
INTRODUCTION

Textural studies of halites formed in modern saline pans (Shearman 1970; Handford 1982; Orti-Cabo et al. 1984; Lowenstein and Hardie 1985) have formed the basis for refined interpretations of the depositional settings in which ancient halite rocks accumulated (for example, Holdaway 1978; Handford 1981; Lowenstein 1982, 1988; Presley and McGillis 1982; Brodylo and Spencer 1987; Czapowski 1987; Hovorka 1987; Moretto 1987; Dumas 1988). There are, however, dramatic textural differences between modern porous halite crusts and tightly cemented buried halites (Fig. 1). This paper is concerned with the diagenetic processes responsible for converting halite sediments into halite rocks.

Studies of modern halites have established that syn depositional-diagenetic modification of halite layers may be extensive (Shearman 1970; Handford 1982; Lowenstein and Hardie 1985). Important early-diagenetic features include dissolution cavities, void-filling clear halite cements, and displacive crystals of halite. There is no published information, however, on the formation of similar diagenetic features in halites buried to depths below approximately one meter.

The purposes of this paper are (1) to summarize the petrographic textures of modern saline pan halites to document syndepositional features: (2) to describe the petrographic features of shallow-buried (up to 200 m) Quaternary halites to document shallow-burial diagenetic processes; and (3) to compare ancient halite rocks of the Permian Salado and Rusler Formations with modern and shallow-buried halites to establish the approximate time, in terms of burial depth, over which diagenetic features in the ancient halites may have formed. Studies of ancient halite rocks indicate that saline pan deposits are abundant in the geologic record (see references above). Therefore, the results derived from this study may have widespread applicability.

GEOLOGIC SETTING AND GENERAL DESCRIPTION OF MODERN SALINE PAN HALITE, QUATERNARY HALITE, AND PERMIAN HALITE

Modern Saline Pan Halite

Modern saline pan halites from the non-marine closed basin of Saline Valley, California and from the marginal marine Salina Omotepec, Baja California, Mexico were studied in detail (Fig. 2A). The saline pan of Saline Valley is about 5 km² in area and occurs in the topographically lowest part of the closed basin. The saline pan is floored by layered salts and is surrounded by a brine-saturated saline mudflat that contains crystals of evaporite minerals. The saline mudflat grades outward into a dry mudflat, a sandflat, and finally into alluvial fans (Hardie 1968; Hardie et al. 1978). Hand samples and box cores taken from depths of < 0.3 m along a north-south transect across the saline pan (June-July, 1986) were studied petrographically. The saline pan of Salina Omotepec is less than 10 km² in area and is located in a shallow depression.
DIAGENESIS OF SALINE PAN HALITE: COMPARISON OF PETROGRAPHIC FEATURES OF MODERN, QUATERNARY AND PERMIAN HALITES

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ABSTRACT: Petrographic studies of modern saline pan halites (Saline Valley, CA; Salina Omotepec, Baja California, Mexico) and Quaternary shallow-buried (0–200 m) halites (Saline Valley, CA; Bristo Dry Lake, CA; Searles Lake, CA; Qarhan saline pan. Qaidam Basin, China; Lake Uyuni, Bolivia) show that the diagenetic modification of halite begins contemporaneously with deposition, is most intense within the upper few meters of burial, and is essentially complete within the first 45 m of burial. Halite crusts from modern saline pans that have undergone repeated episodes of flooding, evaporative concentration, and desiccation contain abundant syndepositional diagenetic features. These "mature" halites are dominated by dissolution features and fabrics (formed during flood stages) and cementation features (formed during desiccation stages). Interlayered mud beds contain varying amounts of displacive halite crystals.

At shallow burial depths, halites retain many textural features of "mature" modern saline pan halite. Halites below the first few meters are no longer susceptible to dissolution from floodwaters but continue to be cemented by clear halite. Within the first 10 m of burial, cementation reduces the porosity of halite crusts to less than 10%. The remaining pore spaces are completely filled by burial depths of approximately 45 m. Displaceable growth of halite in muds continues at shallow-burial depths and is probably limited to the first few tens of meters of burial depth. The mechanisms for cementation and displacive growth of halite at shallow-burial depths probably include (1) evaporative concentration of groundwater brines and (2) cooling of surface brines when they sink below the sediment surface.

Undeformed halites from the Permian Salado and Rustler Formations of New Mexico contain delicate syndepositional textures and abundant clear halite cements that are comparable to those observed in modern saline pan halites and shallow-buried halites. The Permian halites are interpreted to have undergone a depositional and early diagenetic history similar to the modern and Quaternary analogs.

Complete cementation of saline pan halites at shallow burial depths has important implications for the origin of saline formation waters in sedimentary basins. Parent evaporite brines may not be stored in the pores of halite rocks and later expelled during burial compaction if the rocks are cemented early, and tightly crystallized halite rocks may also impede the downward migration of dense syndepositional brines.

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Studies of modern halites have established that syndepositional-diagenetic modification of halite layers may be extensive (Shearman 1970; Handford 1982; Lowenstein and Hardie 1985). Important early-diagenetic features include dissolution cavities, void-filling clear halite cements, and displacive crystals of halite. There is no published information, however, on the formation of similar diagenetic features in halites buried to depths below approximately one meter.

The purposes of this paper are (1) to summarize the petrographic textures of modern saline pan halites to document syndepositional features; (2) to describe the petrographic features of shallow-buried (up to 200 m) Quaternary halites to document shallow-burial diagenetic processes; and (3) to compare ancient halite rocks of the Permian Salado and Rustler Formations with modern and shallow-buried halites to establish the approximate time, in terms of burial depth, over which diagenetic features in the ancient halites may have formed. Studies of ancient halite rocks indicate that saline pan deposits are abundant in the geologic record (see references above). Therefore, the results derived from this study may have widespread applicability.

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Modern Saline Pan Halite

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of the supratidal flat. It grades landward successively into mudflat, sandflat, and alluvial fan sub-environments (Thompson 1968; Shearman 1970; Castens-Seidell and Hardie 1984). Seaward, the saline pan is bordered by saline mudflat and tidal flat sub-environments. Samples of halite were collected from the saline pan in January, 1982 and January, 1983. Halite from other saline pans, including Carlsbad Lake, NM; Great Salt Lake, UT; and Death Valley, CA, was also examined (Lowenstein and Hardie 1985). The saline pans and surrounding saline mudflats examined contain halite as 1) layered halite crusts, 2) displacive halite crystals in mud layers, and 3) surface efflorescent crusts. Efflorescent crusts will not be discussed in detail because they are ephemeral features that are not preserved below the surface. Modern saline pan halite is characterized by porous centimeter- to decimeter-thick halite crystals that are separated from one another by sharp planar surfaces or by millimeter- to centimeter-thick partings of siliciclastic mud (Saline Valley) or gypsum (Salina Omotepec). Individual halite crystals are distinguished by variations in the texture and fabric of halite crystals and by the shape of voids (Fig. 1A). Most commonly, crusts consist of centimeter-sized crystals of halite with abundant fluid-inclusions (chevron halite with a vertical fabric) and clear halite crystals relatively devoid of fluid inclusions. Modern saline pan halite crusts contain abundant cavities and can have porosities in excess of 50% (Fig. 3; Lowenstein and Hardie 1985).

Muds interlayered with halite crusts in the saline pan, as well as in the surrounding saline mudflat, may contain crystals of displacive halite (Gornitz and Schreiber 1981; Handford 1982; Lowenstein and Hardie 1985). Halites in muddy sediments from Saline Valley are subhedral to euhedral, randomly-oriented cubes that range in abundance from isolated crystals to aggregates of halite crystals surrounded by mud. The amount of displacive halite in near surface mud layers may be considerable. Locally the amount of displacive halite may equal the amount of mud.

**Shallow-Buried Halite**

Several arid closed basins in the southwestern U.S. contain thick Quaternary halite deposits. For example, layered halites are found in Saline Valley (over 100 m, J. Crowley, unpubl. data), Bristol Dry Lake (over 300 m, Bassett et al. 1959), and Searles Lake (over 400 m, Smith et al. 1983). The textural features of shallow-buried halites were studied in detail from samples recovered in 6 cm wide borehole cores from Saline Valley and Bristol Dry Lake at depths of up to 200 m (Fig. 2A, B). Cores from Saline Valley and from Bristol Dry Lake were taken at the floors of the valleys where modern saline pan and saline mudflat sub-environments exist. The age of these deposits is not known. However, age dating of similar evaporite deposits from nearby Searles Lake indicate that sediments buried to depths of 230 m are approximately 1 m.y. old (Searles Lake sediments dated using paleomagnetic methods, Smith et al. 1983; 14C dating, Phillips et al. 1983). Thus, the shallow-buried halites studied are probably Quaternary (Holocene and Pleistocene) deposits. General descriptions of the cores were reported by J. Crowley et al. (1959, Bristol Dry Lake). The cores are composed of centimeter- to meter-thick layers of evaporites, mud, and subordinate sands and gravels. Additional core samples of shallow-buried Quaternary halites were examined from Searles Lake, CA (< 31 m depth), Qarhan saline pan, Qaidam Basin, China (< 12 m depth) and Lake Uyuni, Bolivia (6 m depth).

Shallow-buried halite, as seen in the cores, may be structureless or may be composed of centimeter thick layers of halite separated by millimeter- to centimeter-thick siliciclastic mud partings. Mud partings are commonly disrupted, and in some cases they are completely intermixed with subhedral to euhedral, randomly-oriented halite crystals and crystal masses (top of Fig. 4). Individual crystals of halite may contain fluid-inclusion banding, or they may consist of only clear halite. Most commonly, halite layers are dominated by clear-halite crystals that contain patches of fluid-inclusion banded halite (bottom of Fig. 4).

Shallow-buried halite layers show a marked decrease in porosity with depth (Fig. 3). In contrast to surface halite crusts with porosities commonly in excess of 50%, halite layers near 10 m from Saline Valley (as well as Searles Lake, Qarhan playa, and Lake Uyuni) have porosities of less than 10%. Halite layers from Saline Valley are tightly cemented and contain no visible porosity at all depths below about 45 m.

Siliciclastic mud layers are structureless and commonly contain subhedral to euhedral halite crystals (Fig. 5). Mud is commonly included within halite crystals, and fluid inclusion-rich patches are present in some crystals. Mud intervals may contain large amounts of halite. The volume of halite can even exceed the volume of siliciclastic mud. In these cases the halite consists of clear equant crystals with incorporated mud. Mud occupies the interstices between crystals, ranging from isolated millimeter-sized patches, to thin linings separating crystals, to large, isolated, centimeter-sized pockets.

**Permian Halite**

The Salado and Rustler Formations are part of the Permian Ochoan Series of west Texas and New Mexico (Fig. 2A, C), a sequence up to 1,300 m thick dominated by evaporites and capped by siliciclastic red beds (Jones 1972). Both formations underlie an area of about 150,000 km² and contain bedded halite in the subsurface. The Salado evaporites are up to 700 m thick and are composed of generally undeformed flat-lying beds of halite, muddy halite, anhydrite-polyhalite, dolostone, mudstone, and potash salts (Lowenstein 1988). The Rustler Formation is up to 150 m thick and consists of halite, muddy halite, gypsum, anhydrite, dolostone, and siliciclastic mudstone and sandstone (Lowenstein 1987). Halites examined from the Salado Formation were obtained from underground
HALITE LAYERS ARE STRUCTURELESS OR BEDDED. WITH CENTI-

METER-TO DECIMETER-THICK HALITE LAYERS SEPARATED BY PART-

INGS OF SILICICLASTIC MUDSTONE, ANHYDRITE OF POLYHALITE (FIG.

1B). HALITE CRYSTALS ARE GENERALLY CLEAR, BUT PATCHES WITH

CLOUDY, FLUID-INCLUSION BANDED CHEVRONS ARE NOT

UNCOMMON (FIG. 6). THE HALITE ROCK IS TIGHTLY CEMENTED AND

CONTAINS NO VISIBLE POROSITY. HALITE BEDS WITH ABUNDANT

MUDSTONE (MUDDY HALITE) COMMONLY-contain anhedral to
euhedral centimeter-sized cubes of displacive halite, as
isolated crystals or as halite crystal aggregates (FIG. 7).
The surrounding mudstone matrix is structureless, but in
places irregularly shaped pockets and disrupted lenses of

mudstone occur.

DEPOSITION AND SYNPEDOTIONAL DIAGENESIS OF
MODERN SALINE PAN HALITE

LOWENSTEIN AND HARDIE (1985) use the saline pan cycle
to interpret the processes responsible for the production
of modern halite crusts and interlayered muds. The saline
pan cycle is summarized below because it provides a basis
for interpreting the shallow-buried and Permian halites.
The saline pan cycle consists of a flood stage, a saline lake
stage, and a desiccation stage. During the flood stage,
dilute floodwaters (marine or non-marine) become pond-
ed on the saline pan and dissolve the underlying halite

crusts. The textural features produced during the flood

stage include (1) a horizontal truncation surface formed
where floodwaters dissolve the surface halite crust(s) (FIG.
8); (2) cavities formed by dissolution where undersatu-
rated waters percolate through halite crusts (FIG. 1A, 8);
and (3) mud partings formed by the settling of muds from
suspension (FIG. 1A). Mud may be washed in by floods
or may be locally derived by reworking of mud from
dissolved halite layers. The muds drape the truncation
surface and settle into dissolution cavities where they may
form a layer of internal sediment. The combination of
dissolution of halite and evaporative concentration cause
the ephemeral lake to reach saturation with respect to
halite (saline lake stage). Halite initially crystallizes at the
brine-air interface as (1) millimeter- to centimeter-di-
ameter, skeletal, inverted-pyramidal hopper crystals; (2)
millimeter-diameter, square to rectangular shaped plates;
and (3) coalesced aggregates of hoppers and plates forming
rafts (ARTHURTON 1973; LOWENSTEIN AND HARDIE 1985. fig-

Fig. 1A.—Hand sample of modern saline pan halite (Saline Valley, CA). Scale bar is 5 cm long.
FIG. 1B.—Core sample of ancient buried halite (Permian Salado Formation, NM). Scale bar is 5 cm long. The modern halite crusts are porous and layered (layering defined by partings of mud as well as differences in halite crystal textures and pore shapes). The Permian halite contains no porosity. The thin layers at the top and bottom of the Permian sample are polyhalite.

Figures 10-12). These surface-nucleated crystals settle to the bottom of the brine pool, where they may form a loose pile of "cumulate" crystals. Halite crystals on the floor of the saline lake are commonly overgrown by bottom-precipitated halite. Competitive overgrowth on crystals at the lake bottom produces millimeter- to centimeter-long, vertically-oriented, elongate chevron halite crystals that contain alternating bands of fluid-inclusion rich halite and clear, fluid-inclusion poor halite (Figs. 8: see also Shearman 1970, figures 3, 5A; Lowenstein and Hardie 1985, figures 2, 12, 14). Continued evaporation of the saline lake causes the brine level to drop below the saline pan surface to form a perennial groundwater (desiccation stage). Halite continues to precipitate from the groundwater brine as (1) clear, euhedral, void-filling cements

<table>
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<td></td>
<td>BR-2</td>
<td>307 m</td>
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Fig. 2.—A) Location map of the evaporite deposits studied in detail: Saline Valley, CA; Bristol Dry Lake, CA; Salina Omotepec, Baja California, Mexico; Salado Formation and Rustler Formation, NM-TX. B) Depths of shallow-buried halites studied. C) Stratigraphic section of the upper Permian Ochoan Series.
SHALLOW-BURIED QUATERNARY HALITE
Syndepositional Textures and Fabrics

Shallow-buried halites from all the cores studied contain textures interpreted to be syndepositional in origin, including (1) dissolution features produced by contact of halite with undersaturated surface waters (flood stage), and (2) crystal growth textures and fabrics diagnostic of precipitation from a standing body of halite saturated brine (saline lake stage).

The most prominent syndepositional dissolution features are near-horizontal surfaces that truncate fluid-inclusion banding of the underlying chevron halite crystals. Horizontal truncation surfaces are directly overlain by a mud parting, by fine cumulate halite crystals, or by chevron halite. Syndepositional solution cavities are identified as near-vertical fingers of clear halite that crosscut layered chevron halites (Fig. 11). Individual fluid-inclusion banded chevrons on the margins of solution cavities may be truncated (Fig. 12). A thin layer of mud (internal sediment) may separate the truncated fluid-inclusion banded halite from the surrounding clear halite. All of the solution features described above are widely recognized in halite layers of modern saline pans (Figures 1A, 8, 9; Lowenstein and Hardie 1985, figures 2–8).

Halite layers commonly contain fluid-inclusion banded chevrons and fine cumulate crystals precipitated in a saline lake. Chevrons are readily identified by their vertical fabric and by the patches of fluid-inclusion banding in the cores of crystals (Figs. 4, 12). Cumulate layers are composed of fine-grained (sub-millimeter to millimeter size), unoriented, well-sorted crystals of halite. Rafts are recognized in cumulate layers as laterally-linked, sub-horizontal crystal aggregates (Fig. 13).

Diagenetic Features

The shallow-buried halites examined contain two major types of diagenetically formed halite: (1) clear halite cements, and (2) displacive halite in mud layers. Cements at shallow burial depths consist of clear halite crystals that fill open cavities or intercrystalline pore spaces. At depths of less than a few tens of meters, where cementation is incomplete, clear halite crystal overgrowths contain euhedral terminations into open voids (Fig. 14). The pore spaces in these shallow-buried halites thus become angular in shape. At greater depths of burial, where cementation is virtually complete, halite cements consist of a mosaic of clear halite crystals. These clear halite cements are most easily identified where they fill a cavity. In these cases a sharp contact separates the truncated chevron halite framework from the clear halite cavity-filling cement (Fig. 11, 12; see also Shearman 1970 and Lowenstein and Hardie 1985).

Mud-rich intervals contain abundant crystals of displacive halite with incorporated mud (Fig. 5). These crystals are identical to those found in near-surface mud layers of modern saline pans and saline mudflats. They are diagenetic crystals that grow in situ within brine-soaked muds.
Aggregates of finer grained, anhedral to subhedral halite also occur in muddy intervals. These crystals, however, probably represent remnant fragments of halite crusts preserved in mud rich layers.

A major question about the diagenetically-formed halite in Quaternary deposits from Saline Valley and Bristol Dry Lake is whether it formed syndepositionally or formed during burial. The question of timing may not be resolved by petrographic study because of the difficulty in distinguishing syndepositional cements and syndepositional displacive crystals from those formed during burial (Hardie et al. 1985). However, indirect evidence in favor of syndepositional and very shallow burial cementation may be obtained from the plot of porosity versus depth (Fig. 3). This diagram shows that most porosity in halite layers is lost by 10 m burial depth and that rapid loss of porosity occurs within the first few meters of burial. It is concluded that early diagenetic cementation by clear halite is entirely responsible for the trend shown in Figure 3. This interpretation is supported by the lack of evidence for compaction in halite layers such as broken or strained crystals, pressure solution boundaries or stylolites, and the fact that primary textures are preserved in an undeformed condition. Once cemented, Quaternary halites buried to depths of 200 m show no petrographic evidence of further diagenetic modification.

Displacive growth of halite within muds is also interpreted to occur predominantly in the uppermost few me-
Fig. 5.—Thin section photograph, as seen in plane light, of displacive halite crystals in excess of detrital mud matrix (Saline Valley, CA, a 53.9 m). Displacive halite consists of clear, subhedral to euhedral cubes with abundant intercrystalline mud and patches of fluid-inclusion rich halite (arrows). Scale bar is 0.25 cm long.

Displacive halite consists of clear, subhedral to euhedral cubes with abundant intercrystalline mud and patches of fluid-inclusion rich halite (arrows). Scale bar is 0.25 cm long.

ters (at the near surface), although petrographic evidence is again equivocal. This interpretation is based on (1) the abundance of displacive halite in muds at very shallow burial depths (Fig. 10) beneath some modern saline pans and saline mudflats (i.e., Saline Valley). (2) evidence for abundant near-surface precipitation of halite (cements in interbedded halite layers), and (3) the rapid drop in porosity of halite layers at very shallow burial depths which may block the flow of brine needed to form large volumes of displacive halite at depth.

**Origins of Early Diagenetic Halite**

The large volume of diagenetic halite formed in the shallow subsurface (< 10 m) of modern saline pans may be produced by (1) mixing of brines, (2) evaporative concentration, and (3) cooling of brines.

The mixing of compositionally different brines to produce a new brine that is supersaturated with respect to halite has been proposed as a possible mechanism for the precipitation of halite (Raup 1970). The mixing of MgCl₂ and CaCl₂-rich brines with halite-saturated brines has been shown to be very effective in causing the precipitation of halite (Raup 1970; Lerman 1970). However, analyses of surface brines and interstitial brines from Saline Valley show that they are all similar in composition (Fig. 15). Thus, brine mixing is probably not a viable mechanism for the precipitation of large volumes of diagenetic halite at least for the modern Saline Valley setting.

Evaporative concentration of groundwater brines has been reported from modern saline pans (Valyashko 1972). Experiments by Hsü and Siegenthaler (1969) indicate that shallow groundwaters may be evaporated by the mechanism of evaporative pumping, and replenished by lateral recharge. It is not clear, however, that such a mechanism will produce a groundwater brine supersaturated with respect to halite. Groundwater brines may be drawn to the surface by capillary forces. These brines will evaporate to dryness near the surface and form surface efflorescent crusts. Significantly, the surfaces of modern saline pans typically contain large cracks that bound meter-scale salt polygons. In Saline Valley the cracks penetrate several tens of centimeters below the surface, well below the level of the groundwater brines. Such cracks may provide conduits for direct evaporation of groundwater brines at depth, resulting in the precipitation of diagenetic halite.

Changing brine temperatures from the surface to the shallow subsurface may lead to the precipitation of halite in the shallow subsurface (Foshag 1926). The solubility of halite (in the system NaCl-H₂O) increases slightly with
increasing temperature (by 0.14 moles NaCl/1,000 moles H₂O per °C between temperatures of 20°C and 100°C; Braitsch 1971). In the saline pans studied, shallow surface brines may reach temperatures as high as 70°C by solar heating, especially during the summer months when air temperatures commonly exceed 40°C (pers. observation: Hunt et al. 1966). Evaporative concentration of these surface brines may increase their density and allow them to sink. Once below the sediment surface, the brines will cool and become supersaturated with respect to halite. Groundwater brines from Saline Valley range in temperature from 10°C to 25°C (measurements during November, Crowley, unpubl. data; and February, Hardie 1968). Therefore, a drop in brine temperature from 70°C to 20°C in the system NaCl-H₂O would result in the precipitation of 7 moles NaCl/1,000 moles H₂O or 5.04 g NaCl/kg H₂O. Repetition of this brine cooling cycle, on a daily interval or seasonally, may lead to the precipitation of large volumes of diagenetic halite in the shallow subsurface.

PERMIAN HALITE

Syndepositional Textures and Fabrics

Previous work on halite beds from the Salado and Rustler evaporites has shown that they contain syndepositional features that are comparable to those found in mod-
ern saline pan halite deposits (Lowenstein 1982, 1988; Hardie et al. 1985; Lowenstein and Hardie 1985; Casas 1988). Textures diagnostic of syndepositional dissolution by undersaturated floodwaters include (1) horizontal surfaces that truncate the tops of chevron halite crystals and which are overlain by mudstone, anhydrite, polyhalite or halite (Fig. 16; 2) fingers of clear halite (filled solution cavities) that truncate fluid-inclusion banded chevron halite layers (Fig. 16; and (3) rounded fluid-inclusion bands in the interiors of chevron halite crystals (Hardie et al. 1985; Lowenstein and Hardie 1985). Features that record subaqueous crystallization of halite (saline lake stage) consist of layers composed of vertically aligned fluid-inclusion banded chevrons (bottom of Fig. 6) and less common cumulate layers of fine grained, well sorted cubes and laterally-linked rafts (Fig. 17).

**Diagenetic Features**

The major types of diagenetically-formed halite reported from the Salado and Rustler evaporates are clear-halite cement overgrowths, cavity filling cements (Fig. 6, 16), and displacive halite (Fig. 7) (Lowenstein 1982, 1987, 1988). The cement origin of the clear halite in tightly crystallized ancient halite rocks is discussed by Shearman (1970) and Lowenstein and Hardie (1985). Based on the smooth, curved, sharp boundaries between clear halite and cloudy fluid-inclusion banded halite and the truncated internal banding of the cloudy halite, Lowenstein and Hardie (1985, p. 641) conclude that the clear halite formed by “preferential dissolution along primary grain boundaries, resulting in new intergranular voids and enlargements of existing ones, followed by growth of clear halite cement into these voids.” A major unresolved problem, however, is whether the clear halite in ancient halite rocks formed as an early syndepositional cement or as a later burial cement. The same problem of timing also applies to the formation of displacive halites in muddy layers of ancient halite rocks (Hardie et al. 1985). This study of modern and shallow-buried Quaternary halites suggests that much of the diagenetically-formed halite in the Salado and Rustler evaporites formed early, probably within the first ten meters of burial. This conclusion is based on (1) the striking similarity in the appearance of primary syndepositional features diagnostic of accumulation in a saline pan setting in modern, Quaternary, and Permian halites; (2) the identical textures of diagenetically-formed halites (clear-halite cements and displacive halite) in modern, Quaternary, and Permian halites; (3) the evidence that void spaces in halite layers are rapidly eliminated below the surface of modern saline pans (Fig. 3); (4) the preservation of delicate, undeformed, primary textures in the Permian halites, together with the lack of compaction features such as interpenetrating grains, stylolites, or strained crystals; and (5) rare, direct petrographic evidence of syndepositional dissolution followed by syndepositional-diagenetic growth of clear halite cement in Permian halites. For example, Figure 16 illustrates a
finger of clear halite that sharply truncates layers of fluid-inclusion banded chevron halite. Three layers of muddy internal sediment within the clear halite finger establish that the finger was once an open cavity, and that at least three episodes of mud infiltration followed by growth of clear diagenetic halite took place. Furthermore, the waters that carried the muds into the solution cavity were probably dilute, because the clear halite is smoothed by dissolution along the contact with the muddy internal sediment. These clear halites are not euhedral crystals resembling the clear halite cements that line vugs in modern saline pans (Fig. 9). Such internal sediments that overlie dissolution truncations in clear halite cements leave little doubt about the syndepositional origin of the cements in Figure 16.

**IMPLICATIONS FOR THE ORIGIN OF HIGH SALINITY FORMATION BRINES**

The conclusion that saline pan halites are completely cemented within the first few tens of meters of burial has important implications for the origin of saline formation waters in sedimentary basins. Recent papers discussing the origin of deep formation waters all agree that their high salinities are in some way related to evaporites or their parent brines (Carpenter 1978; Land and Prezbindowski 1981, 1983; Stoessell and Moore 1983; Spencer 1987; Hardie, in review). Three mechanisms for producing the high salinities of deep formation waters are (1) compaction-driven discharge of evaporite parent brines from the void spaces of deeply buried halite rocks (Car-

**FIG. 8.** Thin section photograph, as seen in plane light, of near-surface saline pan halite (< 0.3 m; Saline Valley, CA) with abundant dissolution features, including: (1) horizontal dissolution-truncation surfaces (black arrows) commonly overlain by chevrons, and (2) dissolution voids (clear areas) commonly with curved shapes defined by truncated halite crystals. In the lower half of the photograph the voids form vertically aligned pipes. Dissolution cavities may also crosscut horizontal dissolution-truncation surfaces (white arrow). Scale bar is 1 cm long.
Cementation of halite deposits from the closed basins of the western U.S. at shallow-burial depths effectively arrests compaction and allows the preservation of delicate textures. Similar textures are present in many other ancient halites (for example, Devonian Prairie evaporites of western Canada, Wardlaw and Schwerdtner 1966; Brodylo and Spencer 1987; Permian of Texas Panhandle, Handford 1981; Presley and McGillis 1982; Hovorka 1987) indicating that they, too, have apparently undergone similar depositional and early-diagenetic histories.

Such buried halites, if cemented at shallow burial depths, cannot store large volumes of the parent brines from which they formed. Thus, mechanisms for producing deep formation brines by expulsion of brines from the pores of buried halites must be re-evaluated (Carpenter 1978).

The formation of tightly cemented halite rock at very shallow-burial depths also places constraints on models that produce formation brines by downward migration of dense syndepositional brines (Spencer 1987; Hardie, in review). Spencer (1987) established that the volume of residual evaporite brines that were parent waters of the Prairie evaporites is more than enough to produce the saline formation waters of the western Canadian sedimentary basin. Spencer (1987) also states that the dense
FIG. 10.—Thin section photograph, as seen in plane light, of displacive halite (Saline Valley, CA; < 0.3 m). The halite crystals are subhedral to euhedral in shape and are isolated by mud (black). The cores of some crystals contain patches rich in fluid inclusions (arrows). Compare with shallow-buried (Fig. 5) and Permian (Fig. 7) displacive halite. Scale bar is 0.5 cm long.

FIG. 11.—Thin section photograph, as seen in plane light, of a layer of fluid-inclusion banded chevron halite truncated by a pipe of clear halite (heavy line: Bristol Dry Lake, CA; 196.6 m). The clear halite is interpreted as a filling of a former dissolution cavity. The dark areas in the pipe of clear halite are mud. Dark areas in the surrounding chevron halite are fluid-inclusion rich crystals. Compare with the large vertical pipes in the modern halite crusts in Figure 1A. Scale bar is 1 cm long.
FIG. 12.—Thin section photograph, as seen in plane light, of a vertically oriented and elongate chevron halite crystal (Saline Valley, CA: 53.9 m). Note the alternating fluid-inclusion rich (dark) bands and fluid-inclusion poor (clear) bands within the crystal. The fluid-inclusion band-ed halite is truncated and surrounded by clear halite. A thin mud coating (internal sediment) directly overlies the truncated fluid-inclusion band-ed halite (arrow). Scale bar is 0.5 cm long.

Syndepositional surface brines should theoretically sink to depths of several kilometers. Such downward flow of brines through halite rocks may easily occur during the early stages of halite accumulation but may be hindered if great thicknesses of halite develop. A possible alternative is that the brines flow laterally into marginal non-evaporitic sediments before they reflux down. Further testing of this model is required.

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Fig. 14.—Thin section photograph, as seen in plane light, of euhedral halite cements with crystal faces (arrows) terminating into voids (epoxy filled) (Saline Valley, CA; 17.7 m). Scale bar is 0.5 cm long.


———. 1987. Post burial alteration of the Permian Rustler Formation
FIG. 16.—Thin section photograph, as seen in plane light, of a centimeter-long pipe of clear halite cement filling a former cavernous void (Rustler Formation). The clear halite truncates the surrounding fluid-inclusion banded halite (dark gray with black patches of interstitial mud) as well as horizontal dissolution-truncation surfaces (white arrow). The muds lining the bottom of the void, and within the void (black arrows), are interpreted as internal sediment derived from floodwaters that infiltrate porous surface crusts. Compare with Figures 1A, 11. Scale bar is 0.5 cm long.


Fig. 17.—Thin section photograph, as seen in plane light, of fine grained cumulate crystals of halite (Salado Formation). Note the laterally-linked crystals forming a raft (arrow). Compare with Figure 13. Scale bar is 0.5 cm long.

