DEPARTMENT OF THE INTERIOR

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Final report on a study of fluid inclusions in core from Gibson Dome No. 1 bore, Paradox Basin, Utah

by

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Introduction

Five small core samples of halite from the Department of Energy Gibson Dome No. 1 Bore (GD-1) were obtained for a preliminary study of the fluid inclusions present. These samples were from evaporite cycle 6 of the Paradox Member of the Hermosa Formation. The aim of this investigation was to see what information such a study might provide as to the geologic behavior of such fluids if these salt beds were used for a nuclear waste repository, as well as the geologic processes involved in the formation and subsequent history of these saline beds.

Samples studied

The studied samples consisted of one-fourth of the 4-inch diameter core from the following depth intervals, measured in feet from the Kelley bushing:

3,148.9 - 3,149.1
3,185.0 - 3,185.2
3,239.1 - 3,293.3
3,279.6 - 3,279.8
3,321.5 - 3,321.7

These samples were selected in consultation with R.J. Hite, USGS, and were released to the USGS per letter dated August 3, 1982, PXX-82-281, from N.A. Frazier, Project Manager, Paradox Basin Exploration Office, to Mr. Fred Conwell, Woodward-Clyde Consultants.

Sample preparation

The selected portions were cut from the core with a diamond cutoff wheel and Almag cutting oil, and then cleaned of cutting oil by washing with trichloroethane. One or more doubly polished plates, mounted with cold-setting epoxy, were then cut from each sample, perpendicular to the bedding and across visible color or textural variations. Grinding and polishing was done with alcohol as a lubricant and coolant, and care was used to avoid any heating. Orientation of these plates relative to gravity was maintained, in case geopetal textures might be present.

Petrographic examination

General features. Although the five samples differed in appearance, and were scattered through a 172-foot interval, relatively few differences could be recognized between the five samples in this reconnaissance and hence they will be discussed here as a group.

Primary inclusions in unrecrystallized salt. Only a very small percentage of the salt crystals in these samples shows good evidence of primary crystallization features from the original crystal growth in a salt basin. The main evidence for primary crystallization is the presence of chevron growth features, outlined by alternating zones of primary fluid inclusion-rich and inclusion-free salt (Roedder, 1984a). The inclusions in most such salt are very small and densely packed (Fig. 1). The change from inclusion-rich to clear salt can be abrupt (Fig. 1 insert). Few inclusions are >10 μm, and many are <1 μm. As is common in such chevron salt, some periods of salt dissolution occurred during deposition of the original salt beds in the Paradox Basin, leaving curving surfaces cutting across the growth banding. Subsequent (presumably slower) growth on these curved surfaces can form a clear extension of the original crystal, in crystallographic continuity (Fig. 2). The orientation of the chevrons can provide geopetal information, as the apex of the chevron points stratigraphically upward (Fig. 3); such geopetal features were rare in these particular samples.

Practically all inclusions making up the chevrons in the GD-1 samples contain a single large daughter crystal that has crystallized out of the fluid after trapping. The only exceptions are inclusions <~3 μm; presumably this difference is merely a result of nucleation problems (Roedder, 1971). The high birefringence of this daughter phase makes these crystals stand out between partly crossed polars (Fig. 4). Occasional larger, primary inclusions within chevron growth (e.g., "X" in Fig. 3) permit estimates of the volume percentages of the phases in such inclusions. These inclusions generally contain ~25 vol.% of the daughter phase (e.g., Fig. 5). In other inclusions another different birefringent phase is also present, as very irregularly distributed separate crystals that may range from 0.5 vol.% to >30 vol.% of the individual inclusion. Only rarely do these primary inclusions in unrecrystallized salt show a tiny vapor bubble; estimated homogenization temperatures for these bubbles would be ~ 40°C.

The large daughter crystals have optical and crystallographic properties, as best can be measured within an inclusion, that match those of carnallite, $KMgCl_3 \cdot 6H_2O$, and all such crystals are assumed to be carnallite in the balance of this report. These properties include: generally parallel extinction, birefringence ~0.03, lower index shows low relief against the fluid phase, (pseudo)hexagonal habit (Figs. 6 and 7), frequently with multiple (pseudo)hexagonal pyramids (Fig. 8). These features, plus their high solubility in water, their very high thermal coefficient of solubility (see below), and the known presence of K and Mg, and of carnallite as a rock-forming mineral this section of the Paradox Basin salt beds, make the identification of the daughter crystals as carnallite fairly unambiguous. However, to be certain, several attempts were made to extract these crystals, using the crushing stage (Roedder, 1970). The extracted single crystals were mounted on fibers and X-ray powder diffraction patterns obtained using the Gandolfi camera technique of Zolensky and Bodnar (1982). The five lines obtained agreed well with the five strongest lines of carnallite.

The density of the other phase or phases that are present in such highly variable amounts is unknown, but the optical properties fit anhydrite, and anhydrite (verified by X-ray diffraction) is also present as crystals embedded in nearby salt. The variable abundance of these crystals in the fluid inclusions, and the lack of any change in them during heating studies (see below) makes it apparent that they are not daughter crystals, but accidentally-trapped solid inclusions -- phases that were present during the growth of the host chevron salt.

Primary inclusions in recrystallized salt. When a mineral recrystallizes in the presence of a fluid phase, inclusions of that fluid can become trapped in the new crystals as primary inclusions in recrystallized host. The time of trapping of such crystals can be immediately after the original crystallization of the host crystal in the salt pan, or during subsequent diagenesis and recrystallization, perhaps millions of years later (Roedder, 1984a).

Much of the halite in these samples is free of chevron growth and appears to have recrystallized. Although the resulting crystals make up a tight fabric of low porosity, they are generally smaller (3-4 mm) than the recrystallized salt at the WIPP site (Roedder and Belkin, 1979). Most of the larger fluid inclusions in the Gibson Dome samples appear to be in such clear, recrystallized salt. During recrystallization, small amounts of the brine present at the time tend to be trapped at the interface between various solid inclusions and the host halite (Fig. 9). In other cases, a solid crystal may be trapped within a fluid inclusion (Fig. 10), or a large number of solid crystals may be trapped (Fig. 11). In the last example, however, a new large, true daughter crystal (x) also formed on cooling from the temperature of trapping to room temperature.

The primary inclusions in recrystallized salt also have large daughter crystals of carnallite, like those in the chevron salt, and sometimes a small shrinkage bubble (~ 0.1 vol.%; Figs. 11 and 12). The volume percent of carnallite is approximately the same in both chevron and recrystallized salt (~ 25 vol.%). Rarely a small ragged mass of opaque material is present, presumably organic matter. Some small inclusions of clear to brownish fluids that were insoluble in water (presumably hydrocarbons) were found in halite in this and other parts of the core.

In addition to the numerous blades of anhydrite, carnallite, etc., that are embedded in the halite host, some highly birefringent, very thin square plates, with inclined extinction, were found that appeared to be in some salt grains (Fig. 13). These, however, turned out to be artifacts, formed on the lower polished surface of the salt sample before it was cemented to the glass slide. Their nature is unknown, and they are mentioned here only as a caveat to other workers.

Secondary inclusions. Very few recognizably secondary inclusions were found in these samples, but in view of the speed with which inclusions in salt can change shape and position, many other inclusions may actually be secondary in origin. The only inclusions that can be assumed to be secondary are those arranged along apparent healed fractures, rather than on growth planes. Since salt cleaves parallel to the common growth plane (100), ambiguity remains in many examples. One possible candidate for secondary origin (Fig. 14) consists of a curving group of liquid inclusions, each containing only liquid and a very small bubble, that occurs in salt in which the primary inclusions all contain large daughter crystals of carnallite. Another possible example is found in some planes of what apparently were originally high pressure gas inclusions, now decrepitated (Fig. 15).

Overall estimate of free water contents. As in most salt (Roedder and Bassett, 1981), water is present in salt bed 6 in a variety of forms (Fig. 16). It is present as bound water in hydrous minerals such as carnallite, as free water in intracrystalline fluid inclusions within single crystals, and as intercrystalline films and fluid inclusions along grain boundaries between crystals. Since these samples have been exposed to air, the intercrystalline, grain-boundary fluid has long since evaporated, leaving air inclusions that generally appear black from total reflection (Fig. 16).

At 38.9% H_2O, the carnallite present in these beds (Hite, 1983) is the major contributor to the total water content. The volume percent of free water present as visible fluid inclusions in these samples can be only roughly estimated from counting of fluid inclusions of various size ranges in a "representative" area. For this estimate, the small inclusions usually make up a rather insignificant part of the total (Roedder and Belkin, 1979). By optical measurement, and an assumption as to fluid density, the larger inclusions in several plates were found to amount to only 35-100 ppm (0.0035 to 0.01 wt.%). The original volume of the free water present as intergranular films and inclusions is even more difficult to estimate. If, however, these intergranular inclusions corresponded to an apparent average "film" thickness of only 4 µm along grain boundaries in salt with 3-mm grains, the fluid in such inclusions would still amount to ~0.2 wt.%.

Microthermometry

Freezing studies. Only one sample (3148.9 - 3149.1) was studied at low temperature on a Chaixmeca freezing/heating stage, (Poty et al., 1976) to determine the low temperature phase relations. Metastable supercooling of the dense brines to a clear glass on cooling to -150°C was common, but usually enough crystals formed to distort the newly-formed vapor bubble. On warming, these deformed bubbles changed to spherical at ~-54°C, indicating actual fluid is present at that temperature. Much more noticeable melting of earlier formed crystals, and recrystallization of other crystals, occurred at ~-34°C. Most of the crystals that formed on cooling remelted by ~-24°C.

Heating studies. Several sample plates were studied on the Chaixmeca stage (Poty et al., 1976) to determine the phase behavior. In particular, determinations were made of the homogenization of vapor bubbles (where present) and of the melting or dissolution of daughter crystals.

Most inclusions in these samples have no vapor bubbles. However, some primary inclusions in recrystallized salt (e.g., Figs. 11 and 12) have very small bubbles at room temperature. A series of such inclusions in sample 3321.5 - 3321.7 showed vapor-liquid homogenization (disappearance of the vapor bubble) at 32.5 to 41.2°C. The daughter crystals had not dissolved at these temperatures.

Studies of the daughter crystals in fluid inclusions can provide information on the temperatures of trapping, and the composition of the fluids present at the time. Heating runs (3-4 hours duration) were made on samples from 3185.0/3185.2, 3239.1/3239.3, and 3321.5/3321.7. In each the large carnallite daughter crystal exhibited a very high thermal coefficient of solubility. Even though these carnallite crystals amounted to ~25 vol.% of the total inclusion and were immersed in a saturated solution, noticeable rounding of the sharp crystal edges occurred on warming just 5°C. The temperature of complete melting or dissolution of this carnallite was 56.1 ± 0.1°C in several runs on three large primary inclusions in recrystallized salt in sample 3321.5/3321.7 (e.g., Fig. 11) and in a series of smaller inclusions in the same plate. Just before dissolution of the rounded crystal was complete, a slight drop in temperature resulted in formation of sharp facets, verifying that equilibrium (at least locally) had been achieved. On cooling after complete dissolution, carnallite reappeared in the three larger inclusions at ~30°C, but did not return in the smaller inclusions. The many other crystals (anhydrite?) in these same inclusions (e.g., Fig. 11) did not show any evidence of dissolution, not even a slight visible rounding of the corners, on heating to 175°C. On cooling to room temperature, the larger inclusions developed a larger vapor bubble than they had originally. Instead of ~0.1 vol.% (Fig. 11), these now amounted to ~2 vol.%, a result of stretching of the halite walls during the overheating to 175°C. Another large inclusion in recrystallized salt from this same depth, containing a carnallite crystal 136 μm in diameter, was studied separately in a 6-hour run; it dissolved at 57.3°C.

Dissolution of similar-appearing carnallite daughter crystals in recrystallized salt from sample 3239.1/3239.3 required much higher temperatures (Figs. 17-19). The carnallite crystal in the large inclusion shown in Fig. 17 dissolved at 120.4°C, but the other six crystals (and the mass of organic matter) showed no evidence of rounding even at 179°C. Before it dissolved completely, new facets were seen to grow on the rounded carnallite grain on temporary cooling from 111°C to 108°C (Figs. 18 and 19). A series of small inclusions adjacent to this large inclusion, in the same halite grain, showed final dissolution of carnallite at 98-102°C. Whether these small inclusions represented primary chevron salt or recrystallized salt could not be determined. On cooling this sample from 179°C, the large inclusion nucleated a bubble (not present before) at 133°C, and a new crystal of carnallite at 102°C. Most of the small inclusions developed bubbles on cooling to ~120°C, and carnallite crystals at ~55°C. At room temperature, these new bubbles comprised ~2 vol. %.

Crushing stage studies

The presence of gases under pressure in the fluid inclusions in these samples was checked by two procedures, dissolution of a sample in water under the microscope, and with the crushing stage (Roedder, 1970). Both procedures showed that gases under pressure were present, but only in the inclusions in recrystallized salt crystals, and those on grain boundaries. Inclusions in chevron salt contain almost no gas. The gas pressures in the inclusions in recrystallized salt can only be estimated very roughly to be in the range of tens or hundreds of atmospheres. This is in agreement with the cracking and popping noices heard from cores immediately after removal from the core barrel, as gas inclusions close to the core surface explode (R.J. Hite, personal communication, 1984).

Interpretation of the results

Composition of the fluids present in the inclusions. Several aspects of the composition of the fluid in the inclusions studied can be judged from the results reported above. The presence of liquid at -54°C almost requires the presence of significant $CaCl_2$ in solution. No other geochemically reasonable composition can yield such low temperatures. In addition, the extensive melting at ~-34°C, and the loss of all new crystals (formed on cooling) at ~-24°C suggests, but does not prove, major amounts of magnesium chloride (Crawford, 1981). The presence of carnallite daughter crystals at room temperature requires that the fluid be saturated with respect to this phase. In pure water at 19°C, this corresponds to ~40 wt.% carnallite, but the solubility will be affected by other constituents present, such as calcium.

The evidence above provides only a qualitative indication of the nature of the fluids present in the inclusions at room temperature: a chloride brine containing major Mg, Ca, and K. The carnallite daughter crystals in the inclusions, and their dissolution on heating, provides some more quantitative data. The volumes of fluid and daughter crystal can be roughly estimated by optical measurements of relatively regularly-shaped inclusions. Using appropriate densities for brine and crystal, the composition of the solution formed by dissolution of the daughter crystal can be calculated. A volume correction is necessary for any solid inclusions of anhydrite. A series of such inclusion measurements average ~30 wt.% carnallite from the daughter crystal alone. On solution, this corresponds, in ppm by weight, to K 47,000, Mg 26,000, and Cl 76,500, but these data are minima, as the amounts present in the fluid phase at room temperature must be added. Thus if the solubility of carnallite at 19°C is assumed to be the same in these solutions as in pure water (this is an invalid assumption, but does provide a useful upper bound), the total ppm by weight after dissolution of the carnallite would be: K 82,000; Mg 51,000; Cl 150,000. To this must be added the probably large but unknown amounts of $CaCl_2$ presumed to be present, and NaCl corresponding to saturation with respect to NaCl. This latter may amount to only a few percent NaCl in divalent-ion-rich solutions (Roedder, 1984b, p. 250). As anhydrite (and probably other sulfates) were present in contact with these same fluids, some (probably small) amount of sulfate is also present. Moskovskii and Sirotin (1981) analyzed some inclusions in potash-rich zones of the Kungurian salt beds, in the El'ton and Baskunchak areas of the Caspian depression, but found considerably lower total salts and K/Mg ratios than those calculated here.

The composition of the inclusion fluid estimated above is much higher in K and Mg than some rapidly flowing fluids encountered in thin interbeds of dolomite, anhydrite and shale in the Paradox Basin salt sequence (personal communication, R.J. Hite, 1984).

Significance of inclusion data

Degree of recrystallization of the salt. The petrographic evidence presented, indicating a major amount of recrystallization of the halite in these samples, might seem to contradict the evidence of little recrystallization, based on the bromine profiles (Hite, 1983). These two statements are not necessarily in conflict. The amount of bromine in salt is a result of the distribution of Br between liquid and crystal during the halite growth. At equilibrium, this distribution is a constant, so no change in the Br content of the salt crystal would be expected if recrystallization occurred via that same fluid, at the same temperature and pressure. Even if recrystallization occurred via an introduced fluid, the Br content of the newly-formed salt need not be greatly changed. These relationships would not hold, however, if the original Br content of the salt crystals did not represent true crystal/liquid equilibrium.

Diagenetic history of the salt beds. The present mineralogy and geochemistry of a salt bed reflects both the original formation conditions and the subsequent changes during burial and diagenesis. It would be good to know the maximum temperatures achieved during the history of the beds, but the plasticity of salt, particularly under long term stress, is such that fluid inclusion homogenization temperatures for halite *cannot* be assumed to be a simple function of trapping temperature (Roedder, 1984a,b). The walls can expand or contract, from internal or external pressure, hence the homogenization temperatures cannot provide either a maximum or a minimum value. If fluid inclusions occur in non-plastic minerals such as anhydrite or authigenic quartz, valid temperatures can be obtained for the growth temperatures *for these phases*.

Much more significance can be given to the dissolution temperatures of the daughter crystals. Except for the possibility of accidental trapping of solid carnallite crystals along with fluid (and this is precluded by the consistency of the thermal data for any given sample), these dissolution temperatures represent true trapping temperatures. If the fluids were unsaturated with respect to carnallite at the time of trapping, these dissolution temperatures would provide minimum values for the trapping temperature, but as there is evidence that carnallite was actually precipitating along with the halite (Hite, 1983), the dissolution temperature is equal to the trapping temperature.

The carnallite daughters in primary inclusions in chevron salt dissolved in the range 56-57°C; such temperatures are not improbable in salt pans. The much higher temperatures of dissolution of the carnallite daughters in primary inclusions in recrystallized salt (98-120°C) are a measure of the temperatures during burial diagenesis. The pressure correction to be added to such solid-liquid homogenization temperatures will be small, but it is important to note that the temperatures obtained are for the trapping of those particular inclusions only. They are thus *minimum* values for the thermal maximum achieved during the history of the beds, as the inclusions studied were not necessarily trapped at the maximum temperature. Even so, they are much higher than the ~69°C indicated by the geothermal gradient (18.5°C; Sass et al., 1983) and the evidence of a maximum of 8000' of additional overburden in the past (personal communication, R.J. Hite, 1984). Hite et al. (1984) found vitrinite reflectance measurements on samples from the GD-1 hole suggested strong suppression of the maturation of vitrinite responsible for the normal change of reflectance. Whether this suppression would be adequate to be compatible with the attainment of temperatures as high as 120°C is not known, but I believe the inclusion data are valid.

Although the volume of a fluid inclusion in salt may change after formation, there is considerable evidence that fluid inclusions in salt maintain their original chemical composition, i.e., they do not leak materials in or out. Hence the composition of the fluids present in them now is probably a valid measure of the composition of the fluid that was trapped in the past, whether it be Permian salt basin brine or a later connate fluid. The inclusion data show that during the original crystallization of the halite in salt cycle 6, and during subsequent recrystallization, the fluids present were very high in K and Mg, and at least in part high in Ca. It would be good to know if there were differences between the solutions from which the original salt crystallized and those present along grain boundaries during the later recrystallization, but the available inclusion data are too inexact to permit quantification of such differences. Certainly the much higher dissolution temperatures for carnallite daughter crystals in inclusions in recrystallized salt must indicate more concentrated fluids were present at the time of this recrystallization, after burial.

Although not proved, it is probable that the fluids present along grain boundaries in these salt samples were similar in composition to those in the inclusions in recrystallized salt. Hanshaw and Hill (1969; see also McCulley et al., 1982) have shown that the fluids present in aquifers above and below the salt beds are very different in composition than the high K-Mg brines reported above. This difference (as well as the presence of carnallite beds) suggests that fluid flow through the salt section must be minor at best.

The fluids present during recrystallization may be from the release of primary fluid inclusions in the immediate vicinity, the release of water from hydrous minerals, or they may have migrated laterally or vertically through the beds from other places. In the Paradox salts, the presence of solid carnallite beds proves that the fluids in the salt pan had evapporated to this stage. In the absence of such obvious beds of carnallite, however, the presence of carnallite daughter crystals in primary fluid inclusions in chevron halite would indicate that the fluids had evaporated at least to near the stage of precipitation of carnallite, and that exploration for potash deposits, either laterally or vertically, might be appropriate. Similarly, the presence of carnallite daughter crystals in inclusions in otherwise carnallite-free recrystallized salt beds would be a valid exploration tool to suggest the possible presence of potash beds elsewhere in the sequence. At the least, such daughter crystals (or inclusion data indicating near saturation with respect to carnallite) indicate that evaporation had gone this far in some part of the basin.

The rare inclusions without daughter crystals (Fig. 14) indicate that at some stage in the history of these beds, a fluid was present that was not as rich in K and Mg chlorides. The composition of the beds is such that external waters, seeping slowly through the probably low permeability salt horizons, would soon contact and dissolve enough carnallite to become rich in K and Mg. Several possible scenarios might be suggested to explain these carnallite-free inclusions: 1) Carnallite was in solution but failed to nucleate. This is unlikely, in view of the fact that nucleation of daughter crystals is volume-dependent and these inclusions are 4 or 5 orders of magnitude larger in volume than inclusions in which carnallite has nucleated (Figs. 1a, 4). 2) A sudden influx of relatively fresh external water might become trapped before it had time to contact enough carnallite to become saturated. 3) A local source of fresh water was involved, e.g., from the dehydration of gypsum. 4) A $CaCl_2$ brine was introduced, in which the solubility of carnallite would be low; Knauth (1982) presented isotopic evidence suggesting that these salt beds might have been penetrated by formation waters. At present there is no good basis for choosing among these (or other) alternatives.

Behavior of the fluids on heating. The intracrystalline inclusions studied represent only a part of the total free water content of these beds, since the fluid in intergranular pores may be one or two orders of magnitude larger in amount, though probably of similar composition. Furthermore, the free water content of these beds is only a relatively small part of the total water present in carnallite-bearing salt. Hence, the behavior to be expected during heating from nuclear waste is conjectural at best. But two aspects are relatively certain: 1) the fluids generated in such salt in the vicinity of a hot canister will be bitterns containing high concentrations of K, Mg and Ca, and 2) the amount of such fluids will be significantly greater than the present amount of free water, as a result of dissolution (and/or decomposition) of hydrous phases. Some aspects of the behavior of such brines in a repository environment have been discussed by Stewart and Potter (1979) and Stewart et al. (1980).

Acknowledgements

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Figure Captions All figures are photographs taken in transmitted light, at room temperature, except as noted. Sample depths are given in parentheses. The scale bars are 100 μm.

Figure 1. Cloud of small primary inclusions in primary chevron salt. Inset shows a close-up of the interface between inclusion-rich and inclusion-free salt from this area. (3239.1/3239.3)

Figure 2. Cloud of primary inclusions, similar to that in Fig. 1, that has been partly dissolved (curving border) and then replaced with clearer, more inclusion-free halite in crystallographic continuity with the original grain. (3148.9/3149.1)

Figure 3. Typical primary chevron growth salt, outlined by bands of fluid inclusions, and some larger inclusions, as at "X." (3185.0/3185.2)

Figure 4. Similar area to that shown in Fig. 3, between partly crossed polars, showing the highly birefringent daughter crystals. (3185.0/3185.2)

Figure 5. Close-up of large primary inclusion at "X" in Fig. 3. Daughter crystal is carnallite.

Figure 6. Small primary inclusion in recrystallized salt, containing a pseudohexagonal daughter crystal of carnallite. The fast ray vibration direction is parallel to the axis of apparent six-fold symmetry. (3185.0/3185.2)

Figure 7. Similar to Fig. 6, but here the pseudohexagonal crystal is elongated perpendicular to the axis of apparent six-fold symmetry. (3239.1/3239/3)

Figure 8. Large primary inclusion in recrystallized salt showing large carnallite daughter crystal exhibiting multiple "hexagonal pyramid" forms. The small object is a single-phase fluid inclusion in the daughter crystal, trapped during the crystallization of the daughter crystal. (3239.1/3230.3)

Figure 9. Solid inclusions of carnallite in halite. During the enclosure of one of these carnallite crystals by the host salt, a film of liquid was trapped as well; shrinkage of the carnallite and liquid yielded the small dark bubble. Partly crossed polars. (3239.1/3239.3)

Figure 10. Solid inclusion of anhydrite(?) trapped along with liquid in a primary inclusion in recrystallized salt. A very small shrinkage bubble is present (arrow). Partly crossed polars. (3279.6/3279.8)

Figure 11. One of several primary inclusions in recrystallized salt containing a large number of small accidentally trapped solid inclusions of anhydrite, a small vapor bubble, and a large daughter crystal of carnallite ("X"). (3321.5/3321.7)

Figure 12. Primary inclusion in recrystallized salt containing a small vapor bubble (arrow) and a large prismatic carnallite daughter crystal. (3239.1/3239.3)

Figure 13. Grain of salt between partly crossed polars showing lath-like crystals of carnallite or anhydrite and a highly birefringent square crystal that is an artifact formed in sample preparation. (3185.0/3185.2)

Figure 14. A healed fracture in recrystallized salt, now outlined by liquid inclusions (± a very small bubble) but without daughter crystals. The curving fracture extends down from the upper right across the center of the field of view. (3321.5/3321.7)

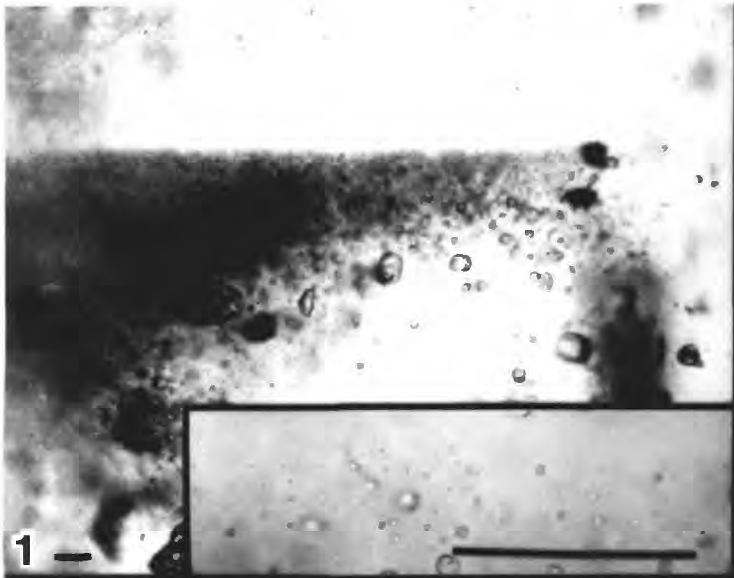
Figure 15. A possible example of multiple fracturing and rehealing. A plane of (presumed) high pressure gas inclusions (round, dark objects) formed during healing of a fracture in salt; on release of external pressure, the internal pressure in these caused a new fracture to open and release the gas; subsequent partial healing of this new fracture formed the vermicular inclusions. (3321.5/3321.7)

Figure 16. Photograph showing three forms of water in salt bed no. 6: A, hydrous minerals (presumed carnallite crystals); B, intracrystalline inclusions; and C, intercrystalline (grain boundary) inclusions (now black due to total reflection by air that has replaced the former liquid). (3148.9/3149.1)

Figure 17. Primary inclusion in recrystallized salt, as found, showing large daughter crystal of carnallite ("X"). (Left part shows same inclusion at another plane of focus.) Six other crystals (marked 1 to 6) are apparently accidental solid inclusions. A small ragged wisp of opaque material (arrow) is presumably organic. (3239.1/3239.3)

Figure 18. Same inclusion as shown in Fig. 17, photographed at 111°C during heating run. Note that most of the carnallite has dissolved.

Figure 19. Same inclusion as shown in Fig. 18, photographed after dropping temperature 3°, from 111° to 108°C. Note the faceting of the formerly rounded carnallite crystal, indicating regrowth (and hence presumably equilibrium). Other crystals are unaffected by the heating, except that some have moved slightly; they are presumably incidental solids trapped along with the fluid.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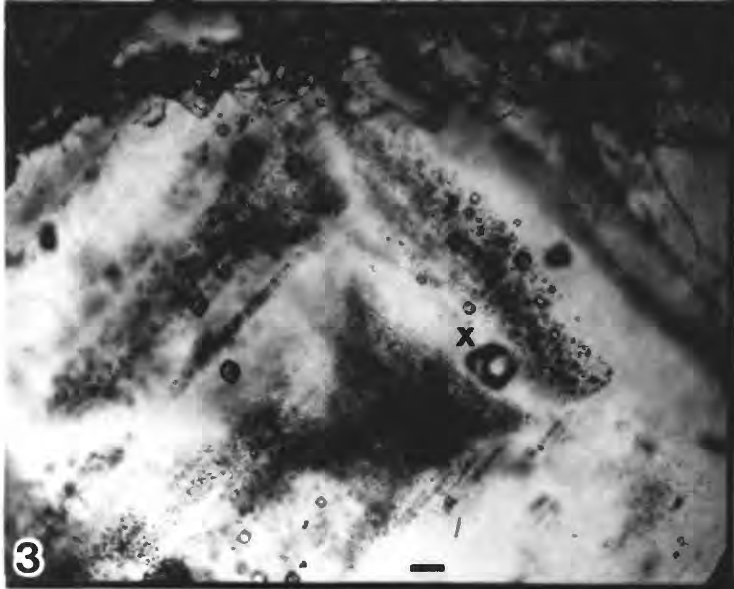

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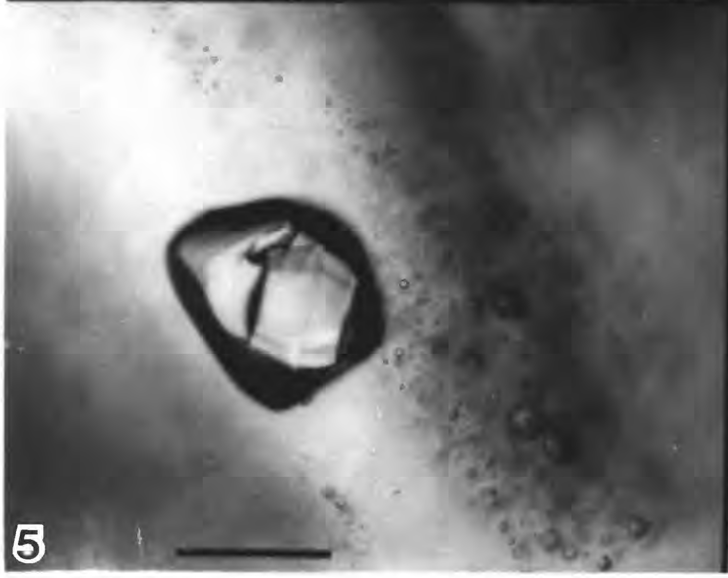
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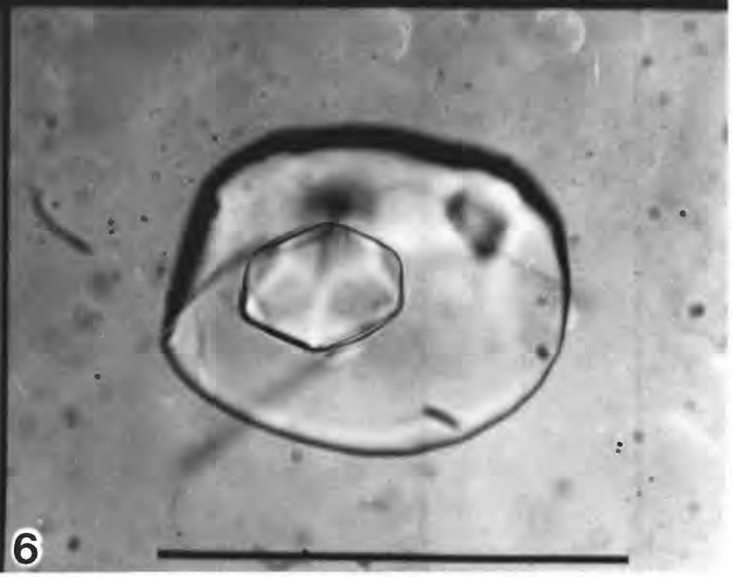
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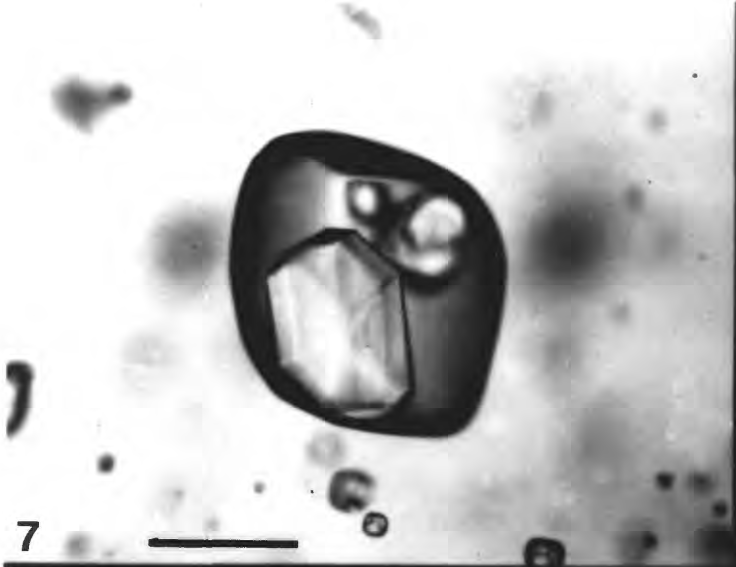
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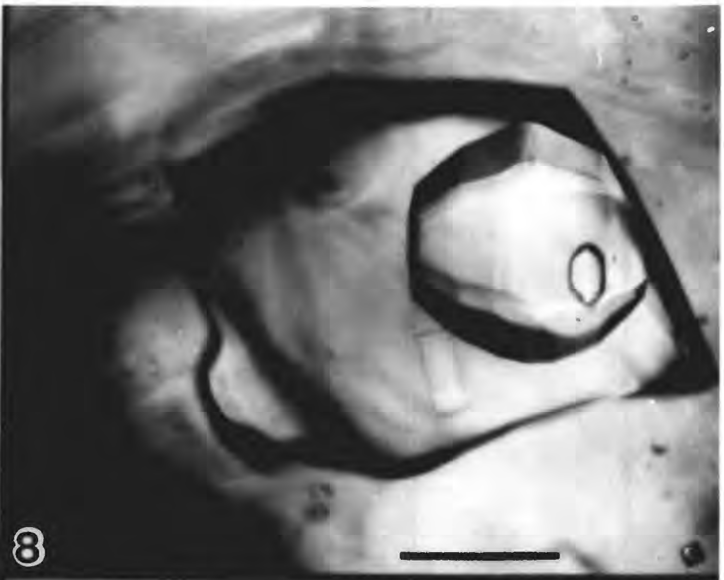
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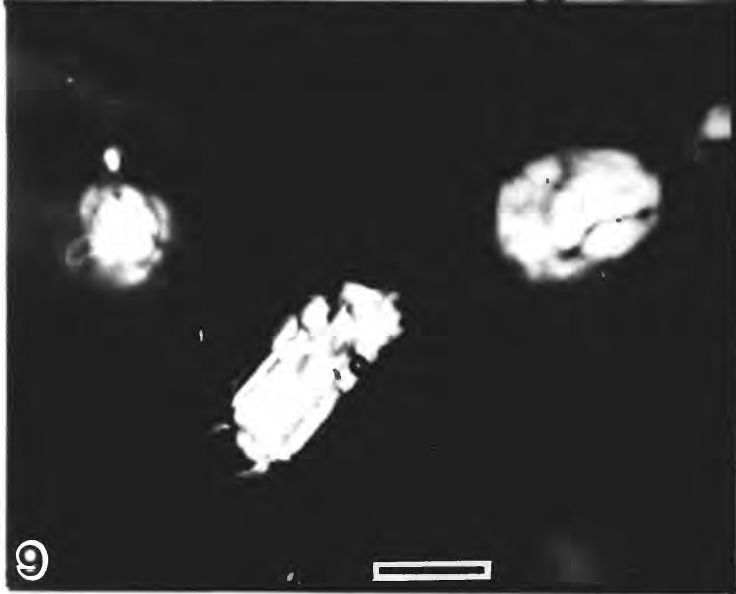
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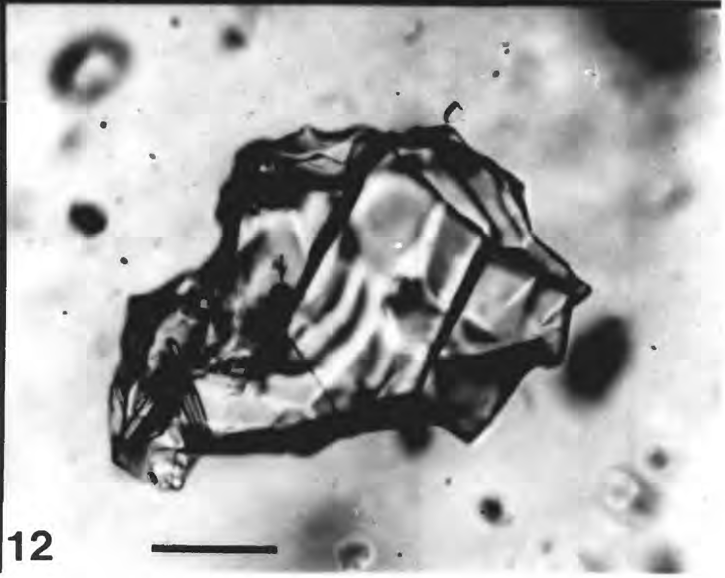
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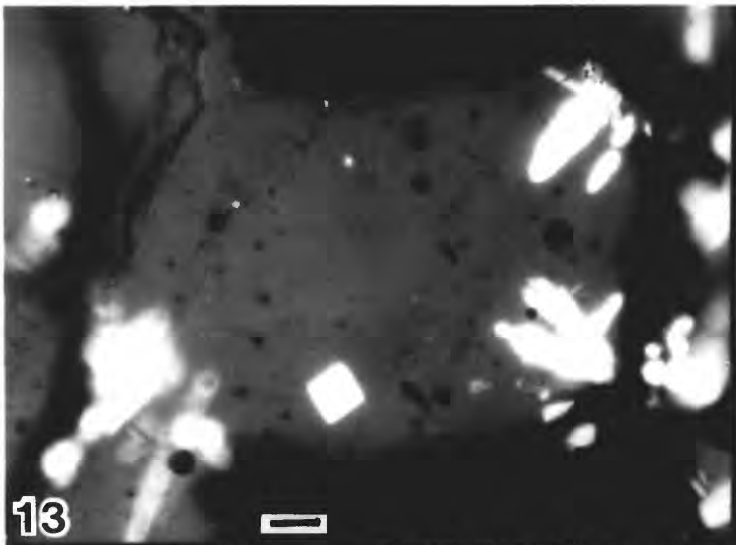
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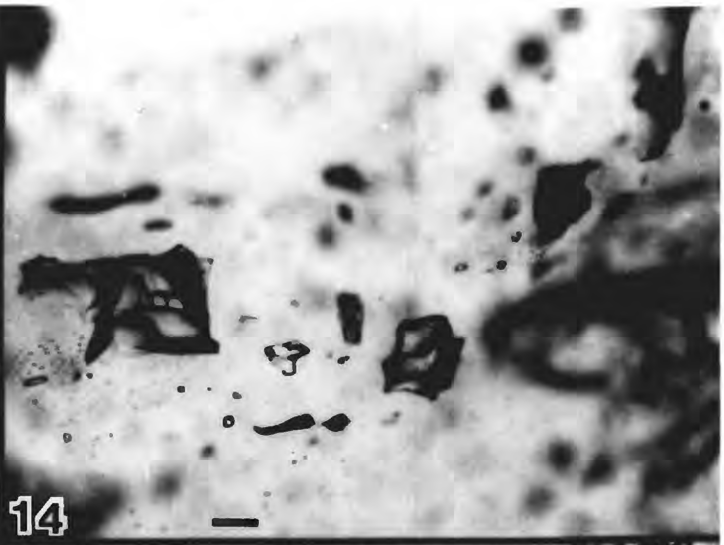
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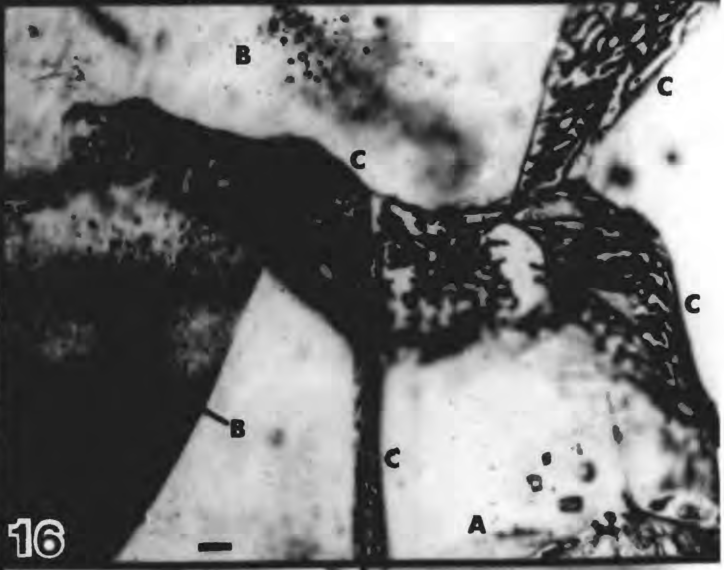
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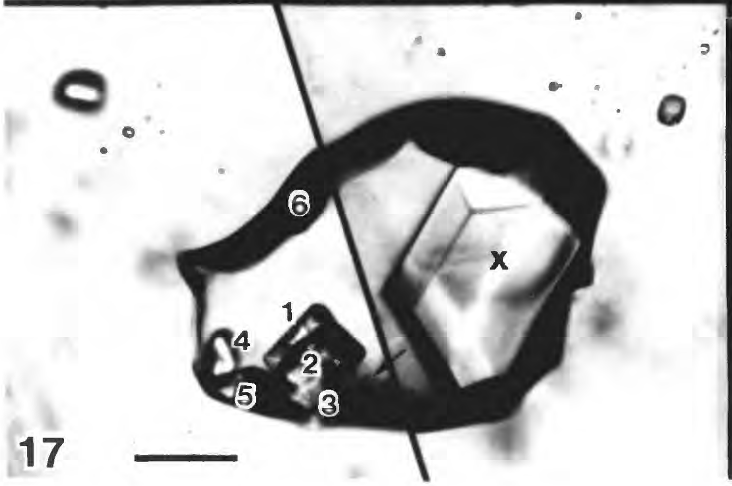
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