and  $\text{K}^+$  in solution. There-



**Figure 8.** Thin section photograph of dark gray fluid inclusion-banded vertically oriented halite. Chevron halite crystal contains internally rounded cube coigns that have syntaxially rehealed (arrow). Clear, inclusion-poor halite located between chevrons and cornets. Sample from Salado Fm. mud-free halite rock. Scale bar is 3 mm long.

fore, a systematic increase in the amount of melting near the eutectic is expected in inclusions from core to rim in a crystal.

A similar change is expected in the final melting temperature of inclusions from core to rim of a crystal. Although it is often difficult to determine the final melting phase, changes are likely in the temperature at which final melting occurs. The final melting phase from most evaporite inclusions is likely to be a hydrate. Melting will therefore be (among others) a function of the activity of  $H_2O$  in solution. A given hydrated phase is therefore expected to melt or dissolve at lower temperatures from solutions with higher concentrations. Primary evaporites are formed as a result of brine evaporation; therefore as a crystal grows, solution concentration increases and inclusions near the core of a crystal melt at higher temperatures than those toward the rim.

In summary, fluid inclusions in syndepositional salt crystals should show the following features:

1. "Normal shrinkage bubbles" or vapor bubbles that do not change on crushing
2. Low homogenization temperature ( $\ll 100^\circ C$ )
3. Low temperature of first melting ( $-50$  to  $-60^\circ C$ )
4. Systematic changes in the quantity of first melt in inclusions from crystal core to rim
5. Systematic changes in the temperature of final melting in inclusions from crystal core to rim.

#### CRITERIA FOR BURIAL ALTERATION FEATURES

Our concern here is to identify features that clearly re-

flect alteration, both diagenetic and metamorphic, due to the increased pressures and temperatures of burial, as well as changes due to metasomatism by invading subsurface waters. We are on somewhat uncertain grounds here because many of the criteria must be inferred rather than

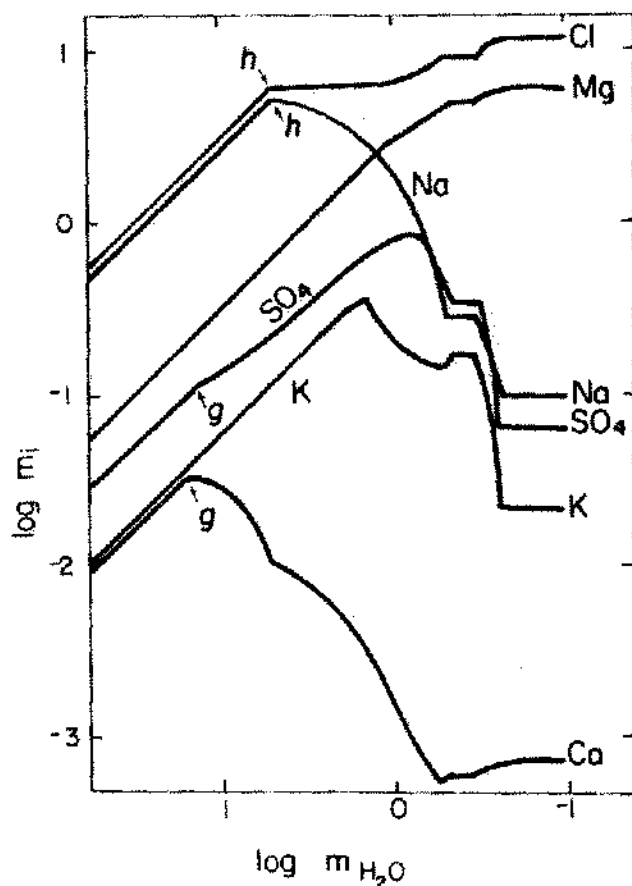


Figure 9. Major element compositional changes predicted during the evaporation of seawater using the methods of Harvie et al. (1980). The stages where gypsum (g) and halite (h) first precipitate are also shown.

obtained directly from comparative studies of active modern systems. Nonetheless, we have put together a tentative working set of criteria, some of which we have listed more as a basis for discussion than as accomplished facts. In the main the criteria involve textures and structures that record disruption, deformation and destruction of primary features, together with mineral assemblages and fluid inclusion data that point to elevated temperatures and pressures.

#### Disruption and Destruction of Sedimentary Structures

The absence of primary bedding or the presence of only scattered remnants of primary bedding or other sedimentary structures in massive crystalline mosaic salts points to destructive secondary crystal growth. The early stages of this destructive growth will be seen as irregular isolated crystalline mosaic patches (see next section) that cross-cut primary sedimentary structures (e.g., Schreiber et al., 1976, Figure 18). This criterion is most persuasive of burial alteration when found in monomineralic (or essentially monomineralic) rocks because then the crystal-

line mosaics must surely be the result of destructive recrystallization. Such crystalline mosaics will have sutured or polygonal grain boundaries (see below) quite distinct from porphyroblasts and from the isolated displacive, incorporative or poikilotopic growth of euhedra and nodules typical of syndepositional intrasediment crystallization (see below).

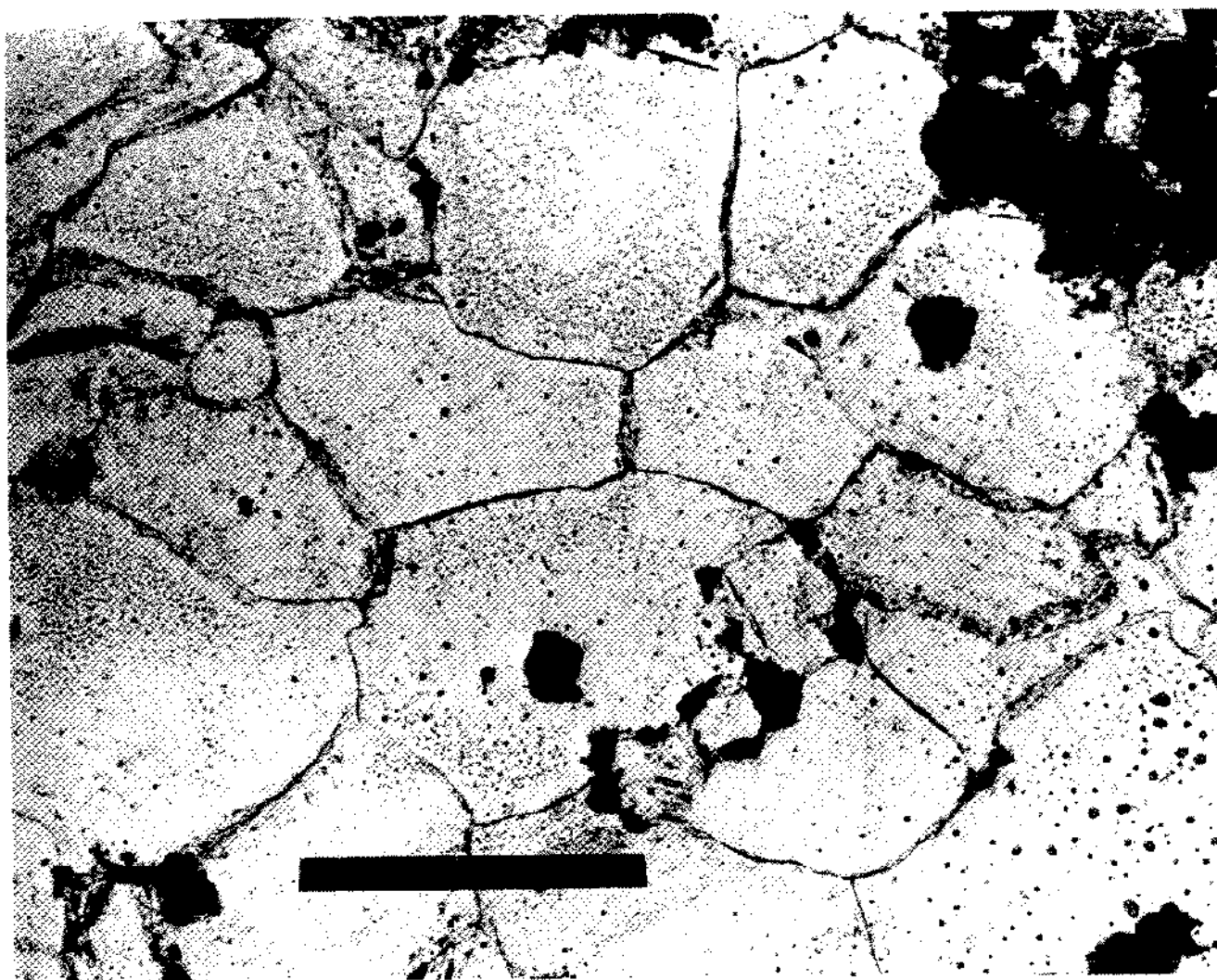
#### Sutured Mosaic Textures

Crystalline mosaic textures in which grain boundaries are sutured in the manner of neomorphic spar of carbonate rocks (compare Hardie and Eugster, 1971, Figure 11A, with Bathurst, 1975, Figures 336 and 338) clearly indicate a secondary grain growth origin. However, the conditions under which this secondary mosaic formed are not known. Such an interpenetration of grains may represent a low temperature, non-equilibrium texture (Voll, 1960); it certainly stands in marked contrast to the equilibrium polygonal mosaic textures formed experimentally by annealing recrystallization (next section). Supportive of this contention are the contrasts between the polygonal texture of marbles and the tortuously sutured boundaries of most diagenetically altered but unmetamorphosed limestones. More insight into the significance of sutured mosaic textures in evaporites must await future work. We are presently trying to attack the problem by looking at young (Quaternary) halite that has been altered by shallow burial of only a few tens of meters.

#### Polygonal Mosaic Textures

Polygonal mosaic textures have long been documented in experimentally treated metals and metallic ore minerals (Buckley, 1951; Burgers, 1963; Stanton and Gorman, 1968). Similar textures are typical of metamorphic rocks (Voll, 1960). There is a consensus that these polygonal mosaic textures are a product of annealing recrystallization whereby grains "optimize" their size, shape and orientation to minimize the energy in the manner of bubbles in foam (Stanton and Gorman, 1968).

Evaporites, because of the ease with which they are altered at the temperatures and pressures of even modest burial, should be very susceptible to such annealing recrystallization. We have found halite in the Permian Salado formation of New Mexico and the Devonian Prairie evaporite of Canada with equigranular mosaic texture (Figure 10; see also Lowenstein, 1983). This halite notably lacks vertical orientation, cumulate textures, banded fluid inclusions or any other feature diagnostic of primary growth. Instead, the anhedral mosaic consists of clear grains that meet at triple junctions that approach 120° angles in typical annealing recrystallization polygonal mosaic fashion (Stanton and Gorman, 1968, Figures 2, 3 and 7). The crystals have few inclusions (large rectangular fluid-filled cavities and blebs of mud), as most of the "foreign" matter appears to have been purged to the hal-



**Figure 10.** Thin section photograph of halite with equigranular mosaic texture ("foam" texture). Note the number of curved crystal boundaries that meet at triple junctions with angles approaching  $120^\circ$ . Mud (black) is included within halite or located at halite crystal boundaries. Small gray bubbles scattered throughout were (artificially) trapped during thin section preparation. Sample from Salado Fm. muddy halite rock. Scale bar is 5 mm long.

ite crystal boundaries during recrystallization (cf. Kühn, 1968, Plate 2, Figure 2). These are all features typical of "foam structure" produced by experimental recrystallization of metals and ores and attests to a destructive burial recrystallization process that leads to complete loss of any primary signature. However, such recrystallization may be very patchy, as we have seen in the Permian Salado evaporite of New Mexico and Devonian Prairie evaporite of Canada where primary, unaltered "chevron" halite co-exists at the same or greater burial depths as "foam" structured halite.

#### Fluid Inclusions

The criteria for post-burial evaporite inclusions are based on the nature of secondary evaporite brines. Secondary evaporite brines are isolated from the earth's sur-

face. Temperature in secondary brines may fall in the same range as primary brines, or may be higher. Temperature and pressure conditions may allow miscibility of fluids that are immiscible under laboratory conditions. Fluids may be multicomponent or single salt systems (e.g., material obtained by dissolution). Temperature and pressure changes are the primary drive for crystallization; therefore, fluid composition remains nearly constant.

Post-burial evaporite inclusions may behave in any of the three manners described upon crushing (see Appendix). "Normal shrinkage bubbles" or vapor bubbles which do not change during crushing are found in primary evaporite inclusions, but inclusions with "vapor under pressure" are almost certainly related to post-depositional processes.



Inclusions with "normal shrinkage bubbles" or "vapor under pressure" may yield reliable information on the temperature of formation measured by homogenization. High temperature of formation is indicative of post-burial conditions. Due to the expansion of halite during heating, temperatures in excess of 50°C may be unreliable; those in excess of 100°C are almost certainly unreliable. Although the exact temperature of formation may be incorrect, the high temperature is indicative of post-depositional formation.

Post-burial evaporite inclusions may contain multi-component brines with relatively low temperature of first melting. Brines that have derived solutes primarily from evaporite dissolution may also form crystals with inclusions. These brines will yield inclusions with higher first melting temperatures ( $\sim -20^\circ\text{C}$ ) and final melting temperatures near those for the simple eutectic salt  $-\text{H}_2\text{O}$  system. Crystallization tends to be driven by temperature-pressure changes, therefore increased concentration of the brines does not occur (boiling is an exception). No systematic change in inclusion melting behavior is expected from core to rim of crystals under these conditions.

In summary, fluid inclusions in evaporites altered by burial may have the following characteristics that are different from inclusions of syndepositional deposits:

1. Vapor under pressure
2. High homogenization temperature
3. High temperature of first melting ( $-20^\circ\text{C}$ )
4. Uniform melting behavior of inclusions.

### Deformation Features

Apart from the obvious macroscopic deformation structures such as folds, fractures, veins, flow banding, pressure solution surfaces, etc. (e.g., Balk, 1949; Goldman, 1952; Müller et al., 1981) there are more subtle microscopic deformation features to look for in thin section or in etched, polished slabs of evaporites (Shlichta, 1968). Stanton and Gorman (1968) have discussed the main types of deformation textures recognized in metalurgical studies and applicable to rocks (see also Voll, 1960, 1976). These deformation textures are (1) deformation twins, (2) slip lines and slip bands, (3) lattice distortion features such as undulose extinction, bent cleavages, etc., (4) sub-grain domains and (5) flattening of grains leading to formation of foliation. We leave the reader to seek help from the above and other works (e.g., Prucha, 1968; Mossop, 1979) in recognizing deformation features in evaporites.

### AMBIGUOUS FEATURES

There are a number of features that could have formed either syndepositionally or after burial. In the absence of other criteria to aid in their interpretation the time of ori-

gin of such features must remain uncertain. To this class of ambiguous features belong (1) mineral growth within the sediment as euhedra or nodules, (2) pseudomorphous replacements and (3) void lining or filling cements.

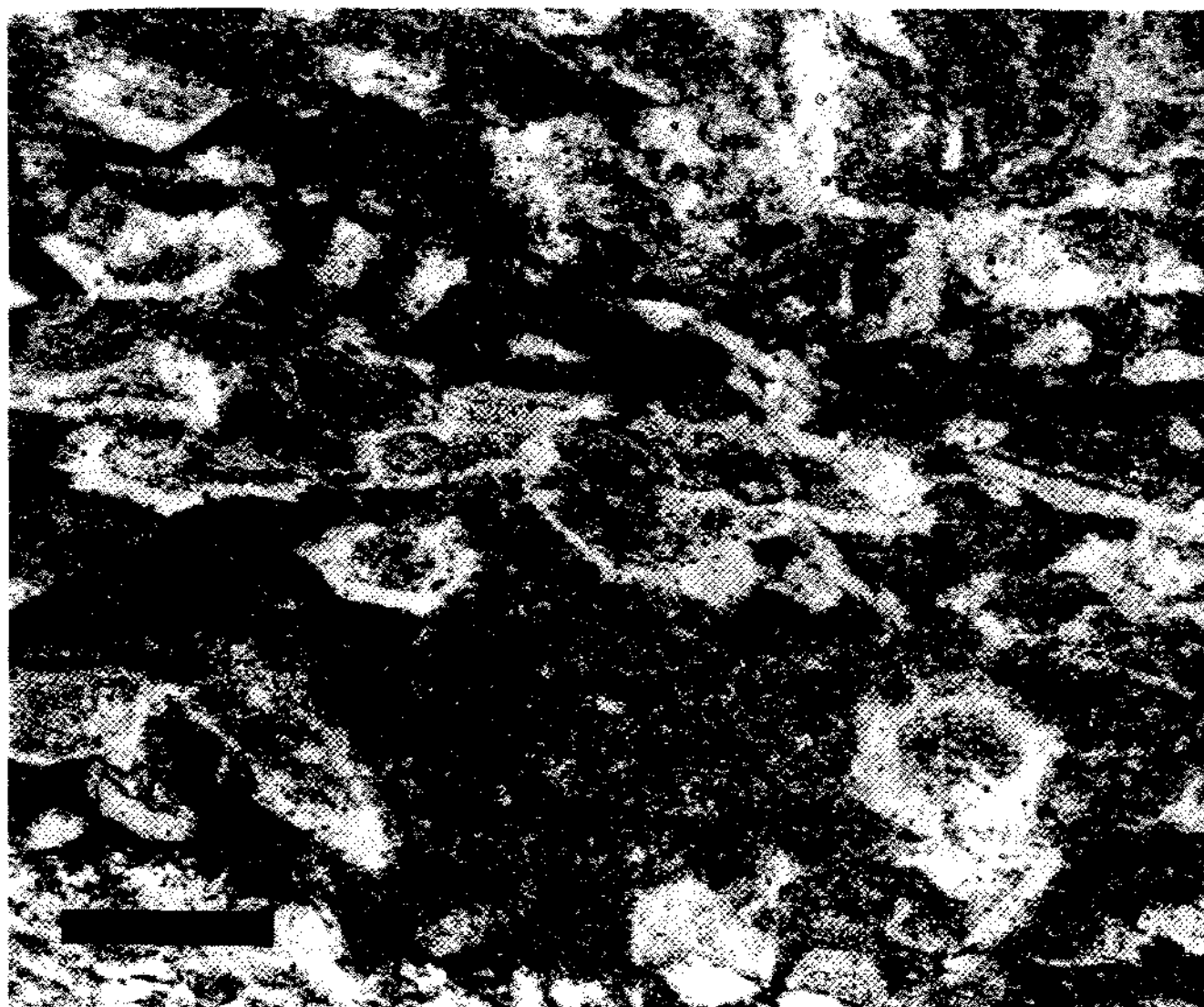
### Intrasediment Growth of Euhedra

Evaporite minerals that have grown within sediment commonly occur as randomly oriented, isolated or interlocking crystals with a euhedral or subhedral habit. Such crystals may incorporate sediment during growth or they may form displacively by pushing aside the host sediment during crystallization. The Permian Salado evaporite of New Mexico (Lowenstein, 1982, 1983) carries many good examples of this style of intrasediment growth by the minerals gypsum (Figure 11), halite (Figure 12), glauberite (Figure 13) and langbeinite (Figure 14).

Incorporative growth provides unequivocal evidence of post-depositional crystallization, but the difficulty is in distinguishing between early syndepositional growth and later metamorphic porphyroblastic growth. There are some indirect ways of getting at the matter of timing. Intrasediment growth of low temperature minerals such as gypsum, mirabilite and epsomite is common in modern playas and sabkhas (Hardie, 1968; Butler, 1970a; Thompson, 1968; Logan et al., 1970; Lowenstein, 1983), so if we find the same low temperature minerals with the same intrasediment growth textures in ancient evaporites then we could argue in favor of a syndepositional origin by analogy. Also, in a rock where the same mineral displays both primary growth textures (see earlier) and intrasediment growth features then it is perhaps reasonable to argue that the intrasediment growth features are syndepositional in origin. For example, the abundance of primary textures in gypsum and halite in the Permian Salado of New Mexico (Lowenstein, 1982, 1983) strongly suggests that the incorporative intrasediment growth euhedra in Figures 11 and 12 are related to near surface crystallization from primary brines. On the other hand, intrasediment growth of euhedra of such elevated temperature minerals as langbeinite (Figure 14) and loewite probably indicates burial crystallization, although as we have pointed out below, temperatures high enough to reach the langbeinite stability field have been reported from some modern evaporite surface sediments (cf. Butler, 1970b).

### Intrasediment Growth of Nodules

It was the discovery of nodules of anhydrite in the Holocene sediments of the Persian Gulf (Curtis et al., 1963; Shearman, 1966; etc.) that essentially rekindled interest in evaporites among sedimentologists. Since then there have been an astonishing number of papers published that have called on nodular anhydrite, or its presumed pseudomorphs, as a criterion for syndepositional growth of evaporites in a sabhka environment. But we must be



**Figure 11.** Thin section photograph of mud-incorporative gypsum crystals (pseudomorphously replaced by microcrystalline anhydrite). Surrounding mud contains magnesite and anhydrite. Sample from Salado Fm. laminated anhydrite rock. Scale bar is 2 mm long.

very wary here because anhydrite nodules can form under a variety of conditions, such as, for example, from the Red Sea hot brines in the Atlantis II Deep under 2000 m of water (see Degens and Ross, 1969, color plate between p. 366 and p. 367). One major mechanism for the generation of anhydrite nodules is the dehydration of gypsum crystals to make porous plastic masses of tiny anhydrite laths that are easily deformed into nodular slugs. This conversion may just as easily occur on deep burial as during primary surface deposition. The same reasoning holds for all other evaporite minerals that are preserved as nodules composed of masses of small crystals embedded in a host sediment, such as, for example, the displacive nodular kiserite shown in Figure 15.

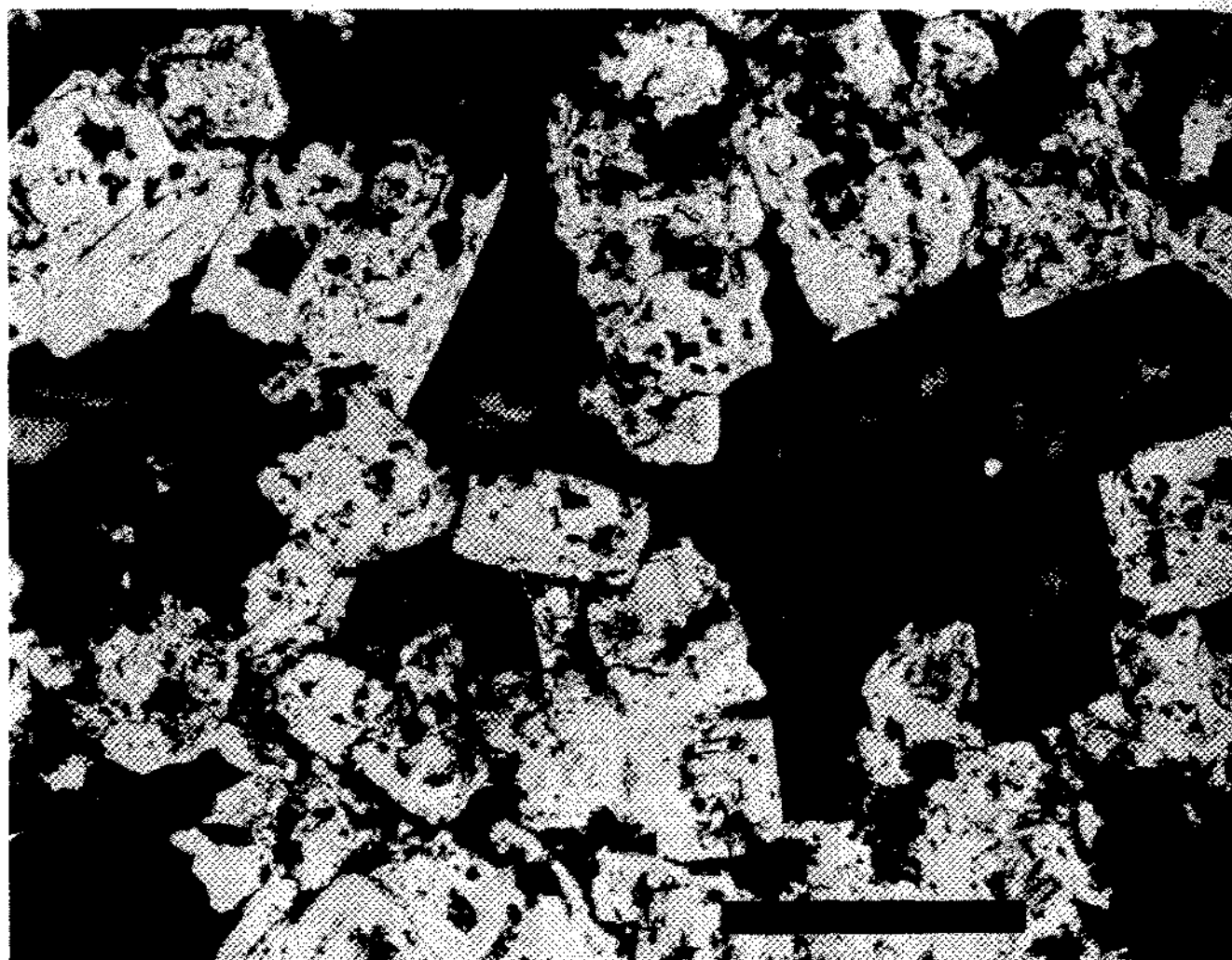
Without independent evidence, then, nodules may not

give unambiguous information about their time, mode or environment of formation.

### Pseudomorphs

Pseudomorphs are unequivocal evidence of secondary replacement. However, the reason that we put such pseudomorphous replacement under ambiguous criteria is that it may not be possible without additional evidence to decide whether the replacement was of syndepositional or later burial origin (cf. Stewart, 1963, p. 42).

Recognition of pseudomorphous replacement rests on the identification of the crystal morphology of the parent mineral, and such replacements have been widely observed in ancient evaporites for gypsum (Schaller and Henderson, 1932; Stewart, 1949, 1951, 1953; Borchert

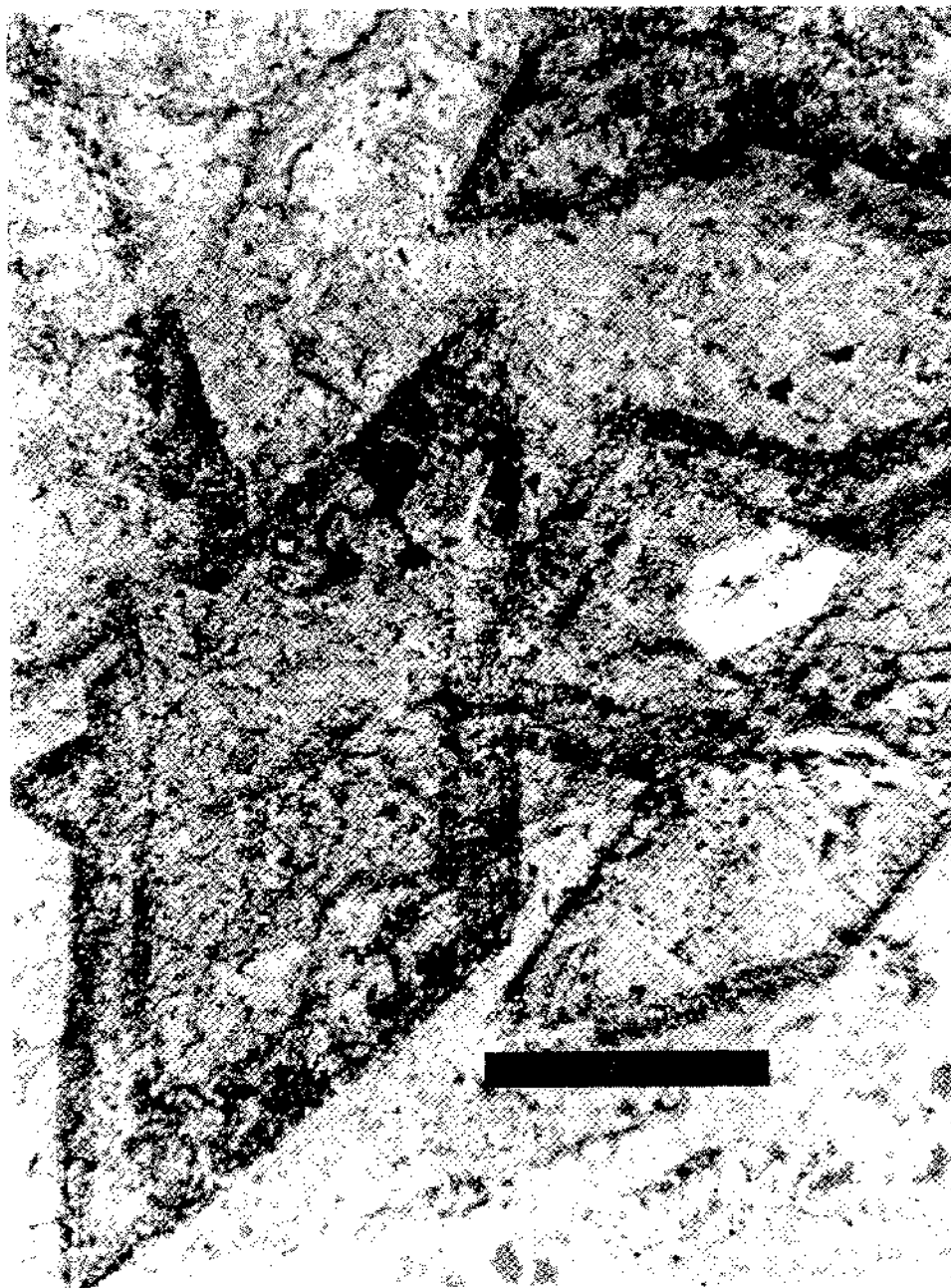


**Figure 12.** Thin section photograph of randomly oriented, interlocking halite cubes. Halite crystals contain incorporated mud (dark gray to black) and sparse fluid inclusion bands (light gray). Dark areas that fill voids between the halite "framework" cubes are composed of large sylvite cement crystals zoned with hematite inclusions. Sample from Salado Fm. "ore zone" muddy halite rock. Scale bar is 5 mm long.

and Baier, 1953; Kerr and Thompson, 1963; Jones, 1965; Nurmi and Friedman, 1977; Handford, 1981; Presley and McGillis, 1982; Crawford and Dunham, 1982; Lowenstein, 1982, 1983; etc.) as well as a number of other salts (Schaller and Henderson, 1932; Stewart, 1963, p. 41; etc.) Pseudomorphs commonly preserve crystalline framework and other primary features of the parent mineral and thus allow interpretation of primary mineralogy, primary processes and depositional environment, despite the mineralogical alteration. For example, the Permian Salado deposit of New Mexico contains pseudomorphs after gypsum (now composed of anhydrite, polyhalite, halite and sylvite) as vertically oriented stubby prisms and as foreset laminac in wave-rippled cross-stratified grainstones (Figures 1 and 16). Clearly, we can read through the alteration and extract important information

about syndepositional processes. However, the timing of the pseudomorphous replacement itself is not directly legible.

Several different types of pseudomorphous replacements have been recognized in evaporite deposits. These are (1) "dehydration pair" replacement (e.g., gypsum  $\rightarrow$  anhydrite), (2) "reaction pair" replacement involving a common component (e.g., gypsum  $\rightarrow$  polyhalite) and (3) "non-reaction pair" replacement wherein the original and replacing minerals have no common components (e.g., gypsum  $\rightarrow$  halite). Borchert and Muir (1964, pp. 126-144) consider all types of pseudomorphous replacement to be metamorphic, but it has been unequivocally established that both dehydration and reaction pair type replacements can form by syndepositional interaction between an early formed mineral and the evaporating



**Figure 13.** Thin section photograph (crossed nicols) of randomly oriented, zoned, incorporate glauberite euhedra, now pseudomorphously replaced by halite (dark gray to black) and anhydrite (lighter gray). Surrounding sediment is microcrystalline anhydrite and magnesite-rich mud. Sample from Salado Fm. laminated anhydrite rock. Scale bar is 5 mm long.

mother-liquors in the normal course of evolution of evaporite brines. For example, both anhydrite and polyhalite can be synthesized at low temperatures (Hardie, 1967 for anhydrite and Autenreith, 1958, for polyhalite), both are predicted from thermodynamic considerations to form from gypsum with progressive evaporation of sea water (Harvie et al., 1980) and both have been found as replacements of gypsum in modern sabkhas (see Butler, 1970a,

for anhydrite, and Holser, 1966, for polyhalite). Nonetheless, we still have no direct and unambiguous way to determine in an ancient evaporite whether such replacements were early or late.

The third pseudomorph type, the "non-reaction pair" replacement, involves minerals totally unrelated chemically to each other. For example, a most common non-reaction pair pseudomorph in ancient evaporites is the re-



**Figure 14.** Thin section photograph of isolated, randomly oriented tetrahedral langbeinite ( $2\text{MgSO}_4 \cdot \text{K}_2\text{SO}_4$ ) crystals with incorporated mud in crystal cores. The larger crystal contains langbeinite in its core (light gray). The rim and the entire smaller crystal have been pseudomorphously replaced by microcrystalline leonite ( $\text{MgSO}_4 \cdot \text{K}_2\text{SO}_4 \cdot 4\text{H}_2\text{O}$ ) plus kainite ( $\text{MgSO}_4 \cdot \text{KCl} \cdot 3\text{H}_2\text{O}$ ). Surrounding area is mud (black) and halite (light gray). Sample from Salado Fm. muddy halite rock. Scale bar is 5 mm long.

placement of euhedral gypsum prisms by halite (Stewart, 1963, p. 41; Lowenstein, 1982, Figures 4 and 5). We have no reported examples of this pseudomorph type in modern evaporites so that conditions necessary for such replacement must be inferred. All we can really say about this replacement process is that it cannot occur during simple equilibrium evaporative concentration of a single solution, as is predicted for chemically related reaction pairs. Thus, for the pseudomorphous replacement of gypsum by halite we must call on the introduction of a new solution capable of dissolving gypsum without chemically reacting with it (i.e., without forming a reaction pair). Replacement by halite may either be simultaneous with gypsum dissolution (i.e., a halite saturated but gypsum undersaturated solution) or may occur later. Again the question of timing, whether syndepositional or after burial, for this replacement sequence observed in ancient

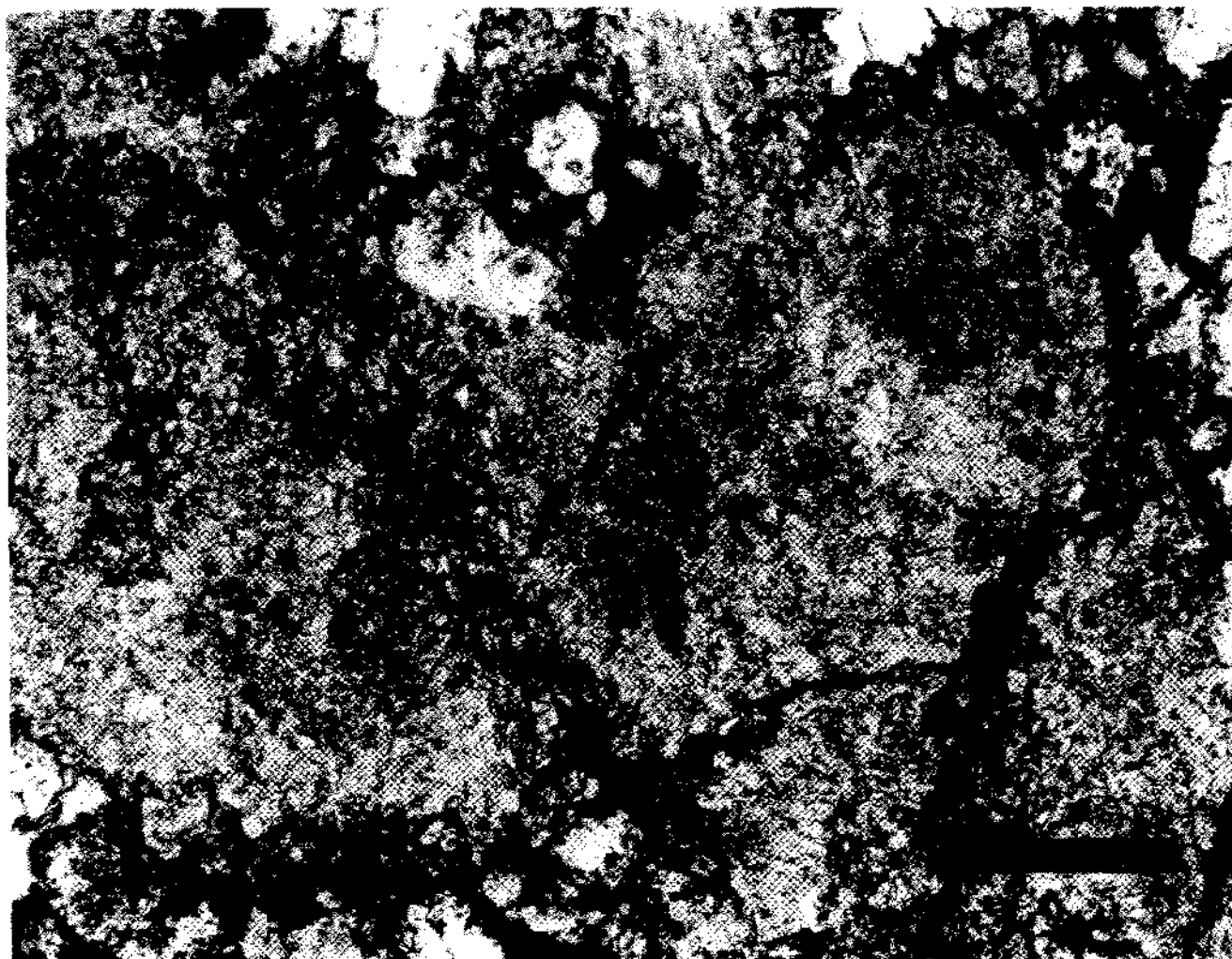
evaporites is ambiguous. However, no matter what the timing, a new solution must come into contact with a previously crystallized mineral. Thus, fluctuating solution compositions and introduction of "alien" brines are prerequisites for this type of pseudomorphous replacement.

### Cements

Cements have gone essentially unnoticed in evaporites despite the fact that undeformed and uncompact buried salts typically have negligible porosities, and yet their analogous unburied primary deposits may contain more than 50% void space (e.g., Lowenstein and Hardie, 1982). This anomaly suggests that cementation must be an important process in evaporite diagenesis.

Cements are post-depositional features, but they could form either syndepositionally (as is common in salt pans, Shearman, 1970, Lowenstein and Hardie, 1982) or on





**Figure 15.** Thin section photograph of displacive kieserite nodules (gray) encircled by mud (black). Kieserite in nodules is a fine grained granular mosaic. The uncertainties involved in interpreting this texture involve the timing of kieserite growth and whether kieserite is a dehydration product of a more hydrated magnesium sulfate mineral (i.e., epsomite); and if so, what was the timing of dehydration? Sample from Salado Fm. muddy halite rock. Scale bar is 5 mm long.

burial. In some cases it may be possible to decide on the timing of cementation from petrographic evidence. For example, meniscus cements surely call for a vadose setting and this in turn implies a syndepositional origin. Also, if erosion or dissolution surfaces cut across cements, or if internal sediment overlies a cement, then there can be little doubt about the syndepositional nature of the cements. All too commonly, though, there is no such direct petrographic evidence and so the timing of cementation remains ambiguous.

We have recognized two basic styles of cementation in modern and ancient evaporites: (1) intergranular cements and (2) vug and cavity cements.

Intergranular cements usually consist of a mineral lining or filling the pore spaces of a primary granular framework. For example, in Figure 12 coarse sylvite cement

fills the voids between cubes of halite in the Permian Salado Formation. These voids are identical in size and morphology to primary unfilled voids so typical of porous crusts of halite in modern salt pans (Lowenstein and Hardie, 1982). Other common features of this type of cementation are isopachous color bands within cement crystals that follow original void boundaries and coarse poikiloblastic crystals that may enclose many framework grains.

Cavities and vugs lined or filled with cement are common in modern evaporite deposits. In halite salt pans vertical and horizontal networks of dissolution cavities and shelter vugs are lined with euhedral cement crystals made of clear halite (Lowenstein and Hardie, 1982). In modern gypsum pans we have seen shelter vugs beneath rumpled surface crusts lined with masses of gypsum "swallow-tail" twins (cf. Warren, 1982, p. 628). Such cavity cementation



**Figure 16.** Thin section photograph of vertically oriented stubby gypsum prisms pseudomorphously replaced by microcrystalline polyhalite. Note gypsum "swallowtail" twin crystal to right of center. Gypsum pseudomorphs, originating from a common substrate, are overlain by peloidal mud (black) and small randomly oriented gypsum pseudomorphs (gray, now composed of polyhalite). Sample from Salado Fm. laminated polyhalite rock. Scale bar is 5 mm long.

has not been explicitly reported from ancient evaporites, but it is likely that the clear rims of halite on cloudy chevrons and cornets so common in ancient halite rocks (e.g., Wardlaw and Schwerdtner, 1966, Plate 2, Figure 4; Lowenstein, 1982, Figure 6C) are cavity cements (cf. Shearman, 1970). The difficulty here is the timing of such cementation. In modern salt pans clear halite rims form syndepositionally as overgrowths on porous chevron and cornet frameworks during the saline lake and desiccation stages (Lowenstein and Hardie, 1982), but similar textures can just as easily be produced on burial. Only the presence of truncation surfaces, internal sediment and renewed chevron overgrowth will provide positive evidence of an early syndepositional origin for such cavity cements. A different type of cavity cement has been commonly observed in ancient evaporites. This is where pseudomorphous replacement takes the form of a void lining cement. For example, in the Permian Salado Formation, gypsum molds that exquisitely preserve the "swallow-tail" twin morphology are lined with an isopach-

ous, euhedrally-terminated fringe of anhydrite and polyhalite, which, in turn, are covered by a void-filling halite cement (Figure 17; see also Schaller and Henderson, 1932, Plate 9). These spectacular features demonstrate that gypsum was first dissolved without destroying the external form of the gypsum crystals and the mold was then filled successively by precipitation of anhydrite then polyhalite and then halite. This sequence provides important information on the nature and composition of cement-depositing brines (Lowenstein, 1983), but the timing of the cementation is unresolved.

Far more attention needs to be paid to cements in evaporite diagenesis studies.

#### Temperature Dependent Salts

The use of salts that have restricted temperature stability ranges is an attractive option in deciding a syndepositional or burial origin. However, a difficulty arises here because there is a large overlap in temperatures experi-



**Figure 17.** Thin section photograph of a vertically oriented gypsum "swallow-tail" twin pseudomorph with void-filling cement texture. Proceeding inward from the pseudomorph rim to the core is: (1) a mud band (arrow), (2) anhydrite stubby prism lining (A), (3) microcrystalline polyhalite lining (P), (4) inward projecting polyhalite prisms with euhedral terminations, and (5) a clear halite core. This cement texture is interpreted as having formed after a gypsum crystal dissolution event, with a relative mineral precipitation sequence of anhydrite  $\rightarrow$  polyhalite  $\rightarrow$  halite. Sample from Salado Fm. laminated anhydrite/polyhalite rock. Scale bar is 1 mm long.

enced by primary depositional environments and secondary burial environments. While brines in modern evaporite settings typically remain at temperatures below 40°C the year around (e.g., Persian Gulf sabkha, Butler, 1970a, p. 125), temperatures near 50°C due to solar heating have been measured in shallow stratified brine ponds (Hudec and Sonnenfeld, 1974) and values of over 100°C

are reached in hot spring brine pools (Holwerda and Hutchinson, 1968). Temperatures of surface sediments on salt flats commonly go above 50°C in the summertime (e.g., Butler, 1970b). In the normal geothermal gradient temperatures of 50°C are reached at about 900 m depth and 100°C at about 2400 m depth. This overlap in environment temperatures means that "high temperature"

salts such as langbeinite, loewite, vanthoffite, etc., stable only at temperatures greater than 40° to 50°C (Stewart, 1963, Figure 10), could be of either syndepositional or burial origin. Nonetheless, despite this ambiguity, the presence of such salts in a deposit tell us that temperatures were above at least 40° to 50°C (they are "minimum temperature" geothermometers). This should at least raise the possibility that the deposit had undergone burial metamorphism because temperatures over 40°C are not the norm in modern surface brine bodies. In contrast the absence of these "high temperature" salts suggests preservation of a low temperature syndepositional mineral assemblage. But here too there is considerable uncertainty because brine composition and stage of brine evolution may have been such that the stability fields of these minerals were never reached even though the temperatures may in fact have been high enough.

These "high temperature" salts have been found in many of the world's potash deposits as (1) unbedded fine- to coarse-grained mosaic patches composed of anhedral crystals, (2) isolated nodules consisting of single crystals or crystalline mosaics and (3) isolated euhedral crystals. Most important of the magnesium sulfate "high temperature" minerals is langbeinite which is found in minable amounts in several evaporites (Rempe, 1982). Spectacular examples of large (cm scale) isolated langbeinite tetrahedral crystals that record a partly displacive partly incorporative growth style occur in the Miocene of Russia (Lobanova, 1953), Permian of Germany (Borchert and Muir, 1964, Figure 20) and Permian of New Mexico (Figure 14, see also Rempe, 1982; Lowenstein, 1983).

Finally, the question of the actual temperatures of formation can be tackled directly using fluid inclusions (see appropriate sections above and the Appendix), but even here we have difficulties. Low homogenization temperatures of inclusions (below 40° to 50°C) in salts with syndepositional textures appear to be accurate and reliable and support a low temperature primary origin for the host (e.g., the Salado halite measurements of Roedder and Belkin, 1979; see also p. 1183-84). Very high filling temperatures of over 100°C, while almost certainly inaccurate (p. 1188), clearly point to substantial burial. Intermediate homogenization temperatures (50° to 100°C) raise difficulties in interpretation, not only because of the environment temperature overlap discussed above, but because of the unreliability of the measurements (pp. 21-22). For example, in the Devonian Prairie halite Hartzell (1963) measured temperatures of between 51°C and 104°C in more than 400 inclusions. Yet these halites exhibit excellently preserved chevron and cornet fabrics typical of primary halites. It is possible that heating on burial has caused the primary inclusions to stretch (see p. 1188 and Roedder and Belkin, 1979) without obliterating the origin syndepositional fabrics. The filling temperatures would then reflect the burial temperatures, but the

host would still retain its primary depositional texture criteria.

## CONCLUDING REMARKS

In this paper we have tried to draw together a preliminary set of criteria for distinguishing syndepositional from burial alteration features. We have mainly tried to utilize advances made recently in understanding syndepositional features of modern evaporites. But the problem remains a good way from resolution, as should be clear from our rather sketchy compilation. Some of the shortcomings of our treatment lie in our lack of first-hand knowledge of many of the great deposits of the world. Nonetheless, we hoped that in committing our rather limited ideas to paper we would prod other workers into searching for better and more comprehensive solutions to this crucial question. The spirit behind our effort is the belief that a full confrontation of this problem should be an absolute priority in any evaporite study of any kind. Without first deciding which features are syndepositional, which are due to burial alteration and which are ambiguous, how can we confidently interpret depositional history, geochemical history, source of inflow waters, hydrologic events, etc. of an ancient evaporite basin? Certainly we can say nothing of the chemistry of ancient oceans and lakes unless we resolve this matter. The danger is especially obvious in the practice of using chemical tracers such as isotopes and trace elements to unravel evaporite origin and history without prior resort to an exhaustive petrographic analysis to delineate syndepositional from burial features.

## ACKNOWLEDGMENTS

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## APPENDIX

*The Use of Fluid Inclusions in Evaporite Studies*  
by R. J. Spencer

## INTRODUCTION

Useful information on evaporite mineral origins may be obtained from fluid inclusions. In addition to defining some of the positive petrographic evidence for syndepositional or burial evaporites, fluid inclusions are present in crystals the origin of which may be ambiguous on the basis of petrographic criteria. For example, crystals formed by intrasediment growth or as void filling cements may contain inclusions that will allow these crystals to be identified in terms of a syndepositional or burial origin. A variety of tests are available which help to decide the origin of the fluid in inclusions; hence the origin of the enclosing evaporite mineral. These tests, mainly involving heating,

freezing and crushing behavior, are outlined below. Details of fluid inclusion methods may be found in Roedder (1962, 1963, 1970, 1972) and Hollister and Crawford (1981).

### PRIMARY AND SECONDARY FLUID INCLUSIONS

The existing terminology on fluid inclusions includes primary and secondary inclusions. In the present context of distinguishing between primary and secondary evaporites these fluid inclusion terms may be confusing so care must be taken with their use. Primary inclusions are inclusions that form at the time of crystal growth, be it syndepositional or post-burial (herein lies the potential for confusion). Secondary inclusions are inclusions which form in a crystal after the crystal has grown; these may be syndepositional or post-depositional. Criteria for recognition of primary and secondary fluid inclusions have been discussed by Roedder (1976, 1979, 1981). The reader is referred to Roedder (1981, p. 135-137) for a summary of petrographic criteria used to distinguish primary from secondary inclusions.

### FLUID INCLUSION MICROTHERMOMETRY

The most common usage of fluid inclusions is in the area of microthermometry. This technique consists of measuring the temperature of phase transitions within an inclusion using a heating/cooling stage. Fluid, trapped in a crystal as the crystal grows, or introduced along fractures after a crystal forms, is isolated by the enclosing crystal. A given volume of fluid is therefore contained in a given volume within the crystal. The changes in volume of solid crystals are generally much less dependent on temperature than the volume of fluids (Figure 18). Therefore, assuming that the volume of an inclusion remains constant after it forms and that the material within the inclusion remains isolated, cooling of the inclusion will result in the shrinkage of the fluid. This results in the formation of two phases (liquid-vapor) within the inclusion. Upon reheating, the fluid within the crystal will expand and eventually refill the inclusion with a single fluid phase. The temperature at which this occurs (temperature of homogenization) gives an indication of the temperature at which the fluid was trapped.

In addition to liquid-vapor two phase inclusions, one or more solid phases may be present in an inclusion (Figure 19). The solids may have been trapped as the inclusion formed (included crystals) or may have grown from the trapped fluid within the inclusion (daughter crystals). Daughter crystal-fluid homogenization in some instances yields reliable data on the temperature of formation of inclusions. Difficulty in distinguishing included from daughter crystals, the sluggishness of many fluid-solid reactions and metastability in fluid-solid interactions cause fluid-solid homogenization to be less reliable than liquid-vapor homogenization in determining the temperature of formation of inclusions.

A second type of microthermometric measurement is that of the temperature of melting after the fluid in an inclusion has been frozen. Two points on the melting curve are generally determined, the temperature of first melting is used to estimate the component salts in solution; this temperature, depending on the ability to observe initial melting, should represent the eutectic melting point for the system. Some of the eutectic tem-

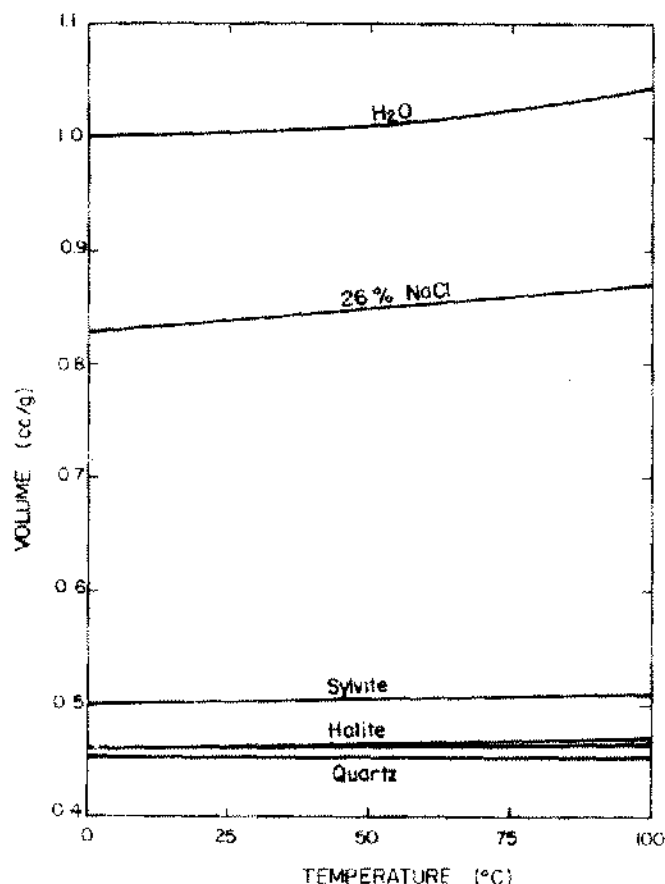


Figure 18. Changes in volume for a constant mass as a function of temperature are shown for quartz, halite, sylvite, water and a 26% NaCl solution.

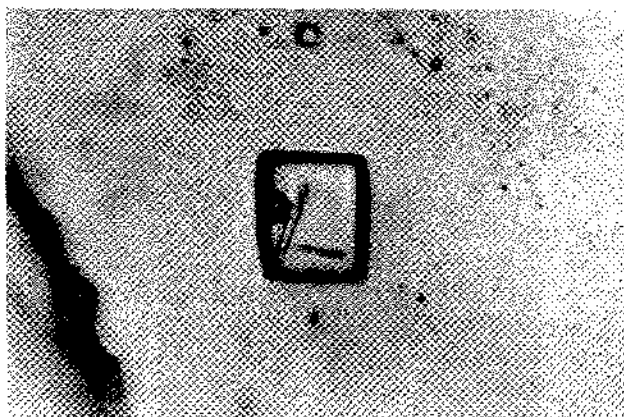
peratures for chloride salts in aqueous solution are given below (after Crawford, 1981).

KCl	-10.6°C	KCl-NaCl	-22.9°C
NaCl	-20.8°C	MgCl <sub>2</sub> -NaCl	-35°C
	(metastable -26°C)		
MgCl <sub>2</sub>	-33.6°C	CaCl <sub>2</sub> -NaCl	-52.0°C
CaCl <sub>2</sub>	-49.8°C	MgCl <sub>2</sub> -CaCl <sub>2</sub> -NaCl	-57°C

Most fluids encountered in evaporite brines will contain the four major cations  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and chloride as well as sulfate and bicarbonate-carbonate in varying amounts.

The second temperature point measured on the melting curve is the temperature of final melting. The temperature of final melting enables the estimation of the concentration of salt in solution. The eutectic system  $\text{H}_2\text{O}$ - $\text{NaCl}$  shown in Figure 20 will be used to illustrate the estimation of concentration. A frozen inclusion in this system would contain ice plus  $\text{NaCl} \cdot 2\text{H}_2\text{O}$ ; first melting would be observed at about  $-20.8^\circ\text{C}$ . Warming above this temperature would require either all of the  $\text{NaCl} \cdot 2\text{H}_2\text{O}$  to melt (if the system contains  $< 23.3\%$  NaCl) or all of the ice to melt (if the solution contains  $> 23.3\%$  NaCl). Continued warming of the inclusion will result in the remaining phase (ice or  $\text{NaCl} \cdot 2\text{H}_2\text{O}$ ) melting; the final melting temperature of ice will yield a composition along curve A (Figure 20), the final





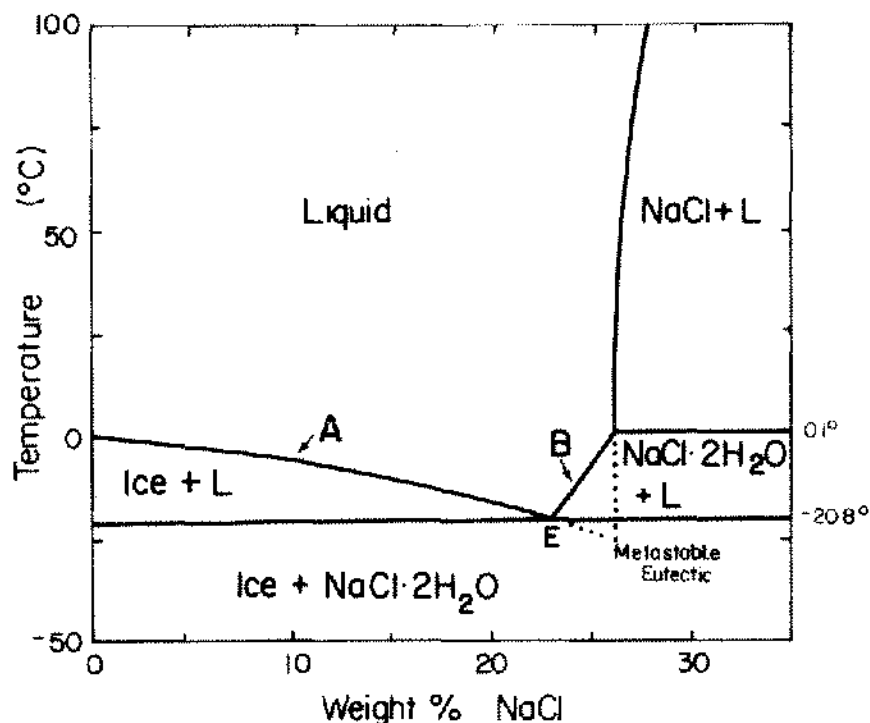
**Figure 19.** Fluid inclusion in halite from the Permian Salado Fm., Bed 119, showing three phases liquid-vapor-solid (anhydrite?). Inclusion is approx. 0.05 mm in length.

ber of gas clathrates may form. Some of the phases that may be present as the last melting solid from evaporite inclusions are listed below.

Ice— $\text{H}_2\text{O}$	Clathrates
Hydrohalite— $\text{NaCl} \cdot 2\text{H}_2\text{O}$	$\text{CO}_2$
Antarcticite— $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$	$\text{CH}_4$
Natron— $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$	
Mirabilite— $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$	

### CRUSHING BEHAVIOR

A relatively seldom used but powerful tool in fluid inclusion work is the crushing stage. The crushing stage allows the observation of an inclusion as it is opened to atmospheric pressure (Roedder, 1970). The grain containing the inclusion is placed in oil between two glass plates and observed as pressure is applied to crack the grain. Two phase

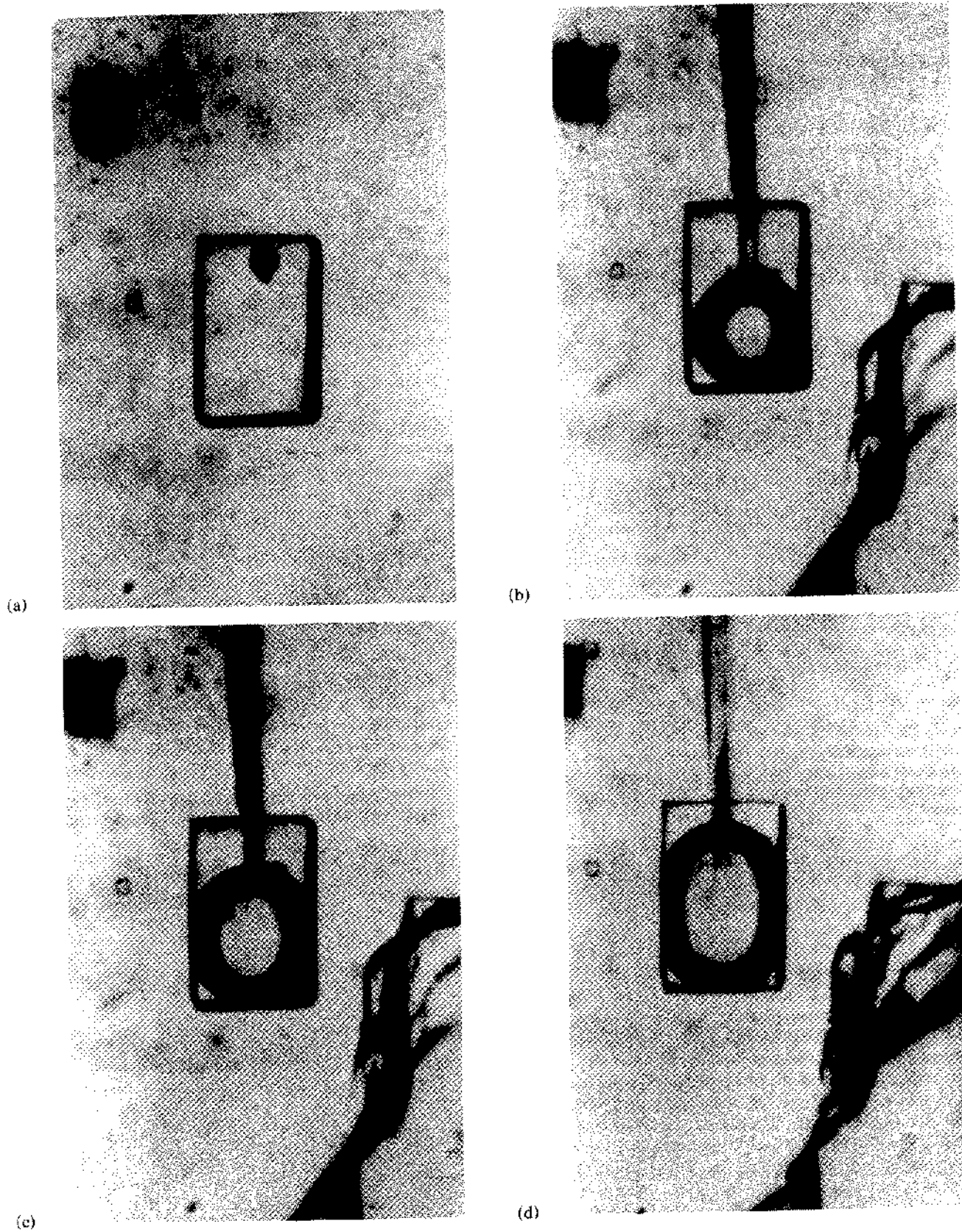


**Figure 20.** The  $\text{H}_2\text{O}$ - $\text{NaCl}$  eutectic system. The eutectic (E) is at  $-20.8^\circ\text{C}$  and the co-existing phases are ice,  $\text{NaCl} \cdot 2\text{H}_2\text{O}$  and an aqueous solution. Systems containing  $< 23$  weight-percent  $\text{NaCl}$  follow curve A above the eutectic temperature while systems containing  $> 23$  weight percent  $\text{NaCl}$  follow curve B. After Crawford (1981).

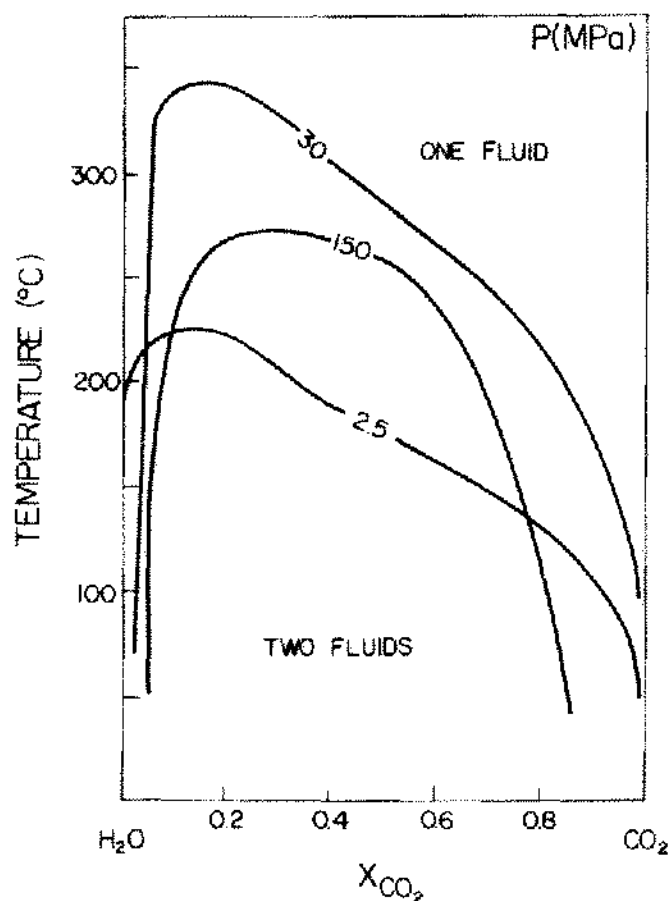
melting temperature of  $\text{NaCl} \cdot 2\text{H}_2\text{O}$  will yield a composition along Curve B (Figure 20). It is important to identify the phase that is melting (a final melting point of  $0^\circ\text{C}$  or  $+0.1^\circ\text{C}$  with ice melting indicates 0%  $\text{NaCl}$  in solution, while with  $\text{NaCl} \cdot 2\text{H}_2\text{O}$  melting there is 26.3%  $\text{NaCl}$  in solution). In practice this is not always possible as a variety of low temperature hydrated salts may form from multicomponent systems. In addition, a num-

ber of gas clathrates may form. Some of the phases that may be present as the last melting solid from evaporite inclusions are listed below.

1. the vapor shrinks and disappears
2. the vapor expands
3. the vapor does not change or shrinks slightly but remains.



**Figure 21.** Time sequence photos showing vapor expansion upon cracking under the crushing stage of two phase vapor-liquid inclusion in halite from the Permian Salado Fm., New Mexico (Bed 119, McNutt zone). (A) inclusion with gas under pressure prior to cracking. (B) crack entering inclusion and beginning of vapor expansion. (C) continued expansion of the vapor. (D) final stage 35 seconds after cracking. Long side of the inclusion is 0.1 mm.



**Figure 22.**  $\text{H}_2\text{O}-\text{CO}_2$  solvus as a function of temperature and mole fraction of  $\text{CO}_2$  ( $X_{\text{CO}_2}$ ) at three different pressures (bars). Above each solvus a single fluid phase is present but below the solvus two phases, one rich in  $\text{H}_2\text{O}$  the other in  $\text{CO}_2$ , are present.

The first case of the vapor shrinking and disappearing indicates a "normal shrinkage bubble" formed due to the decrease in fluid volume on cooling of an inclusion. The pressure in the vapor was less than atmospheric pressure.

The second case where the vapor expands on cracking of the inclusion indicates a noncondensable gas under pressure (Figure 21). This is usually the result of variable fluid immiscibility in systems containing a solvus. An example of such a system is  $\text{CO}_2-\text{H}_2\text{O}$  (Figure 22). An inclusion formed from a single fluid along or above the solvus will contain two immiscible phases ( $\text{H}_2\text{O}$ -rich and  $\text{CO}_2$ -rich) at room temperature. The  $\text{CO}_2$ -rich phase may be a gas under pressure or a liquid or both. Upon cracking this phase will expand. In addition to  $\text{CO}_2-\text{H}_2\text{O}$  systems other aqueous-gas mixtures ( $\text{CH}_4-\text{H}_2\text{O}$ ,  $\text{H}_2\text{S}-\text{H}_2\text{O}$ , etc.) may result in similar behavior. Additionally, a vapor may form under pressure due to reactions within an inclusion after trapping. Organic material trapped in an inclusion may be altered to  $\text{CO}_2$  or  $\text{CH}_4$  within the inclusion, forming vapor under pressure.

The third case of the vapor remaining at its initial size or decreasing slightly upon cracking indicates either leaking or initial two phase liquid-vapor trapping to have occurred. In either

case, erroneously high homogenization temperatures would be obtained from heating this type of inclusion.

### COMPLETE ANALYSIS

Ideally, the behavior of a single inclusion on heating, freezing and crushing should be observed. If this is attempted, heating should be observed first, followed by freezing and then crushing. It is necessary in measuring homogenization temperatures that the integrity of an inclusion be maintained. Inclusions often crack on freezing and are unsuitable for further study after crushing. It may be more practical to divide a crystal into three samples and examine petrographically similar inclusions with each technique.

### SUMMARY

Useful information on evaporite crystal origin may be obtained from fluid inclusions. In addition to petrographic criteria, criteria developed using heating, freezing and crushing observations are helpful. Criteria for primary and secondary evaporitic inclusions are listed in the text. A suggested methodology for using the criteria is to first consider unambiguous petrographic criteria to determine the primary or secondary origin of the crystal. Primary evaporite crystals may contain primary and/or secondary evaporite inclusions. Secondary evaporites should contain only secondary evaporite inclusions. Those crystals which have ambiguous origins on the basis of petrographic evidence may be classified on the basis of inclusion criteria. If a crystal contains primary evaporite inclusions it should probably be considered as a primary evaporite. If only secondary evaporite inclusions are present as primary fluid inclusions the crystal is probably of secondary evaporite origin.

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