# Character and Distribution of Nonclastic Minerals in the Searles Lake Evaporite Deposit California

By GEORGE I. SMITH and DAVID V. HAINES

CONTRIBUTIONS TO GENERAL GEOLOGY

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### ABSTRACT

The Searles Lake evaporite deposit, California, near the southwest corner of the Basin and Range province, was formed by a succession of late Quaternary lakes that filled the basin and then either shrank to form saline lakes or desiccated. The deposit crops out at the surface as a bed of nearly pure halite that covers an area of about 12 square miles; beneath the surface it consists of interbedded salines and muds that lie nearly flat and cover an area of about 40 square miles. This paper summarizes the areal and stratigraphic distribution of the nonclastic minerals in the deposit, correlates their characteristic forms with the stratigraphic units from which they came, and deduces the depositional history responsible for this distribution.

A total of 25 nonclastic mineral species occur in Searles Lake; 10 of these species were first found in a natural state in this deposit. In terms of anions, 9 of the 25 minerals contain sulfate; 8, carbonate or bicarbonate; 7, chloride; 4, borate; 3, fluoride; 3, aluminosilicate; and 1, borosilicate. In terms of cations, 20 of the 25 minerals contain sodium; 6, calcium; 3, magnesium; and 4, potassium. The minerals containing calcium and magnesium are chiefly carbonates; the minerals bearing sodium and potassium may contain any of the listed anions. Ten of the 25 minerals contain water or hydroxyl ions.

The distributions and characteristic forms of these minerals are different in each of the stratigraphic units. The Overburden Mud (late Recent) consists predominantly of interbedded dark-brown mud and cubo-octahedral or water-rounded halite. The Upper Salt (early Recent) consists chiefly of thick beds of cubo-octahedral crystals of halite, pyramidal crystals of hanksite, megascopic to microscopic crystals of acicular trona, and thin beds of borax. The Parting Mud (late Wisconsin) consists of mud containing subhedral to anhedral crystals of gaylussite and pirssonite, with subhedral to massive borax at the top, and local concentrations of microscopic crystals of dolomite, aragonite, halite, gaylussite, and pirssonite. In the Lower Salt (middle Wisconsin) each of the seven saline units and six mud units has a distinct mineral character. In the upper two saline units, intermixed aggregates of fine-grained and coarse-grained acicular trona predominate, but cubo-octahedral halite is locally abundant; the two thin mud layers underlying these units contain subhedral to anhedral megascopic gaylussite, a smaller percentage of euhedral pirssonite, and microscopic

crystals of both. The underlying two saline units consist chiefly of fine-grained trona, cubo-octahedral halite, and finely crystalline burkeite; the mud layers below them contain megascopic and microscopic crystals of gaylussite and northupite and prismatic crystals of borax. The lowest three saline units are composed chiefly of intermixed aggregates of fine-grained acicular trona and coarse-grained bladed trona; the two mud layers that separate them contain fine-grained aragonite and northupite and megascopic gaylussite. The Bottom Mud (early Wisconsin), which is about 100 feet thick, is composed chiefly of mud containing subhedral to anhedral gaylussite, but also contains small quantities of halite, thenardite, nahcolite, dolomite, calcite, tychite, pirssonite, northupite, borax, trona, mirabilite, analcime, adularia, and searlesite. The Mixed Layer (Illinoian? and Sangamon?) is a series of interbedded muds and salines that has not been well explored. The layer consists chiefly of cubic halite, acicular trona, and muds, which here, as well as throughout the rest of the deposit, are composed of microscopic crystals of evaporites, authigenic silicates, clastic silicates, and organic material..

The variation in physical character of minerals reflects the conditions under which they grew. The layers composed of fine-grained chemical sediments are generally interpreted as primary deposits formed on the bottom of the lake, although the microscopic halite crystals in mud layers are thought to have been formed after burial. The layers composed of megascopic crystals are interpreted as deposits recrystallized after burial. Textural evidence shows that most of these crystals grew by volume-for-volume replacement of the material in which they now lie, but it also suggests that most of the resulting mineral species are the same as the primary species.

Experiments by others on megascopic crystals show that kinetic factors are more important in controlling the habit of crystal development than are thermodynamic factors. In crystallization that takes place over geologic periods of time, though, the importance of the slightly lower free energy of large crystals probably exceeds that evident from experiments. The systematic habit variation among the secondary crystals in the Searles Lake deposit seems to indicate that both factors have contributed to the recrystallization processes: that the thermodynamic requirements caused the crystals to grow and the kinetic factors determined the faces actually developed.

Four of the minerals in the Searles Lake deposit—halite, borax, trona, and hanksite—have variations in the development of their faces that can be correlated with their stratigraphic position. The habits of halite and borax are interpreted in the light of experimental data; the conditions that produce variations in the habits of trona and hanksite are inferred from the known geologic history of the deposit.

The stratigraphies, lithologies, mineralogies, and crystal habits of the Mixed Layer (Illinoian? and Sangamon?) deposits show that most of them were formed in slightly saline lakes that were stratified or in short-lived highly saline lakes that desiccated frequently. The character of the Bottom Mud (early Wisconsin) shows that it was deposited in a perennial but fluctuating lake. The lower units in the Lower Salt (middle Wisconsin) represent a series of successively more saline lakes whose desiccation was postponed by intervening periods of lake expansion; the upper units represent two saline lakes that followed two more stages of lake expansion. The Parting Mud (late Wisconsin) represents a perennial lake whose level fluctuated. The Upper Salt (early Recent) was formed by a single episode of desiccation. The Overburden Mud (late Recent) was deposited on the bottom of intermittent saline lakes.

## INTRODUCTION

The Searles Lake [1] evaporite deposit, California, lies near the southwest corner of the Basin and Range province and just north of the Mojave Desert (fig. 1). The deposit was formed by a succession of late Quaternary fresh to saline lakes that alternately filled the basin and then desiccated. General descriptions of the deposit and its geologic setting are given by Gale (1914, p. 265–312), Flint and Gale (1957, p. 689–692), and Haines (1959, p. 140–147).

The deposit crops out at the surface as a bed of nearly pure halite that extends over an area of about 12 square miles. Beneath the sur-
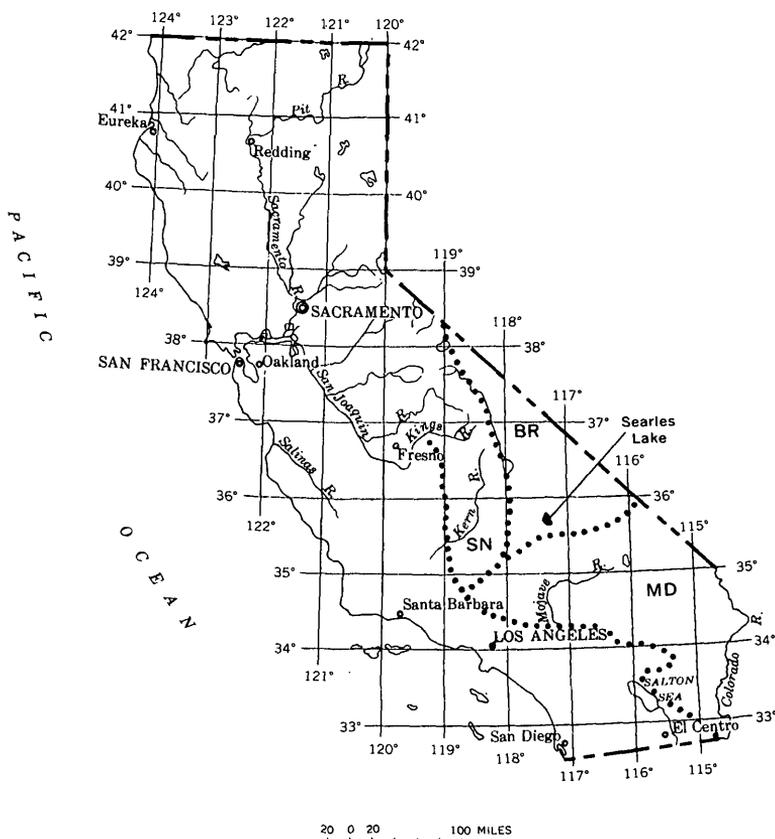


FIGURE 1.—Index map showing location of Searles Lake, Calif. Boundaries of the Sierra Nevada (SN), Basin and Range (BR), and Mojave Desert (MD) physiographic provinces shown by dotted lines.

[1] Searles Lake has been known by several other names which are used in older records. The commonest synonyms are Slate Range Lake, Alkali Flat, Borax Lake, Borax Marsh, Borax Flat, and Searles Marsh. The name Borax Lake has caused confusion in geologic literature because it is commonly not distinguished from Borax Lake in Lake County, Calif., which was the site of the earliest borax mining in the State.

face it consists of interbedded salines and muds that lie nearly flat. The subsurface saline layers have an area of about 40 square miles. Knowledge of this part of the basin fill is based almost entirely on core logs and samples from cores. The upper 150 feet of fill is known from numerous logs of cores obtained by the companies that extract chemicals from the deposit (Flint and Gale, 1958, figs. 2–4), and from logs of 41 cores (GS–1 to GS–41) described by Haines (1959). The deposits below 150 feet are sampled by 5 cores: 1 that extends 875 feet (L–W–D), see Smith and Pratt, 1957), 1 that extends to 628 feet ("Searles deep well," see Gale, 1914, p. 289), and 3 that extend to about 300 feet (kk, s1–34, and S–2, see Flint and Gale, 1958 figs. 3, 4).

This paper summarizes the areal and stratigraphic distributions and megascopic characteristics of the nonclastic minerals in the Searles Lake evaporite deposit. This information is based primarily on the cores described by Smith and Pratt (1957) and Haines (1959) but has been largely verified by inspection of about 70 logs of cores obtained by the American Potash & Chemical Corp. The stratigraphy of the deposit, as described by Flint and Gale (1958) and Smith (1962), is illustrated on figure 2. Many of the minerals in the deposit display several characteristic forms; we have correlated these forms with the stratigraphic units from which the samples came and then translated these data into the hydrologic and geochemical history of the deposit.

## ACKNOWLEDGMENTS

FIGURE 2.—Summary of subsurface stratigraphic units in the Searles Lake deposit. After Flint and Gale (1958) and Smith (1962). Note change in vertical scale at depth of 150 feet.

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## MINERALOGY

A total of 25 nonclastic minerals are known to occur in Searles Lake, 10 of which were first found in a natural state in this deposit. Many of these contain two or three cations or anions and are commonly expressed as "double" or "triple" salts. In terms of anions, 9 of the 25 minerals contain sulfate; 8, carbonate or bicarbonate; 7, chloride; 4, borate; 3, fluoride; 3, aluminosilicate; and 1, borosilicate. In terms of cations, 20 of the 25 minerals contain sodium; 6, calcium; 3, magnesium; and 4, potassium. The minerals containing calcium and magnesium are chiefly carbonates; the minerals bearing sodium and potassium may contain any of the listed anions. Ten of the 25 minerals contain water or hydroxyl ions.

The compositions of these nonclastic minerals are commonly and conveniently expressed as hypothetical combinations of salts, although these formulas do not necessarily bear any relation to the atomic arrangements of the crystals. A list of these minerals and their compositions follows.

| | |
|---|---|
| Adularia | $KAlSi_3O_8$ |
| Analcime | $NaAlSi_2O_6 \cdot H_2O$ |
| Aphthitalite | $K_3Na(SO_4)_2$ |
| Aragonite | $CaCO_3$ |
| Borax | $Na_2B_4O_7 \cdot 10H_2O$ |
| Burkeite | $2Na_2SO_4 \cdot Na_2CO_3$ |
| Calcite | $CaCO_3$ |
| Dolomite | $CaMg(CO_3)_2$ |
| Galeite | $Na_2SO_4 \cdot Na(F,Cl)$ |
| Gaylussite | $CaCO_3 \cdot Na_2CO_3 \cdot 5H_2O$ |
| Halite | $NaCl$ |
| Hanksite | $9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$ |
| Mirabilite | $Na_2SO_4 \cdot 10H_2O$ |
| Nahcolite | $NaHCO_3$ |
| Northupite | $Na_2CO_3 \cdot MgCO_3 \cdot NaCl$ |
| Phillipsite | $KCa(Al_3Si_5O_{16}) \cdot 6H_2O$ |
| Pirssonite | $CaCO_3 \cdot Na_2CO_3 \cdot 2H_2O$ |
| Schairerite | $Na_2SO_4 \cdot Na(F,Cl)$ |
| Searlesite | $NaBSi_2O_6 \cdot H_2O$ |
| Sulfohalite | $2Na_2SO_4 \cdot NaCl \cdot NaF$ |
| Teepleite | $Na_2B_2O_4 \cdot 2NaCl \cdot 4H_2O$ |
| Thenardite | $Na_2SO_4$ |
| Tincalconite | $Na_2B_4O_7 \cdot 5H_2O$ |
| Trona | $Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$ |
| Tychite | $2Na_2CO_3 \cdot 2MgCO_3 \cdot Na_2SO_4$ |

Most of the minerals listed have been repeatedly noted by workers concerned with Searles Lake. Two were not reported in the logs of Geological Survey cores (Smith and Pratt, 1957; Haines, 1959), although they have been noted in other cores. These two are galeite (Pabst and others, 1955, 1963) and teepleite (D. L. Sawyer, written communication, 1958). Galeite has subsequently been found in the Survey cores (Pabst and others, 1963, p. 487), but teepleite has not. Adularia, analcime, and phillipsite were not recognized in the Survey cores at the time they were logged, but were discovered in them after the logs were published. Analcime and adularia were first noted by R. C. Erd (oral communication, 1958) during X-ray studies of a few selected samples and were later found by Hay and Moiola (1962, 1963) to be common throughout the cores; phillipsite was first discovered by Hay and Moiola (1962, 1963).

In addition to these minerals, Gale (1914, p. 296–297) reported the presence of natron, gypsum, anhydrite, and glauberite. It is very possible that these minerals form either near the margins where waters from local surface runoff mix with the brines of the lake or locally on the surface of the lake during hot or cold days. Some may be present as clastic materials. It is not likely, however, that any of the four occurs in large quantities.

A list of all the minerals reported from the Searles Lake deposit has been compiled by Murdoch and Webb (1956, p. 23). It includes most of the minerals listed above plus eight others. Six of these— celestite, colemanite, realgar, cerargyrite, embolite, and gold— almost certainly do not occur within the deposit in normally detectable quantities. Sulfur was also reported and may be present where anaerobic bacterial activity on sulfates has been appreciable. Murdoch and Webb also report ulexite which is probably not present in the subsurface deposits, although mapping in progress shows that it occurs a few inches below the surface of some parts of the lake and in the lake sediments around the edge of the valley. These eight minerals were first attributed to the deposit by Hanks (1889, p. 66), who reported that the listed minerals "have been found associated with borax in San Bernardino County." DeGroot (1890, p. 537) published the same list, obtained either from Hanks' 1889 paper or from a common source, but indicated that all the listed minerals "have been found associated with the borax occurring in the Searles Marsh." Erroneous reports of nitrates in the Searles Lake deposit crept into the literature in a similar manner when they were originally reported from late Cenozoic outcrops on the south edge of Searles Valley and were later listed among those minerals occurring in Searles Lake (Gale, 1914, p. 297).

All the nonclastic minerals described in this report were apparently crystallized from the solutions in the original lake or from the solutions later entrapped in the beds of salines and muds. Most of their components were present in and concentrated from the original lake waters, except for the silica in adularia, analcime, phillipsite, and searlesite, which was probably derived from the solution of clastic materials or volcanic ash after burial.

In the following sections of this report, the occurrences, habits, and some of the megascopic properties of the nonclastic minerals in Searles Lake are described, primarily on the basis of material from the shallow drill holes GS-1 to GS-41 (Haines, 1959) and the deep drill hole L-W-D (Smith and Pratt, 1957); the locations of these and other core holes are shown on figure 3. Descriptions of minerals given in other publications are included where the stratigraphic positions of the specimens can be determined. The optical and crystallographic properties of these minerals are not presented because they are described in standard reference works.

In the following discussion the minerals are grouped according to whether they most commonly occur in saline or mud layers. Most of the minerals are not restricted to a single environment, but are definitely more common in one than in the other. The saline layers chiefly contain minerals composed of sodium, potassium, carbonate, bicarbonate, sulfate, chloride, and borate, which form porous aggregates of light-colored crystals. The mud layers chiefly contain minerals composed of sodium, calcium, magnesium, and carbonate, which form impervious aggregates of megascopic crystals embedded in a laminated or uniformly dark organic-rich marl. The megascopic crystals are generally gaylussite or pirssonite; the marl has a consistency approximated by wet modeling clay and consists of a complex mixture of carbonates and subordinate quantities of other salines, authigenic silicates, clastic silicates, and partly decomposed organic material.

## MINERALS ASSOCIATED WITH SALINE LAYERS

### APHTHITALITE ($K_3Na(SO_4)_2$)

Aphthitalite, a mineral known more widely by the name "glaserite" even though this term lacks priority, is one of the two potassium-bearing minerals in the Searles Lake deposit. It occurs chiefly in the central facies of the middle and upper parts of the Upper Salt. A little aphthitalite is detected in some of the mud layers, but it may have formed during the drying of entrapped brine.

Aphthitalite occurs as colorless or yellowish-orange groups of interpenetrating bladed or tabular crystals or as fine-grained aggregates.
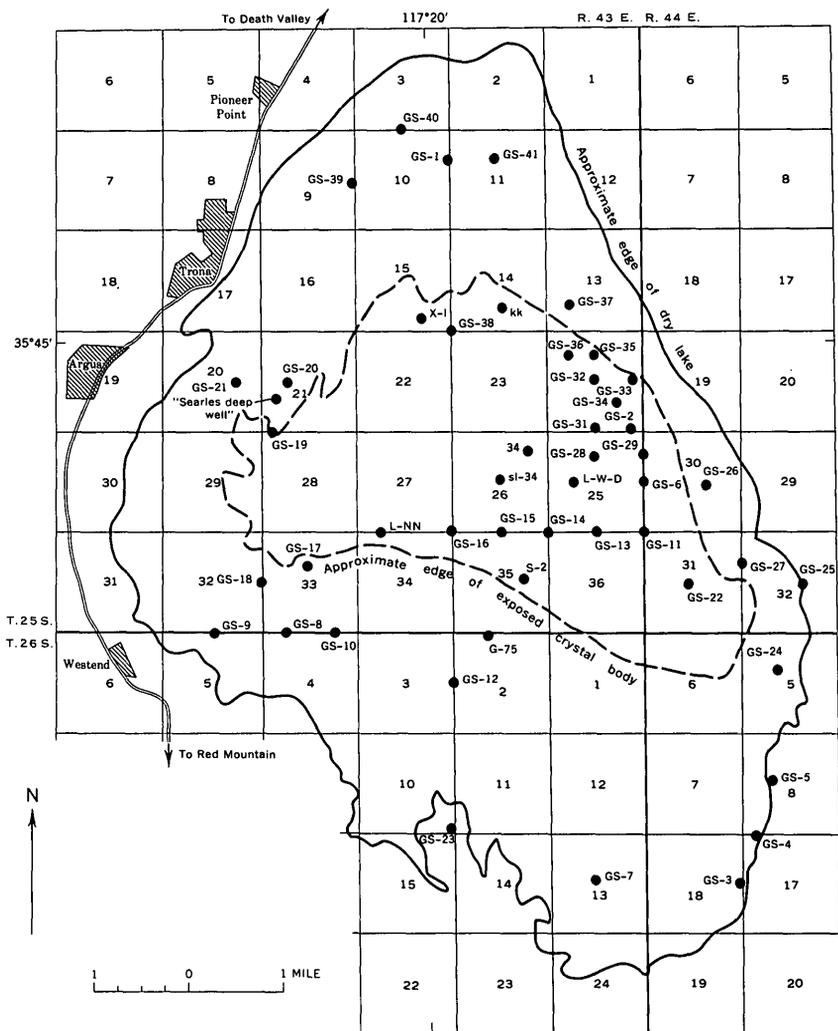
FIGURE 3.—Locations of drill cores described by Smith and Pratt (1957) and Haines (1959), and of all other cores cited in this report.

Some of the tabular crystals are distinctly hexagonal, and some of these have rows of bubbles or fluid inclusions parallel to the hexagonal outline. The blades and plates are generally 3 to 10 mm in the long dimension, 1 to 2 mm thick, and occur in pockets and thin beds. They most commonly occur as aggregates, intergrown with other minerals, and are generally oriented with the long dimension nearly vertical. In a few places, the plates partly penetrate crystals of halite; elsewhere, they grow on the undisturbed surfaces of minerals. Apthitalite is reported from beds composed chiefly of cubo-octahedral halite, bladed and massive trona, anhedral to subhedral borax, and subhedral hanksite.

## BORAX $(Na_2B_4O_7 \cdot 10H_2O)$

Borax is by far the most abundant of the four boron-bearing minerals found at Searles Lake. The highest concentrations of borax are in the Overburden Mud, Upper Salt, Parting Mud, and Lower Salt. A few small crystals are found in the top few inches and the lower part of the Bottom Mud. When fresh, borax is colorless and transparent, although locally the crystals are yellowish orange or light pink due to inclusions of micro-organisms. The surface of borax exposed to the desert air turns white within hours or days as it dehydrates to tincalconite.

Borax occurs chiefly as discrete crystals ranging in size from 0.5 mm to 15 cm. Four crystal forms are common (fig. 4): (1) stubby euhedral,[2] (2) elongate euhedral, (3) subhedral, and (4) anhedral or massive. Subhedral crystals are the most common.

The stubby euhedral crystals of borax are short and prismatic, their lengths parallel to [001] being about 1 to 2 times their width (Gale, 1914, fig. 81). They are most common in the Overburden Mud and the upper part of the Lower Salt. The crystals in the Overburden Mud are mostly in the edge facies; they occur as individuals dispersed in beds composed chiefly of cubo-octahedral halite, pirssonite, hanksite, and clay. In the Lower Salt stubby euhedral crystals occur chiefly in the edge facies of S–7, M–7, M–6, and S–4, although sporadic occurrences are found in the other units. Some of these crystals occur as beds of pure mineral, rarely thicker than 0.5 foot. Others occur in beds that are composed chiefly of other minerals but contain dispersed individual euhedral crystals; these beds are thicker and tend to occur along the top contacts of saline units and along the basal contacts of mud units. In saline units, stubby euhedral borax is most commonly
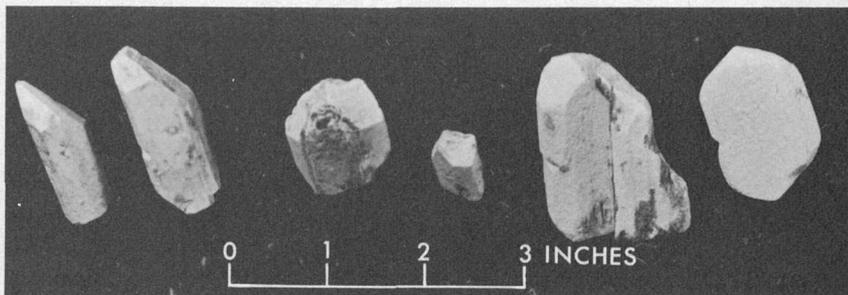


FIGURE 4.—Borax crystals showing habits most commonly noted in Searles Lake. Surface of crystals has dehydrated to white tincalconite since exposed to air.

[2] Doubly terminated crystals of borax and most other minerals in this deposit are rare, and the term "euhedral" is used loosely throughout this report to differentiate between (1) crystals that have most of their faces developed and preserved and (2) crystals that have most of their faces undeveloped or destroyed.

associated with bladed trona, but it also occurs in beds of burkeite and massive trona and in pockets containing halite and fibrous trona. In mud units it occurs in finely laminated marl, some of which contains gaylussite, pirssonite, or northupite.

Elongate euhedral borax crystals are distinctive because their lengths along [001] are 4 to 5 times their widths. Borax with this habit is characteristic of M–5 in the Lower Salt, but is sometimes found in M–4. The crystals are euhedral, from 5 to 40 mm in length, and are oriented with their long dimension parallel to the bedding or laminations (fig. 5).

Subhedral crystals, anhedral crystals, and massive borax lenses commonly occur in the same horizons. They are concentrated in two zones: (1) a zone, 5 feet thick, near the top of the Upper Salt and (2) a zone, 0.1 to 0.3 foot thick, at the contact of the Upper Salt and Parting Mud. In the upper zone, crystals of subhedral to anhedral borax that average about 20 mm in length occur as monomineralic beds 0.1 to 0.7 foot thick and also disseminated in beds of other minerals several feet thick. The chief associated minerals are cubo-octahedral halite, massive trona, and euhedral hanksite; less common minerals are fibrous trona, sulfohalite, and aphthitalite. In the lower
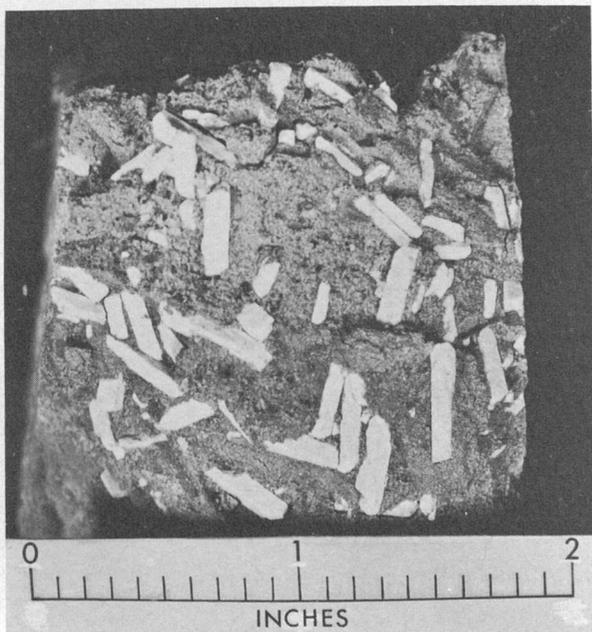


FIGURE 5.—Elongated borax crystals embedded in mud. Length-to-width ratio generally 4 : 1 or 5 : 1. Crystals of this habit found only in the stratigraphic middle of the Lower Salt.

zone, at the contact of the Upper Salt and Parting Mud, subhedral to anhedral crystals, 1 to 25 mm long, form lenses 2 to 75 mm thick in finely crystalline trona (figs. 6, 7) or in mud. The lenses parallel the trona layering and clay laminae. The parallelism of beds, shown in figure 6, suggests that borax was originally precipitated on the bottom of the lake, but in some cores veins of massive borax 2 to 15 mm wide cut across aragonite laminae or trona beds without disturbing them, indicating that some volume-for-volume recrystallization took place after burial and compaction.

### BURKEITE ($2Na_2SO_4 \cdot Na_2CO_3$)

Burkeite, first found in samples from Searles Lake (Foshag, 1935), is a common mineral in the deposit. It is the second most abundant sulfate-bearing mineral after hanksite and about the fifth most abundant carbonate-bearing mineral. It occurs chiefly in the central facies of S–4 and S–5 in the Lower Salt and decreases in abundance toward the margins. Some fine-grained burkeite is found in the Upper Salt as beds less than a foot thick and in unit C of the Mixed Layer as small pods and nodules. Traces were reported by Smith and Pratt (1957, p. 33) from the lower part of the Bottom Mud, but they have since been found to consist of borax and trona.
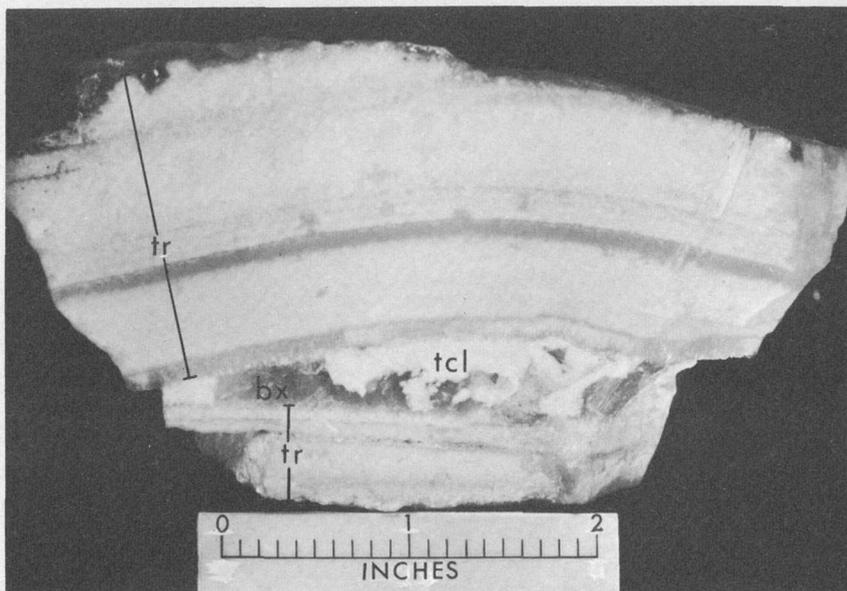


FIGURE 6.—A cut across the basal few inches of the Upper Salt, which consists of beds of trona (tr) separated by a lens of borax (bx) partly altered by the air to tincalconite (tcl). Bedding in trona is made visible by variations in the size of crystals. (See fig. 7.)
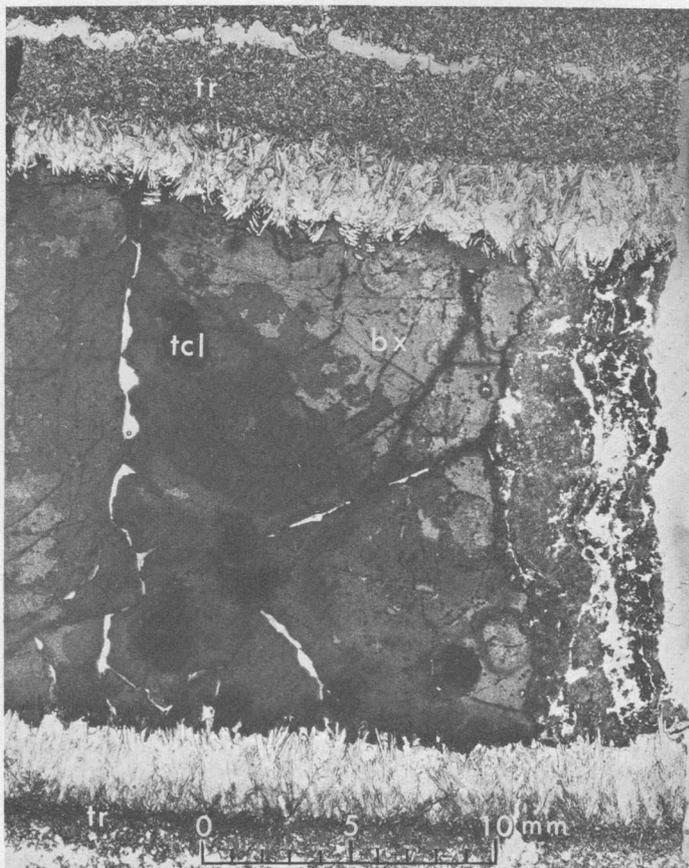
FIGURE 7.—Thin section across the bed of borax shown in figure 6. Part of borax (bx) was dehydrated to tincalconite (tcl) during thin-section grinding. The overlying and underlying beds of trona (tr) have recrystallized and have locally penetrated and replaced the borax.

In the Lower Salt, burkeite occurs as hard massive vuggy layers composed of small intergrown crystals. The specimens studied by Foshag (1935) came from this unit in well G–75 and were described as individual crystals or groups that rarely exceed 4 mm across; the individual crystals were flat, cushion shaped, and generally twinned to an X-shape. The beds of burkeite in the Lower Salt are generally hard, more than 1 foot thick, and pale orange, yellowish gray, or white. Some of these beds are composed of nearly pure burkeite; most, however, contain intermixed trona, and a few contain borax, small pockets of halite, clay, or fibrous trona. A small percentage of burkeite occurs as thin streaks, pockets, and lenses; locally in S–5, it occurs as rounded

nodules; and in a sample from M–4, it forms a rim on borax.   Foshag
(1935, p. 51) reports other associated minerals as follows: euhedral
gaylussite, euhedral pirssonite, octahedral northupite, bladed the-
nardite, octahedral tychite, rhombohedral schairerite, cubo-octahedral
sulfohalite, and euhedral hanksite.

In the Upper Salt, similar beds of burkeite contain interbeds and
pockets of megascopic crystals of hanksite or microscopic crystals of
halite, borax, and trona.

In the Mixed Layer, pods and nodules of burkeite are associated
with trona and halite.

### HALITE (NaCl)

Halite is the most abundant mineral in the Searles Lake evaporite
deposit.   The highest concentrations of it are in the Upper Salt and
in unit C of the Mixed Layer, but it is also an important constituent
of the Parting Mud, of S–4, S–5, S–6, and S–7 in the Lower Salt, and
of units B, D, and E of the Mixed Layer.

The halite crystals are mostly colorless and transparent.   In beds
they generally appear white, but they may be discolored to shades of
gray or black by mud inclusions or to pale orange or pink by micro-
organisms that occur as discrete spherical blebs about 0.1 mm in
diameter.   Inclusions of micro-organisms are most common in halite
from the surface of the lake but they are also found in samples from
as deep as 85 feet (S–5 unit, GS–2).   Also found as inclusions are
spherical bubbles, cubic crystals of halite (which themselves contain
inclusions of micro-organisms), and small trona crystals.

Halite occurs in this deposit in four distinctive forms: (1) mega-
scopic euhedral to subhedral crystals that are most commonly cubes
modified by octahedrons (see Gale, 1914, fig. 77$B$) but may be octa-
hedrons, or octahedrons modified by cubes (see Gale, 1914, figs. 77$C$,
77$D$); (2) megascopic euhedral to subhedral crystals that are almost
invariably cubes; (3) megascopic anhedral crystals; and (4) micro-
scopic crystals.

Megascopic halite crystals of the first type range in length from
less than 1 to 75 mm, averaging about 3 mm.   They predominate in
the lower and middle parts of the Overburden Mud, Upper Salt, and
Lower Salt.   Some occur as linings of vugs and large cavities (fig. 8);
others form friable to well-consolidated aggregates that may con-
tain a large proportion of open space or may be compact and granular.
Many beds of cubo-octahedral halite are nearly monomineralic.   In
the Overburden Mud, such beds may be more than 10 feet thick; in
the Upper Salt, they are generally only 2 to 4 feet thick; in the Lower
Salt, beds of nearly pure halite are generally 1 to 2 feet thick.   The
thickest and purest beds in these units are in the central part of the

deposit. Less pure beds of cubo-octahedral halite are thicker and contain intermixed mud or fine-grained trona, or megascopic crystals of nahcolite, hanksite, borax, sulfohalite, trona, or aphthitalite. As a minor constituent, halite with this habit may occur disseminated in very thin mud layers, or as lenses in trona or burkeite. Distorted crystals are not uncommon; most are flattened to form rectangular prisms, some of which parallel the bedding. Aggregates of such flattened crystals cause lineation, but such features are uncommon and confined to thin layers.

Megascopic cubes of halite predominate in units B, C, D, and E of the Mixed Layer and are the form most commonly found on the present surface of the deposit. They range in size from about 1 to 30 mm, averaging about 5 mm. Most aggregates of these crystals are massive and have a low porosity. Monolithologic beds of them may be as thick as 25 feet, but are mostly only a few inches thick. Where mixed with other minerals, trona is the most common associate; but small amounts of nahcolite, northupite, sulfohalite, burkeite, and thenardite are found.
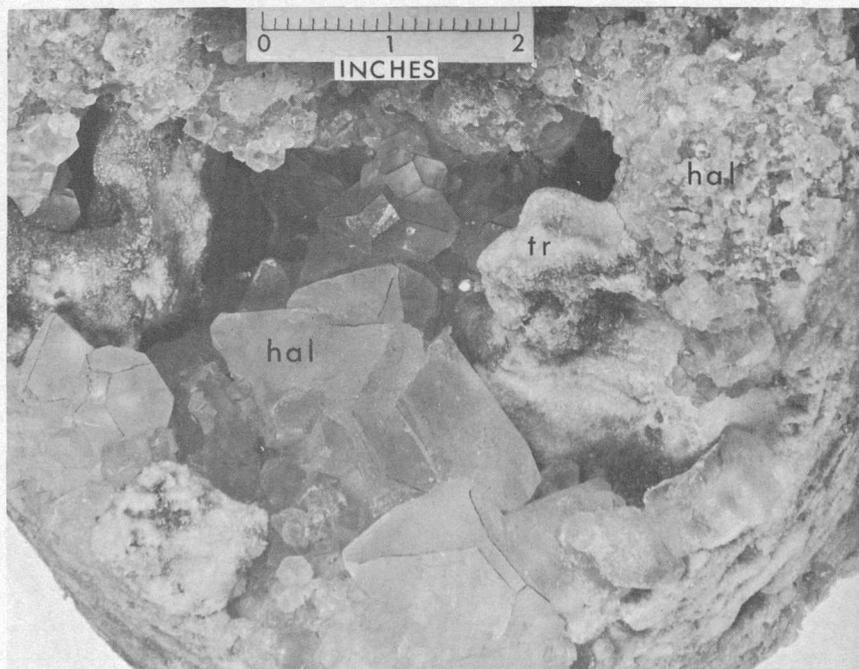


FIGURE 8.—Large halite (hal) crystals in a vug; faces are predominantly octahedrons modified by cubes. Smaller halite crystals are similar. Fine-grained trona (tr) forms part of the inner surface of the vug.

Megascopic anhedral crystals of halite are characteristic of several horizons within the Overburden Mud, especially those between 5 and 15 feet deep in the northeastern part of the deposit. These crystals are normally clear and glassy and 3 to 15 cm in length. Some of them are fractured and angular, others are well rounded. Both habits appear to be the result of wave action and partial solution by undersaturated solutions at times when these horizons formed the surface of the lake. Most such crystals are embedded in greenish mud but a few are associated with hanksite or pirssonite.

Microscopic and submicroscopic crystals of halite have been noted chiefly in the Parting Mud, but have been detected in M–2, M–3, and M–6 of the Lower Salt and throughout the Bottom Mud. Chemical analyses combined with X-ray diffraction show that in parts of the Parting Mud they constitute as much as 35 percent of the sediment. Their habits have not been studied in thin section because they are generally embedded in or coated with very fine grained carbonate minerals.

### HANKSITE ($9Na_2SO_4 \cdot 2Na_2CO_3 \cdot KCl$)

Hanksite was first found in samples from Searles Lake (Hidden, 1885). It is the third most abundant mineral in the saline layers and is by far the most abundant of the two potassium-bearing minerals. Hanksite occurs chiefly in middle and upper parts of the Upper Salt as beds as much as 5 feet thick of euhedral crystals. These crystals commonly range in length from 5 to 30 mm and average about 10 mm, but crystals 150 mm in length may be found. Horizontal striations parallel to $[10\bar{1}0]$ are present on many crystals (fig. 9). Fracture surfaces of these crystals are subconchoidal, and some show small iridescent patches. Most of the crystals are transparent; some of them
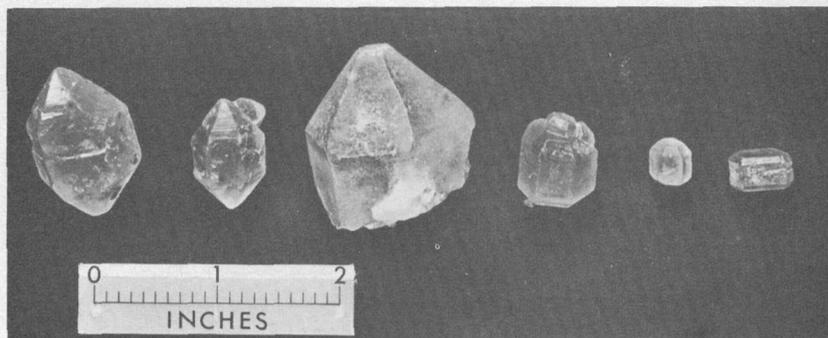


FIGURE 9.—Hanksite crystals found in Searles Lake showing variation in habits. Crystal on left shows only prism and pyramid faces; toward the right, the basal pinacoid becomes more prominent, the pyramids less so, and the overall length-to-width ratio decreases. The pyramids are commonly striated.

are colorless, but most are tinted faint yellow, orange, brown, or gray. Discrete inclusions of mud are common in crystals embedded in mud; in most crystals such mud inclusions are randomly distributed, but in a few they are zonally arranged parallel to the hexagonal outlines of the crystal. Some of the crystals tinted orange contain visible blebs of micro-organisms, and some of the crystals tinted brown and gray contain microscopic inclusions of mud.

Hanksite occurs chiefly in three forms: (1) as individual euhedral crystals that are singly or doubly terminated with prominent pryramidal faces (Gale, 1914, fig. 84*A*, and the three crystals in the left half of figure 9 of this report); (2) as individual euhedral to subhedral crystals that are doubly terminated with prominent basal pinacoid faces (see Gale, 1914, fig. 84*B*, and the three crystals in the right half of figure 9 and in figure 10 of this report); and (3) as aggregates of subhedral to anhedral crystals.

Most of the singly or doubly terminated crystals with prominent pyramids also have well-developed to dominant prismatic faces; in a few crystals, however, the prismatic zone is suppressed, and the crystals are bounded dominantly or entirely by pyramidal faces. The basal pinacoid may be present as a minor face. Crystals of pyramidal
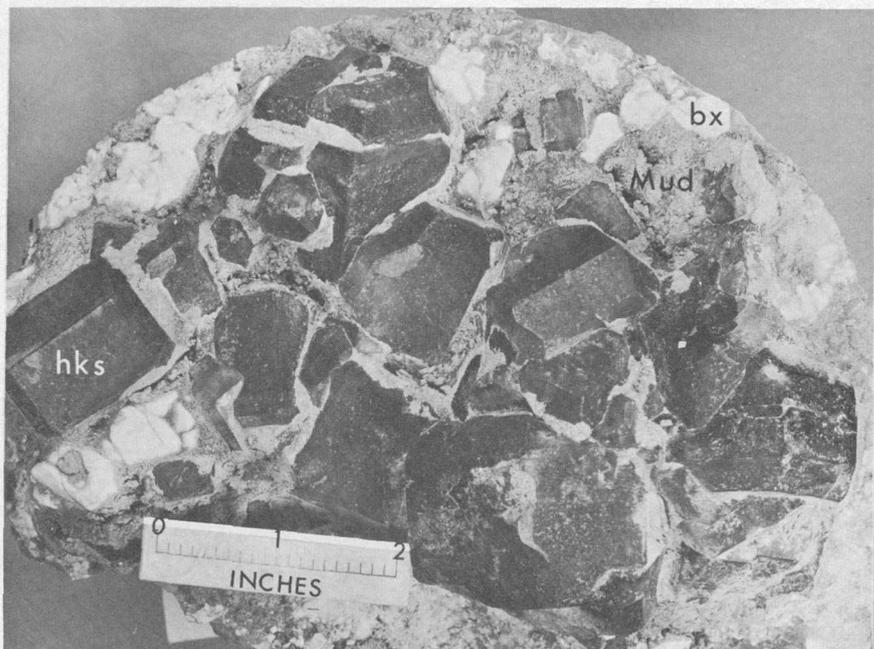


FIGURE 10.—Euhedral hanksite (hks) and borax (bx) crystals embedded in greenish mud. The hanksite crystals are chiefly the stubby variety with pinacoid and prism faces predominating. The borax has altered to white tincalconite in the air.

hanksite generally occur in friable intergrown aggregates that are vuggy to cavernous. Most such aggregates of this mineral lie near the top of the Upper Salt, but beds containing a large percentage of such crystals are common throughout this unit. Many of the beds in the upper part are nearly monomineralic; others contain a small percentage of mud, halite, borax, and fibrous or massive trona that is either interstitial to the hanksite crystals or is in pockets and thin layers. As a minor constituent, pyramidal hanksite crystals occur dispersed as thin layers or small vugs in burkeite or as disseminated crystals in beds of trona, halite, or mud.

Euhedral to subhedral hanksite crystals with dominant basal pinacoid faces are found chiefly in the middle and lower parts of the central facies of the Upper Salt and in S–3, S–4, and S–5 in the Lower Salt. They occur as euhedral individuals or densely packed intergrown masses (fig. 10). They range in length from 1 to 16mm, averaging about 10 mm. The intergrown masses commonly have interstitial bladed or massive trona or massive northupite. Small quantities of pinacoidal hanksite crystals are intermixed with fibrous trona in halite, in vugs within blackish mud, or in massive and bladed trona. In the Upper Salt, hanksite crystals of this type form beds, as thick as 0.7 foot, associated with pockets of massive trona and disseminated sulfohalite octahedra or with minor interstitial halite with which the hanksite crystals may be intergrown.

The aggregates of subhedral to anhedral hanksite crystals occur sporadically as beds as thick as 2 feet in all parts of the Upper Salt. These aggregates are commonly vuggy, and many of the vugs are lined with euhedral hanksite crystals or small quantities of fibrous or fine-grained trona, halite, borax, or dark-colored mud.

### NAHCOLITE (NaHCO$_3$)

Nahcolite is relatively uncommon among the minerals in Searles Lake and was one of the more recent minerals to be discovered in the deposit (Foshag, 1940). It occurs in small amounts in S–1 and S–6 of the Lower Salt, in the Bottom Mud, and in units A, B, C, and D of the Mixed Layer. It has not been found in the Upper Salt.

Nahcolite crystals are transparent to tranlucent and colorless to faint yellow or olive brown. Crystals from the Lower Salt and top part of the Bottom Mud range in length from 3 to 20 mm, and may average about 5 mm in length; those from the rest of the Bottom Mud and Mixed Layer are rarely more than 10 mm long and are mostly less than 1 mm long. The crystals form intergrown and interpenetrating aggregates that are as thick as 0.2 foot in the Lower Salt and as thick as 2 feet in the Bottom Mud and Mixed Layer.

The aggregates in the Lower Salt may contain interstitial massive or bladed trona, northupite, tychite, thenardite, or black mud with or without gaylussite.  In well 34, Foshag (1940, p. 770) reports some associated borax.  Aggregates in the Bottom Mud and unit A of the Mixed Layer contain or are associated with trona, gaylussite, and northupite; aggregates in unit B of the Mixed Layer are associated with trona, gaylussite, and halite; in unit C they are associated with trona and halite; and in unit D with pirssonite.

Megascopic crystals of nahcolite are generally twinned to form "fishtail" crystals (fig. 11).  Both contact and penetration twins are found, and this twinning is responsible for V-shaped or chevronlike striations on the crystal surfaces (Foshag, 1940, p. 773–775, figs. 4–12).  The striations give a silky luster to the surfaces on which they are present, but most are difficult to see without magnification.

### SULFOHALITE ($2Na_2SO_4 \cdot NaCl \cdot NaF$)

Sulfohalite, first discovered in well cuttings from the "Searles deep well" in Searles Lake (Hidden and Mackintosh, 1888), is probably the most abundant fluoride-bearing mineral in the deposit. Small quantities of it are found throughout the mud and saline units
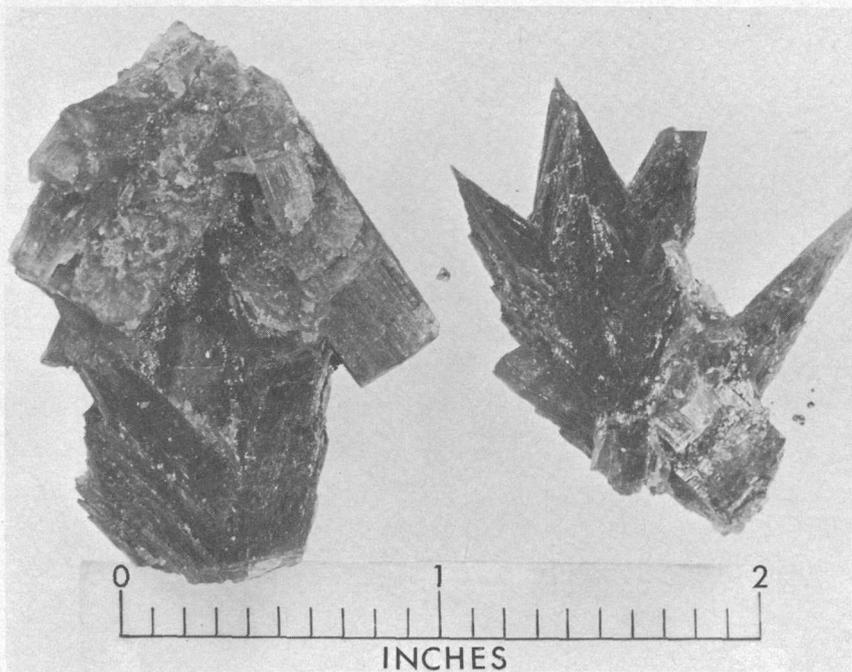


FIGURE 11.—"Fishtail" twinned nahcolite crystals from the top of the Bottom Mud. Dark color is due to mud inclusions.

of both the Upper and Lower Salt, though it is more common in the Upper Salt. Traces are found in units B, C, D, and E of the Mixed Layer.

Sulfohalite generally occurs as euhedral to subhedral octahedrons, some of which are modified by small cube and dodecahedral faces. Occurrences of massive sulfohalite have been noted.

The most common habit of sulfohalite in the Upper Salt is as disseminated octahedra in a matrix of mud, halite, trona, hanksite, or borax. Locally, however, zones containing as much as 10 percent sulfohalite octahedra occur in beds as much as 10 mm thick. In the Lower Salt, sulfohalite occurs in M–5 and S–5 as crystals associated with northupite and tychite. In the Mixed Layer, sulfohalite octahedra are associated with halite, trona, tychite, thenardite, northupite, gaylussite, pirssonite, and mud.

### TEEPLEITE ($Na_2B_2O_4 \cdot 2NaCl \cdot 4H_2O$)

Teeple (1929) first prepared the compound that now bears his name while studying the phase relations applicable to the Searles Lake brines. He predicted (1929, p. 180) that this mineral would occur in Searles Lake if the brines were to reach the end point of crystallization, but it was first found in Borax Lake, Lake County, Calif. (Gale and others, 1939). More recently, however, samples of teepleite were obtained from the lower part of the Lower Salt (D. L. Sawyer, written communication, 1958). These specimens may be either naturally formed deposits or a product of reactions that occurred as the brines in different saline layers of the Lower Salt were mixed during drilling.

### THENARDITE ($Na_2SO_4$)

Thenardite is perhaps the third most abundant of the sulfate minerals at Searles Lake. It occurs in the Overburden Mud, near the top of the Upper Salt, in S–7 and S–5 of the Lower Salt, locally in the top part of the Bottom Mud, and in the lower part of unit C of the Mixed Layer. It is most common near the margins of the deposit.

Thenardite occurs in euhedral to subhedral crystals, most of which are tabular or bladed and twinned. (See Gale, 1914, figs. 79A, B, and C.) The crystals are yellow or colorless, transparent or translucent, and range in length from 5 to 95 mm averaging about 20 mm. They occur in vuggy layers where they form interpenetrating aggregates, radiating aggregates, or cruciform twins.

In the Overburden Mud and Upper Salt, thenardite occurs as thin vuggy layers containing interstitial fibrous trona, mud, halite, or borax or as thicker beds containing pockets of massive trona. In S–7 and S–5 of the Lower Salt, similar beds as thick as 0.2 foot are

associated with interstitial clay and bladed or massive trona. In the Bottom Mud, it forms vuggy aggregates of large euhedral to subhedral crystals associated with trona and nahcolite. In the Mixed Layer, thenardite is associated with halite, trona, sulfohalite, and pirssonite.

### TINCALCONITE ($Na_2B_4O_7 \cdot 5H_2O$)

Cryptocrystalline aggregates of secondary tincalconite form on the surface of borax crystals after they have been exposed to dry air for a few hours or days (fig. 4).

Primary crystals of tincalconite have been reported only twice from Searles Lake. They are megascopic minerals that were clearly formed in the deposit, though it is possible that this happened only within the last few years as a result of the brine mixing that occurs during core drilling. Such crystals were first described from well X-1 by Pabst and Sawyer (1948). The specimens—clear rhombohedron individuals—were found in cores taken from about 2 feet above the base of the Lower Salt in the central part of the lake in unit S-1. Within those crystals, small inclusions of northupite and gaylussite were noted. The second occurrence of coarsely crystalline tincalconite was found in saline layers within the Overburden Mud in core GS-2. These crystals formed a smooth solid coating on the surface of a large borax crystal, but crystal faces are developed in small vugs between the coating and host mineral (fig. 12).

### TRONA ($Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$)

Trona is the second most abundant mineral in the evaporite deposit after halite. It occurs in every saline unit, but is most abundant in the lower parts of the Lower and Upper Salts and in units A and B of the Mixed Layer.

Most trona crystals are translucent and white, but beds of them may be white, grayish yellow, light orange, grayish green, or dark greenish gray. Some of the difference in color results from variations in crystal size (fig. 7) and some of it from inclusions of microorganisms, mud, or other evaporite minerals.

Trona occurs in this deposit chiefly in three forms: (1) fine-grained aggregates composed of microscopic acicular crystals, (2) coarse-grained aggregates composed of fibrous or acicular crystals, and (3) coarse-grained aggregates composed of bladed crystals. Fine-grained trona is the most abundant form and is most likely to be in beds containing no other forms of trona or other minerals, but trona with all three habits may be closely associated.

Fine-grained aggregates composed of microscopic acicular crystals of trona occur in every saline unit of the deposit. They are most
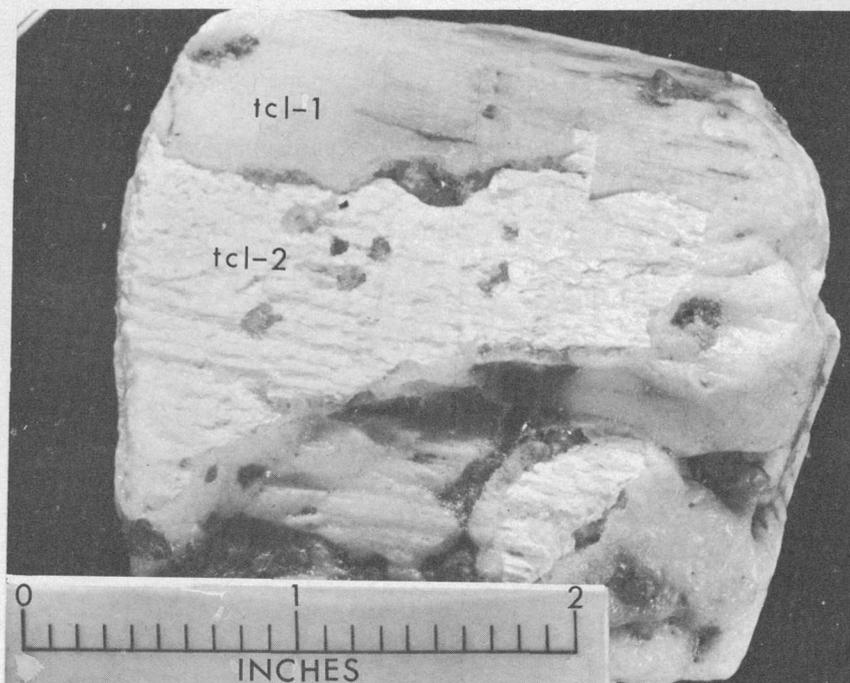
FIGURE 12.—Two forms of tincalconite. A primary form (tcl-1) was crystallized as a coating on the underlying borax crystal while still in the brine; it forms a dull very light gray coating with a smooth outer surface and euhedral crystals on the inner surface where a vug occurs. The secondary tincalconite (tcl-2) was formed after the borax surface was exposed to the air. The dark patches are crystals of other minerals and mud. Sample from GS-2, near the middle of the Overburden Mud.

prominent at the base of the Upper Salt where they form a succession of massive beds, each a fraction of an inch to a foot thick, that combine to form a layer as much as 12 feet thick (Haines, 1959, pl. 10). These beds are commonly wavy and contorted and are separable either by slight differences in color (fig. 6) or by intervening narrow vuggy layers lined with much larger fibrous or bladed trona crystals. Similar but thinner layers of trona occur throughout the middle and upper parts of the Upper Salt and in all saline units of the Lower Salt. In the edge facies of the Upper Salt and throughout the Lower Salt, fine-grained aggregates of trona are generally mixed or interbedded with individual crystals or aggregates of megascopic bladed or fibrous trona. In the Upper Salt, some of the fine-grained trona beds contain large crystals of halite, borax, or hanksite, small crystals of burkeite, or mud; in the Lower Salt, such beds contain halite, burkeite, borax, and mud. In the Bottom Mud, small nodules of fine-grained trona occur most commonly in thin beds or pods or in the interstices of bladed trona aggregates, but the mineral also occurs as a minor con-

stituent in small pockets and lenses and as a filling in the interstices of other minerals.

Coarse-grained aggregates composed of megascopic fibrous or acicular trona crystals are most commonly arranged in a matted patern but also in small groups that are systematically orientated.   In the Upper Salt, Lower Salt, and some parts of the Mixed Layer, these aggregates have a high porosity; in most parts of the Mixed Layer, though, they have a medium to low porosity.   Such aggregates are prominent in the edge facies of the Upper Salt, in all saline units in the Lower Salt, but especially in S-6 and S-7, and in all units except E of the Mixed Layer.   The acicular crystals range in length from about 1 to 25 mm and average about 3 mm.   The individual crystals are euhedral to subhedral and are marked by striations parallel to [010], which is also the direction of elongation of the fibers.   Although individual crystals are colorless and transparent, aggregates of them are mostly white or yellowish gray.   Some are discolored gray by interstitial mud or orange-pink micro-organisms that coat the exterior or are included within the crystals.   Fibrous trona occurs in the Upper and Lower Salt as beds containing interstitial mud, sulfohalite, or thenardite, and as thin layers and small pockets in halite, hanksite, borax, burkeite, northupite, fine-grained trona, and bladed trona.   It occurs in the Mixed Layer most commonly as thin beds, some of which contain interstitial fine-grained trona.   In unit A, these beds may also contain halite, gaylussite, pirssonite, nahcolite, tychite, and searlesite; in unit B, halite, gaylussite, pirssonite, and nahcolite; in unit C, halite, pirssonite, sulfohalite, burkeite, thenardite, and northupite; in unit D, halite, pirssonite, sulfohalite, and tychite; and in unit F, halite and pirssonite.

Megascopic bladed crystals are the least common of the three forms of trona in the evaporite deposit.   Nevertheless, they are very characteristic of the edge facies of S-7 and all parts of S-4, S-3, S-2, and S-1 of the Lower Salt, and a few parts of the Mixed Layer.   The blades are lathlike crystals that are most prominently elongated parallel to [010] but they also have their widths elongated to 2 to 4 times their thicknesses.   They range in length from 2 to 45 mm and average about 10 mm (fig. 13).   Striations on them parallel [010].   They are generally colorless and transparent to translucent.   Blades of trona occur characteristically as layers as much as 2 feet thick consisting of interpenetrating aggregates embedded in fine-grained trona or some other mineral (fig. 13).   Some of these aggregates contain thin beds of finely laminated mud.   Locally the trona blades cut upward across the mud laminae, but the laminae are also slightly bent upward near the margins of the blades, indicating that the crystal
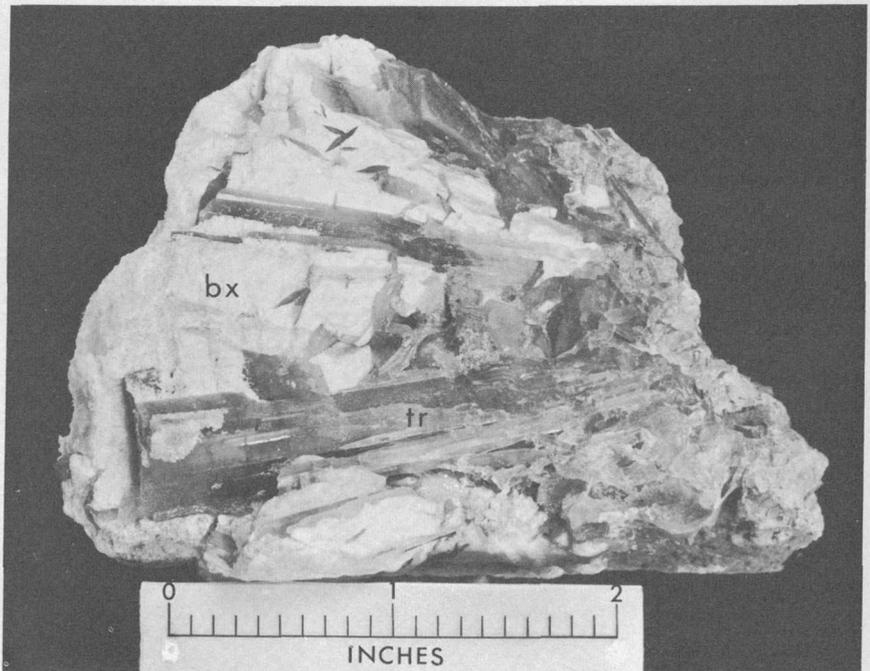
FIGURE 13.—Trona (tr) blades penerating borax (bx) altered to tincalconite. Note the lenticular cross sections of blades in the upper part of specimen.

growth took place after burial but that differential compaction of the clay was not completed until still later. In the Upper Salt, blades of trona occur sporadically where they are associated with borax, fibrous or finely crystalline trona, and hanksite. In S-7 of the Lower Salt, bladed trona is closely associated with microscopic crystals of pirssonite, stubby euhedral borax, fibrous trona, and thenardite; in S-5, with massive trona, cubo-octahedral halite, stubby euhedral borax, and pirssonite; in S-4, S-3, S-2, and S-1, with fibrous and fine-grained trona, stubby euhedral borax, fine-grained massive northupite, and locally with burkeite (S-4), tychite (S-3, S-1), pirssonite (S-5, S-3), and nahcolite (S-1).

## MINERALS ASSOCIATED WITH MUD LAYERS

### ADULARIA (KAlSi$_3$O$_8$)

An authigenic monoclinic K-feldspar, probably adularia, is found in samples from the lower half of the Bottom Mud and from most units of the Mixed Layer (R. C. Erd, oral communication, 1958; Hay and Moiola, 1962, 1963, p. 323). It forms as much as 20 percent of non-tuffaceous sediments and as much as 50 percent of tuffaceous layers. Individual crystals are mostly a few microns in size and generally are

intergrown to form aggregates. Adularia forms major percentages of samples containing gaylussite, pirssonite, aragonite, and searlesite, but forms only low percentages or is absent in samples containing analcime.

### ANALCIME ($NaAlSi_2O_6 \cdot H_2O$)

Analcime crystals, a few microns in diameter, have been found in samples from the top of the Overburden Mud, from the lower part of the Parting Mud, from mud layers within the Lower Salt, from the Bottom Mud (between 150 and 170 ft and near 220 ft), and from mud layers within the Mixed Layer (R. C. Erd, oral commun., 1958; Hay and Moiola, 1962, 1963, p. 323). It forms as much as 10 percent of nontuffaceous sediments and as much as 20 percent of tuffaceous layers. Analcime coexists with major amounts of pirssonite, gaylussite, aragonite, searlesite, and dolomite, and only minor to trace amounts of adularia.

### ARAGONITE ($CaCO_3$)

Prominent beds of almost pure aragonite occur as white laminae in the upper third of the Parting Mud (see fig. 14), in M–2 and M–3 of the Lower Salt, in the lower third of the Bottom Mud, and sporadically in the Mixed Layer. Aragonite has been identified repeatedly by X-ray diffraction, but crystals of it have not been studied or confirmed optically because they are only a few microns in size. In all thin sections studied, the heat of grinding has recrystallized the mineral to coarser grained carbonate.

The aragonite laminae, which commonly are lenticular, range in thickness from about 0.01 to 2 mm and are composed of white to dark-gray aggregates of very small crystals. The laminae have sharp boundaries with the enclosing dark-gray or green mud and are generally much thinner than the darker layers that separate them.

### CALCITE ($CaCO_3$)

Calcite is much less common than aragonite. Very small percentages of small crystals have been found at the base of the Upper Salt and in the Parting Mud and Bottom Mud. Those in the Upper Salt are euhedral; those in the mud layers are mostly of unknown form because detected only by X-ray diffraction. Calcite is associated with adularia, aragonite, halite, searlesite, thenardite, analcime, and lower than normal (though major) percentages of megascopic and microscopic gaylussite. In the Parting Mud it is extremely rare and is restricted to white laminae composed chiefly of aragonite. In the Bottom Mud, microscopically visible crystals of calcite form small, lenticular, monomineralic lenses or pockets, 0.5 to 2 mm long, that are white, yellow, or dark green. These occur in finely laminated
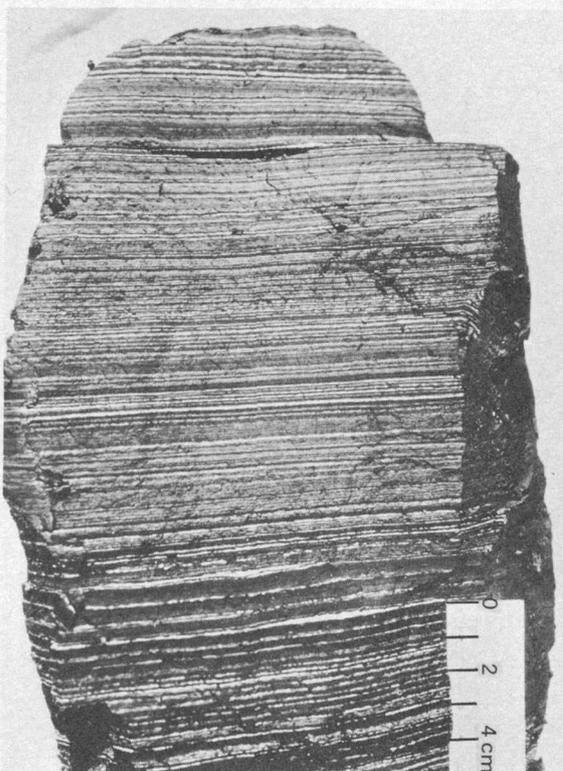
FIGURE 14.—Thin beds of aragonite (white layers) in the Parting Mud. Maximum thickness of an aragonite layer in this sample is about 1 mm.

mud, which in one sample (from GS–14, 125.0 ft) contains large amounts of megascopic gaylussite and microscopic dolomite and small amounts of microscopic halite, thenardite, and gaylussite.

### DOLOMITE (CaMg(CO$_3$)$_2$)

Dolomite occurs as clay-sized crystals in some mud layers in the Searles Lake deposit. In a few samples it is nearly pure and forms distinctive buff- or tan-colored veinlets or blebs; more commonly, however, it is intermixed with other components and can be only detected by X-ray methods.

The highest known concentrations of dolomite are at the top and base of the Parting Mud and in the top few feet and the bottom 40 feet of the Bottom Mud, but several percent of dolomite are detected sporadically in intervening parts of both sections. Small euhedral crystals occur in trona at the base of the Upper Salt (R. C. Erd, written communication, 1963). Dolomite is virtually absent from the mud layers within the Lower Salt and from the Overburden Mud.

In the Parting Mud the highest concentrations of dolomite are accompanied by megascopic crystals of gaylussite or pirssonite and microscopic crystals of gaylussite or pirssonite, aragonite, halite, and trona. Although dolomite and aragonite coexist, the highest concentrations of dolomite are in layers with low concentrations of aragonite and vice versa. In the Bottom Mud, dolomite is accompanied by megascopic crystals of gaylussite and microscopic crystals of gaylussite, halite, analcime, trona, thenardite, borax, adularia, and clastic minerals.

### GALEITE (Na$_2$SO$_4$·Na(F,Cl))

Galeite, a mineral which has the same formula as schairerite but which contains a slightly lower percentage of fluorine, was first described by Pabst and others (1955, 1963) from cores drilled by the American Potash & Chemical Corp. The first crystals of galeite so identified came from a depth of 113 feet in core L–NN. Although unit M–5 lies at that depth in core L–NN, most of the other specimens used in the investigation of Pabst and others (1963, p. 487) apparently came from a lower horizon, below the layers richest in burkeite, and thus probably unit M–2, M–3, or M–4. Those crystals were white, either barrel shaped or tabular, and 1 mm or less in size. They were intimately associated with gaylussite, northupite, trona, or (less commonly) tychite.

Galeite was not reported in the core logs by Haines (1959), but crystals from M–2, described from GS–17 (107.4 ft) and GS–41 (93.9 ft) as schairerite, have been subsequently studied and identified as galeite (Pabst and others, 1963, p. 487). These crystals are the same color and size as those previously described by Pabst; the crystals from GS–17 are mostly tabular, and the ones from GS–41 are barrel shaped. In these two samples, galeite is associated with trona, northupite, gaylussite, and clay.

### GAYLUSSITE (Na$_2$CO$_3$·CaCO$_3$·5H$_2$O)

Gaylussite is one of the common minerals at Searles Lake and is probably the most abundant calcium-bearing mineral. It is generally confined to mud layers and is especially prominent in the Parting Mud, in M–2, M–3, M–4, M–6, and M–7 of the Lower Salt, in the Bottom Mud, and in the units A and B of the Mixed Layer.

Gaylussite occurs mostly in three forms: (1) megascopic euhedral crystals, (2) megascopic subhedral to anhedral crystals, and (3) microscopic crystals that can only be detected by X-ray diffraction. The two megascopic forms do not generally occur together, although microscopic crystals of gaylussite occur in most of the beds that contain larger crystals. Associated in places with the subhedral and anhedral gaylussite is massive gaylussite, which forms anastomosing

veinlets in mud and acts as a cement in binding large masses of mud together.

The megascopic euhedral gaylussite crystals are wedge shaped (Gale, 1914, figs. 87A, B), clear, colorless, and transparent. They range from silt sizes to about 5 mm long, although most are between 1 and 2 mm long. Some contain inclusions of mud or reddish-brown micro-organisms. The crystals generally occur as individuals or intergrown clusters of two or three individuals that are either disseminated in mud or concentrated in thin beds. Some of these beds are "graded," with the crystals decreasing in size from the top of the bed to the bottom. Beds of euhedral gaylussite crystals are charateristic of M-2, M-3, M-4, and M-5 in the Lower Salt; in M-5 the euhedral crystals are silt to sand size and form an abnormally low percentage of the bed. A few beds containing disseminated euhedral gaylussite crystals occur in the Bottom Mud and Mixed Layer. The beds containing high concentrations of euhedral gaylussite crystals are mostly free of other megascopic minerals, although a few have included northupite nodules or borax crystals, and some alternate with thin beds containing clay, massive or nodular northupite, or bladed trona.

Megascopic subhedral to anhedral crystals of gaylussite average about 5 mm long, but frequently are larger and may be more than 50 mm long. The crystals near the top of the Bottom Mud are abnormally large and average about 15 mm in length. The crystals occur as randomly oriented disseminated individuals or as friable aggregates of crystals in pockets or layers that may be several inches thick. The individual crystals in the aggregates do not generally show any preferred orientation. In a few beds, though, they are in radial arrays or in rows of vertical crystals. These megascopic crystals have grown in the muds after deposition, and where they penetrate enclosing laminated beds, the fine laminae are generally not disturbed by warping or bending due to crystal growth (fig. 15); this indicates a volume-for-volume replacement after compaction was complete. Subhedral and anhedral crystals of gaylussite are most abundant in the Parting Mud and units A and B of the Mixed Layer, but they occur also in M-6 and M-7 of the Lower Salt. In the Parting Mud, they occur with megascopic crystals of borax and microscopic crystals of gaylussite, halite, dolomite, and aragonite. In M-6 and M-7 they lie near (but not in direct contact with) megascopic crystals of pirssonite and coexist with megascopic crystals of borax and microscopic crystals of aragonite. In the Bottom Mud and Mixed Layer, crystals with this habit generally constitute 30 to 75 percent of the layer in which they occur. Generally there are no other megascopic crystals in the bed, but microscopic crystals of adularia, analcime,

dolomite, calcite, halite, and gaylussite are detected by X-ray diffraction of the fine material that forms the matrix.

Microscopic crystals of gaylussite occur in most layers containing megascopic gaylussite. In the central facies of units M–6 and M–7 they occur in layers containing both megascopic and microscopic crystals of pirssonite.
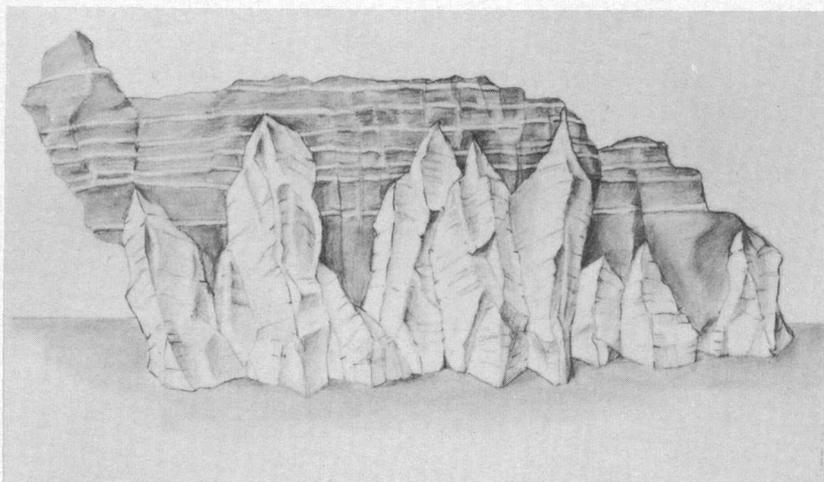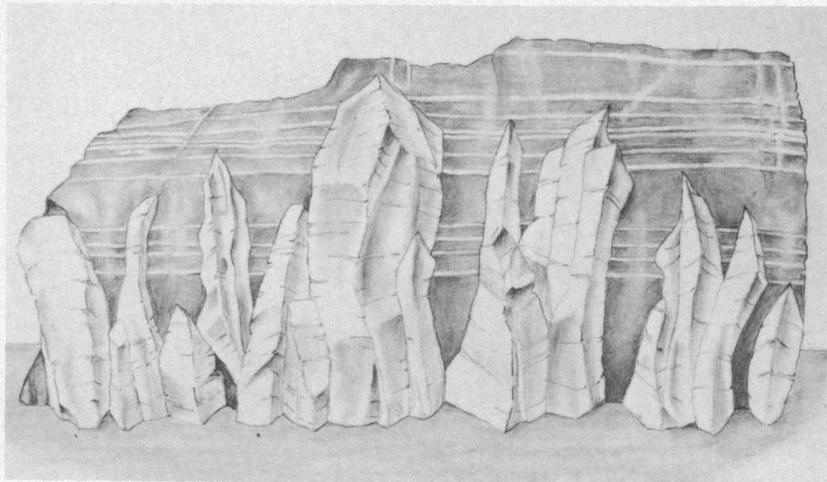


FIGURE 15.—Sketches made from photographs of relations between gaylussite (vertical crystals) and laminated muds that indicate volume-for-volume replacement of muds. Upper specimen about 4 cm wide; lower specimen about 3 cm wide. Drawing by Esther T. McDermott.

## MIRABILITE (Na$_2$SO$_4$·10H$_2$O)

Beds of mirabilite are known only from a zone 10 to 30 feet below the top of the Bottom Mud. Fine-grained aggregates of the mineral occur in pockets and beds as much as several inches thick, enclosed in mud containing gaylussite. In most occurrences, the mineral aggregates are clear or translucent and relatively free of mud.

Large tonnages of mirabilite are formed artificially by the American Potash & Chemical Corp. at Searles Lake by spraying brine from the Upper Salt into the air when the temperature is near freezing. Naturally occurring encrustations of the mineral may also form in some of the surface brine pools on the lake during these cold periods.

## NORTHUPITE (MgCO$_3$·Na$_2$CO$_3$·NaCl)

Northupite was first found and described in samples taken from the "Searles deep well" at a depth of 450 feet in Searles Lake (Foote, 1895). It is perhaps the most abundant magnesium-bearing material in Searles Lake, as it is relatively common in the Lower Salt, Bottom Mud, and Mixed Layer, but is very sparse in the Upper Salt. Northupite occurs as (1) octahedra, (2) nodules composed of microscopic crystals, and (3) layers or veins composed of aggregates of microscopic crystals.

Northupite octahedra are mostly colorless or yellow, transparent or slightly clouded. They range from 0.1 to 3 mm across and average about 1 mm. They occur as disseminated crystals, as intergrown and interpenetrating groups, and as aggregates arranged in the form of beds 2 to 10 mm thick or pockets 5 to 50 mm long. In the edge facies of the Upper Salt, northupite octahedra are embedded in trona that lies a few inches from the base of the unit. Northupite octahedra occur in the marginal facies of M–6 and in thin mud layers within S–7, where they are intimately associated with microscopic crystals of pirssonite, sulfohalite, or tychite. Octahedra occur in all units in the Mixed Layer, but are most common in unit D. They are closely associated with gaylussite and pirssonite in unit A, with no megascopic minerals in unit B, with pirssonite in units C, D, and F, and with pirssonite and halite in unit E.

Northupite occurs more commonly as nodules composed of microscopic crystals Nodules of northupite in this form occur most commonly disseminated in finely laminated mud beds, a few of which contain gaylussite, borax, or burkeite. The nodules are white to grayish yellow, soft, round to oval masses, ranging in size from 0.05 to 5 mm and averaging 1 mm. The nodules that are round are randomly distributed or faintly arranged in layers; the nodules that are oval shaped form distinct layers that parallel laminae in the clay. Nodules

are most abundant in M–4 of the Lower Salt, but are present also in M–2, M–3, and M–5 and in a clay layer in S–4; their percentages are highest in the central part of the deposit and lower toward the margins.

Northupite also occurs as slightly contorted but well-defined layers composed of aggregates of microscopic crystals. The fine-grained material is generally soft, creamy, and very pale orange. These layers average about 10 mm in thickness, but range from 1 to 20 mm. They are most abundant in M–3 and M–4 of the Lower Salt, but occur also in S–1, S–2, S–3, S–4, S–5, and M–6. A few thin beds are found in the Bottom Mud. This is the only form of northupite that occurs in both mud layers and saline layers free of mud; octahedra and nodules of northupite occur only in mud units. In the mud layers, the layers of fine-grained northupite are generally in beds free of megascopic gaylussite or pirssonite crystals, although they may contain microscopic gaylussite crystals or nodules of northupite. In the saline layers, the layers of northupite are generally associated with fine-grained, fibrous, or bladed trona.

### PHILLIPSITE ($KCa(Al_3Si_5O_{16}) \cdot 6H_2O$)

Phillipsite crystals, generally 10 to 20 microns long, are found in large percentages in tuffs in the Parting Mud and Bottom Mud (Hay and Moiola, 1963, p. 323). They are lathe-shaped grains that coat grains and cavities or form a cement. Apparently they are not associated with other authigenic silicates or with salines.

### PIRSSONITE ($CaCO_3 \cdot Na_2CO_3 \cdot 2H_2O$)

Pirssonite, another mineral first found in Searles Lake (Pratt, 1896), is perhaps the fifth most abundant mineral in it after halite, trona, hanksite, and gaylussite. It occurs most abundantly in the Parting Mud, in M–6 and M–7 of the Lower Salt, and in units C, D, E, and F of the Mixed Layer, but forms a minor or trace constituent of all other mud layers except M–2 and M–3 of the Lower Salt and the basal part of the Upper Salt. Pirssonite occurs most commonly as megascopic but small euhedral crystals, but is also common as megascopic subhedral to anhedral crystals and as microsopic crystals.

The megascopic euhedral crystals generally have a distinctive habit consisting of a tabular shape and a pair of dominant faces that have diamond- to hexagonal-shaped outlines (Gale, 1914, fig. 86B). The crystals generally occur as individuals disseminated in a mud matrix, but some form aggregates of interpenetrating individuals. The individuals range in length from 0.1 to 10 mm and average about 3 mm. Most are colorless and transparent, although mud inclusions give some a grayish, yellowish, or greenish tint. Euhedral crystals

are most abundant at the base of the Parting Mud and in the central facies of M–6 and M–7 of the Lower Salt, where they form as much as 35 percent of some beds. They are associated chiefly with megascopic crystals of borax and microscopic crystals of halite, dolomite, northupite, pirssonite, gaylussite, and aragonite. A few layers of such crystals are noted in the Mixed Layer, but they are not abundant.

Megascopic subhedral to anhedral crystals of pirssonite occur near the base of the Overburden Mud, at the top of the Parting Mud, and in most beds in the Mixed Layer that contain a high concentration of the mineral. They consist of elongated, rough, pointed, and twinned(?) crystals which range from about 1 to 50 mm long and probably average between 5 and 10 mm long—somewhat larger than the euhedral forms of pirssonite. Some parts of the Mixed Layer contain anhedral pirssonite as thin veins and as a matrix of highly indurated siltstone.

Major to intermediate percentages of microscopic pirssonite crystals have been found in the Parting Mud and in M–5, M–6, and M–7 of the Lower Salt; traces are found in the basal few inches of the Upper Salt and the top few inches of the Bottom Mud. They are associated with megascopic crystals of trona or gaylussite and microscopic crystals of halite, dolomite, calcite, aragonite, searlesite, and northupite.

### SCHAIRERITE ($Na_2SO_4 \cdot Na(F,Cl)$)

Schairerite, first described from Searles Lake (Foshag, 1931), is an uncommon mineral in the deposit. The sample described by Foshag came from a saline layer near the base of the Lower Salt and was composed of steep trigonal rhombs, with the [$10\bar{1}1$], [$10\bar{1}2$], and [$10\bar{1}0$] faces most prominent. Haines (1959) reported schairerite from the M–2 unit of cores GS–17, GS–22, and GS–41; it was found at only one horizon in GS–22 and GS–41, but in GS–17 it occurred at two horizons. As noted above, though, the crystals identified as schairerite from two of these localities are now known to be galeite, to which it is optically, chemically, and structurally very similar. The minerals from the third locality may have been similarly misidentified. The mineral reported as schairerite occurs as crystals less than 1 mm in diameter which form lenticular pockets or nodules, 2 to 30 mm long, embedded in finely laminated mud containing gaylussite. Foshag (1931, p. 139) reported schairerite associated with gaylussite, pirssonite, thenardite, trona, tychite, hanksite, and calcite and inclusions of tychite, pirssonite(?), and thenardite(?).

## SEARLESITE ($Na_2O \cdot B_2O_3 \cdot 4SiO_2 \cdot 2H_2O$)

Searlesite was first found in Searles Lake (Larsen and Hicks, 1914) in a sample of core taken from the "Searles deep well" at a depth of 540 feet. According to Gale (1914, p. 308), the mineral was embedded in mud and formed spherulites of radiating fibers that were either colorless or white. Small to large percentages of searlesite have been found more recently in samples from the base of the Upper Salt, the Bottom Mud, and some of the mud layers in the Mixed Layer (Hay and Moiola, 1962; R. C. Erd, written communication, 1962). In the bottom few inches of the Upper Salt, it occurs as rectangular plates about 0.2 mm long embedded in trona crystals. In the Bottom Mud, between 176 and 181 feet in the L–W–D core, a moderate to high percentage of fine-grained searlesite occurs in beds composed chiefly of megascopic and microscopic gaylussite and smaller percentages of adularia, calcite, and microscopic halite. In unit A of the Mixed Layer similar concentrations occur associated with trona; in unit F it occurs as small radiating fibers embedded in thinly bedded siltstone that is cemented by massive pirssonite.

## TYCHITE ($2Na_2CO_3 \cdot 2MgCO_3 \cdot Na_2SO_4$)

Tychite is another mineral first discovered in samples from Searles Lake (Penfield and Jamieson, 1905). It is the least abundant of the three magnesium-bearing minerals in Searles Lake and is found as disseminated crystals in the marginal facies of M–2, M–3, and M–5, in mud layers within S–2 and S–3, in the top few inches of the Bottom Mud, and in units A and D of the Mixed Layer. It has not been found in the upper part of the deposit.

Tychite occurs as euhedral octahedra, although some are modified by small cube faces. The crystals generally are colorless and transparent and range in size from a fraction of a millimeter to about 2 mm. The octahedra mostly occur as isolated individuals embedded in clay, but they may be found in interpenetrating clusters of two or more individuals. Clay inclusions are common. In the Lower Salt, tychite is associated with gaylussite, nahcolite, trona, and was noted as an inclusion (along with northupite octahedra) in sulfohalite; in the Bottom Mud it is associated with gaylussite and traces of pirssonite; and in the Mixed Layer it is associated with trona, sulfohalite, and pirssonite.

## SUMMARY OF MINERAL OCCURRENCES

A summary of the distribution and characteristic forms of the minerals in the several stratigraphic units follows. Their distribution is considered in terms of both stratigraphic and lateral positions. The

stratigraphic terms used are those shown on figure 2. Their lateral positions are discussed in terms of "edge facies" and "central facies." These facies are not rigorously defined by areal positions, but generally the cores GS–2, 6, 8, and 10–22, and L–W–D have been considered representative of the central facies, and cores GS–1, 3, 4, 5, 7, 9, 23–27, and 39–41 have been considered representative of the edge facies.

### OVERBURDEN MUD

The Overburden Mud, the youngest of the units, consists almost entirely of interbedded dark-brown mud and cubo-octahedral halite; halite predominates in the central facies and mud predominates in the edge facies. Some horizons contain rounded anhedral halite, especially in the northeastern part of the deposit. Isolated beds of pyramidal hanksite and stubby euhedral borax crystals occur locally; one occurrence of tincalconite has been noted. Subhedral to anhedral pirssonite is common in the edge facies of the unit; thin beds of thenardite and fine-grained to bladed trona are found near the top of the edge facies.

### UPPER SALT

The Upper Salt is the thickest saline unit in the well-explored part of the deposit. The upper half of the central facies consists chiefly of thick beds of cubo-octahedral halite, pyrimidal hanksite, and fine-grained trona, and thin beds of subhedral, anhedral, or massive borax; small quantities of aphthitalite and sulfohalite also occur in this part of the unit. The lower half of the central facies consists mostly of thick beds of fine-grained trona and cubo-octahedral halite, but contains some thin beds of pyramidal hanksite and subhedral to massive borax. The edge facies of the Upper Salt are composed chiefly of fine-grained or fibrous trona, cubo-octahedral halite, and pyramidal or subhedral hanksite; local or small quantities of burkeite, thenardite, and stubby euhedral or subhedral to massive borax occur locally. Beds of both pinacoidal and anhedral hanksite occur sporadically through the Upper Salt.

### PARTING MUD

The Parting Mud consists chiefly of laminated or uniformly dark mud containing subhedral to anhedral crystals of gaylussite and, in the central facies, pirssonite. Subhedral to massive borax occurs near the top contact. Microscopic crystals of dolomite occur mostly near the top and bottom contacts; laminae composed of microscopic aragonite crystals occur throughout the upper third of the unit. Large percentages of microscopic crystals of halite are found throughout most of the unit, and similar-sized crystals of gaylussite and

pirssonite occur wherever megascopic crystals of these minerals are found.

## LOWER SALT

In the Lower Salt, each saline and mud unit has a distinct mineral character.

*S–7.*—Intermixed fine-grained and fibrous trona predominate; cubo-octahedral halite is abundant in the central facies. Stubby euhedral borax is found in both central and edge facies; small quantities of massive vuggy burkeite are in the central facies; similar quantities of thenardite are in the edge facies.

*M–7.*—The muds of this unit contain subhedral to anhedral megascopic crystals of gaylussite, a smaller percentage of euhedral pirssonite crystals that are concentrated in the central facies, and microscopic crystals of both gaylussite and pirssonite. Stubby euhedral crystals of borax occur in the edge facies.

*S–6.*—Intermixed fine-grained and fibrous trona predominate; cubo-octahedral halite is abundant in the central facies. A few concentrations of massive vuggy burkeite occur in the central facies; stubby euhedral crystals of borax and megascopic twinned crystals of nahcolite are in the edge facies.

*M–6.*—These muds contain gaylussite and pirssonite crystals like those in M–7. Octahedral and fine-grained northupite occur sporadically in the edge facies; local concentrations of stubby euhedral borax crystals are found throughout the unit.

*S–5.*—This is the thickest saline unit in the Lower Salt. Fine-grained massive trona and cubo-octahedral halite predominate; a smaller amount of massive vuggy burkeite is present. Some beds of fibrous and bladed trona also occur in the upper part of this unit, especially in the edge facies. The most consistent concentrations of halite and burkeite are in the central facies, but high concentrations occur locally in the edge facies. Small quantities of stubby euhedral borax crystals are found in the central facies. Trace quantities of massive sulfohalite, massive northupite, and fine-grained thenardite are found in the edge facies; similar quantities of pinacoidal hanksite occur sporadically throughout this layer.

*M–5.*—This is a very thin mud layer containing a low percentage of both microscopic and very small megascopic euhedral gaylussite crystals. An interbed of salines is commonly present in the central facies. Elongated prismatic borax crystals occur in both the central and edge facies. Tychite, euhedral and microscopic pirssonite, nodular northupite, and sulfohalite occur in the edge facies.

*S–4.*—Fine-grained, fibrous, and bladed trona predominate; cubo-octahedral halite and massive vuggy burkeite are subordinate; the

halite is mostly in the central facies, the burkeite in the edge facies. Small quantities of stubby borax crystals and massive fine-grained northupite are found in the edge facies; pinacoidal hanksite crystals occur sporadically in the central facies.

*M–4.*—This mud layer contains chiefly euhedral gaylussite, but has a trace of euhedral pirssonite. Prismatic borax crystals are common in the central facies; stubby borax crystals occur in both the edge and central facies. A few percent of nodular and fine-grained northupite are present in most parts of the unit.

*S–3.*—This unit is mostly intermixed fine-grained and bladed trona; some of it is fibrous trona. Several percent of massive northupite is found locally; a few local concentrations of massive burkeite, stubby euhedral borax, cubo-octahedral halite, and pinacoidal hanksite occur in the central facies. Tychite octahedra occur in mud layers within this unit.

*M–3.*—This mud layer is characterized by euhedral gaylussite crystals and prominent laminae composed of fine-grained aragonite. A few percent of nodular or fine-grained northupite occurs throughout the unit; similar quantities of thenardite, stubby euhedral borax, and tychite occur sporadically in the edge facies.

*S–2.*—This unit consists chiefly of intermixed fine-grained and bladed trona, but contains some fibrous trona. Several percent of massive northupite occurs locally, chiefly in the edge facies. A few local concentrations of massive burkeite are in the central facies and stubby euhedral borax in the edge facies. Interbeds of mud contain tychite. Halite is absent.

*M–2.*—The muds constituting this unit contain euhedral gaylussite crystals and prominent laminae composed of fine-grained aragonite. Fractional percentages of thenardite, nodular northupite, and tychite occur locally in the edge facies of this unit; traces of galeite occur in both the edge and central facies.

*S–1.*—This unit is chiefly trona; in the central facies most of it is bladed or fine grained, a little is fibrous. Trona with these habits predominates in the edge facies where it is associated with local concentrations of stubby euhedral borax, euhedral twinned nahcolite, and massive fine-grained northupite. Octahedral tycite occurs in interbedded mud layers near the edge. The single occurrence of tincalconite from the Lower Salt came from this unit. Halite is absent.

## BOTTOM MUD

The Bottom Mud, which is about 100 feet thick, is composed chiefly of mud containing subhedral to anhedral gaylussite. Other minerals occur, in major to trace amounts, as thin beds, pods, isolated megascopic crystals, and microscopic crystals. The distribution and char-

acter of these minerals vary according to the stratigraphic position of the sample within the unit. In the top 5 feet, uncommonly large crystals of subhedral to anhedral gaylussite and microscopic crystals of dolomite are generally present; megascopic crystals of borax and thenardite and microscopic crystals of calcite, tychite, northupite, and pirssonite are found locally. In a zone extending from about 5 to 30 feet below the top, beds and pods of mirabilite and layers of questionably identified tychite or northupite are found in addition to gaylussite. In the muds that lie 30 to 50 feet below the top, megascopic crystals of subhedral to anhedral gaylussite and microscopic crystals of gaylussite and analcime are the major components; locally there are small quantities of microscopic dolomite, adularia, and calcite. In a zone that lies between 50 and 60 feet of the top, megascopic subhedral to anhedral gaylussite and microscopic gaylussite, searlesite, and adularia are the main constituents. From 60 feet to the base of this unit, disseminated crystals of gaylussite, beds of fine-grained euhedral nahcolite, laminae of microscopic aragonite, microscopic crystals of gaylussite, and small but locally prominent amounts of microscopic dolomite occur. A small percentage of halite, possibly crystallized from pore brines, is found in most samples.

### MIXED LAYER

The Mixed Layer, as its name implies, is a series of interbedded muds and salines that has not been well enough explored to divide into thin and relatively homogeneous units. Generalized descriptions of the units follow.

*Unit A.*—Saline layers predominate in unit A. They consist mostly of fibrous trona and smaller quantities of fine-grained trona, nahcolite, and traces of searlesite; halite is missing, and this characteristic distinguishes this unit from unit B which underlies it. The mud layers contain chiefly subhedral gaylussite and small quantities of euhedral megascopic gaylussite, smaller quantities of pirssonite, and traces of octahedral northupite and tychite. Laminae of aragonite are locally conspicuous.

*Unit B.*—In unit B saline layers predominate. They consist of fibrous trona and megascopic cubic halite, with small quantities of fine-grained trona and nahcolite and traces of sulfohalite. The mud layers contain mostly megascopic subhedral to anhedral gaylussite, small percentages of euhedral gaylussite, traces of pirssonite and octahedral northupite, and locally conspicuous laminae of aragonite.

*Unit C.*—Unit C consists mostly of beds of megascopic cubic halite, some fibrous trona, and traces of nahcolite, burkeite, sulfohalite, and thenardite. The preponderance of halite over other saline minerals

distinguishes this unit from units A and B above it.   The subordinate mud layers contain subhedral to anhedral pirssonite, a little euhedral pirssonite, and traces of gaylussite and northupite.

*Unit D.*—In unit D mud layers predominate slightly.   They mostly contain subhedral to anhedral pirssonite, although some contain euhedral pirssonite, and a few contain octahedral northupite and possibly calcite.   Gaylussite is absent from the muds of this and all deeper units.   The saline layers consist of about equal percentages of cubic halite and fibrous trona, small quantities of fine-grained trona, and traces of nahcolite, octahedral sulfohalite, and octahedral tychite.

*Unit E.*—About two-thirds of unit E consists of mud layers containing large percentages of subhedral to anhedral pirssonite, and traces of octahedral northupite and octahedral sulfohalite.   The saline layers are composed of cubic halite that locally contains traces of included octahedra northupite; trona and nahcolite are absent from the saline layers, and this absence distinguishes the unit from unit D above it.

*Unit F.*—Unit F consists chiefly of mud containing subhedral to anhedral pirssonite, common aragonite laminae, and isolated northupite octahedral.   A few thin beds of fibrous trona and cubic halite are found, but the near absence of such beds distinguishes unit F from other units in the Mixed Layer.

## SIGNIFICANCE OF VARIATION IN PHYSICAL CHARACTER OF MINERALS

### DIFFERENCES IN CRYSTAL SIZES

Fine-grained layers of chemical sediments are generally interpreted here as primary deposits; that is, deposits that have not changed their mineralogy or texture appreciably since first formed as a precipitate on the bottom of the lake.   Such aggregates normally form when the precipitating solutions become greatly oversaturated, so that crystal nuclei form rapidly, and none of the growing crystals has a chance to become very large before either meeting physical interference from the many other crystals or exhausting the available ions from the solution.   (See Buckley, 1951, p. 23–35; Gibbs, 1930; La Mer, 1952.) In natural solutions, the most likely way to achieve these conditions appears to be by rapid evaporation of an open lake surface or by mixing dissimilar waters.

Coarse-grained layers of chemical sediments may be interpreted as secondary deposits that were recrystallized in brine pools on the surface of a saline lake or within the deposit after burial.   However, diagnostic replacement textures are generally necessary to confirm this interpretation.   Large crystals are also formed in primary de-

posits if crystallization takes place slowly enough. Furthermore, some minerals (such as halite) characteristically grow rapidly, whereas others (such as hanksite) grow slowly. Also, the temperature and the catalytic effect of other substances in solution can significantly alter normal crystal growth rates.

In the saline layers of Searles Lake, many of the aggregates of fine-grained to microscopic minerals have textural relations supporting the premise that they are original precipitates formed on the bottom of a lake; they retain original bedding, and no relations have been observed that indicate crystals of this size to be secondary. Recrystallization can be demonstrated in some of the saline aggregates composed of megascopic crystals, but it is generally not possible to distinguish recrystallization that occurred virtually at the surface from that which occurred at depth, because the saline aggregates are normally too rigid to permit compaction, which is the criterion most frequently used in making this distinction.

In the mud layers of the deposit, the fine-grained to microscopic minerals are generally interpreted as primary deposits formed on the bottom of the lake or a very short time after burial. The only major exceptions are the microscopic crystals of halite disseminated in muds (described below). Textural evidence is abundant indicating that the megasocpic crystals in the muds grew partly or entirely by volume-for-volume replacements of the material in which they now lie (fig. 15); some of these replacements may have occurred when only a few inches of mud covered the site of growth, but most appear to have occurred after the present compaction of the host material had been nearly completed as a result of its long and deep burial.

The microscopic halite crystals in mud layers, however, were probably all formed after burial. These layers were, of course, deposited during expanded and relatively dilute stages of the lake, and an appreciable percentage of halite is thus anomalous. It seems almost certain that these halite crystals were not precipitated from the lake, but were concentrated and precipitated during compaction of the muds when water was lost from the pore spaces of the mud more readily than the dissolved sodium chloride; this loss apparently caused a rise in the residual sodium chloride concentration that exceeded the solubility of halite. Residual concentration of sodium chloride during compaction is an effect that has been noted in the formation of oil-field pore brines (De Sitter, 1947, p. 2039–2040; Wyllie, 1955, p. 288–301; von Englehardt, 1961), as well as during early stage compaction of younger sediments (Siever and Garrels, 1962). A small percentage of the other minerals in the mud layers may have formed after burial by the same mechanisms that produced halite, but the total percentage

of most minerals is too great to be entirely attributed to this mechanism.

### DIFFERENCES IN DEVELOPMENT AND PRESERVATION OF CRYSTAL FACES

Most of the euhedral megascopic minerals in the Searles Lake deposit grew after burial, and the preservation of their crystal form means that they have neither encountered physical obstacles during growth nor suffered solution or replacement since.  It is evident that whether or not there was physical interference between minerals of the same species depended on the number of crystals that grew and on their ultimate size.  The number of crystals that grew may have depended in part on the number of nuclei that were available.  The common association of very small (primary) and large (secondary) crystals of the same species, however, makes it seem more likely that an excess of nuclei were available, and that the slightly lower free energy of large crystals acting over geologic time permitted a few select nuclei to grow at the expense of other small crystals.  The present size of such crystals depends on the time during which they were allowed to grow, on whether or not there was a large percentage of the mineral components available at the time they were growing, and on whether the porosity of the host material was high enough to allow local migration of the components via pore solutions.

The lack of subsequent replacement or solution reflects a stable brine composition since crystallization.

### DIFFERENCES IN CRYSTAL HABIT

Only four of the minerals in the Searles Lake deposit have variations in the development of their faces that can be correlated with their stratigraphic position.  Three of these—halite, trona, and hanksite—are characteristically in the saline layers; a fourth—borax—may be in either saline or mud layers.  Of these minerals, only the habits of halite and borax can be interpreted in the light of experimental data.  The origin of the habit variation among trona and hanksite crystals must be inferred from the chemical character of the depositing solutions; these inferences are based on conclusions developed below.  Some variety has been noted in the habits of gaylussite and pirssonite (see Gale, 1914, figs. 86, 87), but no systematic study of their distribution has been made.

The degrees to which different faces are developed on crystals are the combined results of characteristics inherent to the mineral, plus those introduced by the physical and chemical environment extant at the time of their growth.  In theory, growing crystals tend to produce faces that will reduce their total free energy to a minimum.  In actual

experiments on crystals more than a few microns in size, kinetic factors seem more important than thermodynamic factors in controlling the development of different faces (Van Hook, 1961, p. 64). In crystallization processes that take place over geologic periods of time, the degree of thermodynamic control probably exceeds that evident from experiments, and the evidence that large crystals grew from small crystals after burial is in accord with this principle, but the existence of habit variation among some of these large crystals probably means that kinetic factors are instrumental in determining the crystal faces actually developed.

In natural and thus impure solutions, kinetic factors may be the combined product of many variables. It has long been known that the quantity and type of nonparticipating components ("impurities") in a crystallizing solution are highly effective in causing differences in the crystal habit because they hinder the growth of the crystal in each direction differently. This seems to be because different quantities of such components are adsorbed (or cocrystallized) on a growing crystal according to the affinities between the nonparticipating ions in solution and the crystal structure presented by each face. They then slow normal crystal growth by temporarily blocking the participating ions from reaching their proper crystal position (see Van Hook, 1961, p. 64–68, 97–98, 132–133) and possibly by increasing the viscosity of the solution adhering to each face so that it decreases the speed with which new ions can reach them (Gibbs, 1930, p. 45). Those faces that grow most slowly are preserved and expressed as faces on the final crystal.

Other properties of the crystallizing solution have also been shown correlative with differences in the resulting crystal habits. These properties include the degree of supersaturation (Kern, 1952, 1953; Svanoe, 1959; Seager, 1953), pH (Garrett and Rosenbaum, 1958b; Wells, 1946, p. 230; Svanoe, 1959), temperature (Van Hook, 1961, p. 97), surface tension (Milone, 1947; Milone and Ferrero, 1947), and interaction between the nonparticipating and participating components of the solution (Wells, 1946, p. 229). It is difficult to measure the importance of some of these properties relative to the adsorptive and other direct effects of any components added to produce them, but the available evidence indicates that they are to some degree directly responsible for the changes produced in crystal habit. (See Van Hook, 1961, p. 133–134.)

### HALITE

Halite crystallizes from a pure salt solution to form cubes. Octahedral faces on halite are promoted by impurities, such as magnesium chloride, potassium chloride, sodium iodide, sodium bromide, sodium hydroxide, hydrochloric acid, urea, dyes, and other organic com-

pounds.  (See Van Hook, 1961, p. 65–68; Buckley, 1951, p. 556; Gibbs, 1930, p. 48; Fastert, 1912; Milone and Ferrero, 1947.)  The addition of such compounds of course also alters the surface tension and pH of most solutions, and these related effects have been credited by some as the prime cause of habit change.  Octahedral faces on halite are also produced by a high degree of supersaturation (Kern, 1952; Kern and Tillman, 1953).

The cubo-octahedral halite in the Lower Salt and Upper Salt units of Searles Lake evaporites could be a result of any or several of these factors.  The pH of the associated brines are high (9.5 or more).  The brines also have a relatively high surface tension and contain a small percentage of nonalkaline metals, complex organic compounds, and metal-organic compounds (Teeple, 1929, p. 18, 36–38).  The conditions required to produce the cubo-octahedral habit, though, were clearly not in existence during the deposition of the underlying Mixed Layer and the Overburden Mud which contain cubic halite almost exclusively.  The brines associated with those layers are relatively simple carbonate-chloride waters that probably had lower surface tensions, and may have had lower pH values and percentages of the effective metallic and organic compounds.

## BORAX

Borax crystals produced by a pure sodium borate brine are nearly equidimensional.  Decreasing the pH of the brines to a level well below 9.7 and increasing the sulfate content of this solution to a level above that normally found in Searles Lake brines, however, is known to produce distinctly elongate crystals (Garrett and Rosenbaum, 1958; Garrett, 1959, p. 677).  Most of the euhedral borax in the Searles Lake deposit is of the nearly equidimensional variety, and it is consistent with other evidence to conclude that these crystals formed in a high-pH and low-sulfate environment.  It also is reasonable to conclude that the elongate crystals in units M–4 and M–5 of the Lower Salt grew in an abnormally low-pH and high-sulfate environment.  A relatively high-sulfate percentage in the associated brines is clearly indicated for this period of the lake by the high percentage of burkeite in the overlying saline units.  Although more difficult to determine, the pH of the water was probably also lower than it had been up to that time because carbonates and bicarbonates had been precipitated extensively up to this point in the lake history, and an increasing percentage of the total dissolved solids was made up of the more neutral sulfates and chlorides.

## TRONA

Most of the trona in the Searles Lake deposit is acicular.  The core-log data report megascopic crystals of this habit frequently,

and microscopic studies of very fine grained trona aggregates show that they are composed of very small acicular crystals and thus represent the same habit. This widespread extent is compatible with laboratory experiments which show that, although organic additives change the crystal size, the acicular habit persists throughout a wide range of crystallizing conditions (Garrett, 1959, p. 677).

As Garrett's studies were aimed at producing stubby crystals, it is possible that a distinction was not made between bladed and acicular crystals. Bladed crystals of trona in the Searles Lake deposit are distinctly less common, and most of them are in the lower half of the Lower Salt. As indicated below, the brines in those lakes had a relatively low concentration of nonparticipating components, and this condition may have favored the bladed crystal habit. However, the coexistence of bladed and acicular trona in the same beds shows that the bladed habit must also be produced by other differences in the environment of crystallization that can be generated and maintained very locally. This probably rules out variations in total pressure and temperature. It also means that if brine composition was the control, crystallization occurred at a time when the brine movements and intermixing were at a minimum so that the brine inhomogeneities could be maintained. Appreciable brine migration probably took place just after each layer's deposition (while equilibrium between brine densities was being attained) and probably resumed after pumping was started by the chemical companies. In the interim, however, brine movements may have been very small. It seems likely that any such differences, created during a period of noncirculation, probably were the result of impurities introduced by dissolved or replaced minerals in the immediate surroundings.

### HANKSITE

The pyramidal and pinacoidal habits of hanksite are concentrated in certain parts of the saline layers, but minerals with both habits locally are only a few inches apart and are in contact via pore spaces with the same brines. This proximity indicates that differences in temperature, pressure, and present-day brine composition are not the major controls of the mineral's habit. The preponderance of the pyramidal form in the deposit shows that it was favored when the crystals were grown from brines capable of producing large quantities of the mineral; the pinacoidal form, which is most common in the middle of the Lower Salt and in the lower and middle parts of the Upper Salt, grew from brines that produced relatively small quantities of hanksite. This suggests that the pyramidal form was promoted by brines whose compositions fall well within the hanksite field of stability, and that the pinacoidal habit was promoted by brines whose

compositions fall near the edge of the field. These differences in the composition of the parent brine would also be reflected in the composition of the metastable assemblage of minerals from which the hanksite probably crystallized (Gale, 1938, p. 869). Considering all these factors, the variables that seem most likely to be responsible for the observed differences in habit are the presence or absence of minor amounts of certain nonparticipating ions—derived either from the assemblage of metastable parent minerals or from solution of nearby salines during periods of minimum brine migration.

## LAKE HISTORY INDICATED BY CHARACTER AND DISTRIBUTION OF MINERALS

The history of lakes that occupied Searles Valley is a history of climate-controlled fluctuations in their levels. As indicated by Gale (1914, p. 265–270), Searles Lake was the third of a longer chain of lakes that occupied successively more arid basins. When these lakes were connected, they received most of their water from the east side of the Sierra Nevada, which drained into the first lake and overflowed. The downstream lakes also received water from their local drainages, but the quantity was very small compared to that received from upstream. This meant that whenever Searles Lake was the last in the chain of lakes (which it was throughout much of middle and late Wisconsin time), a small increase or decrease in regional precipitation, acting on the combined drainage areas of the connected lakes, drastically increased or decreased the quantity of water flowing into Searles Lake. It thus had a history of extremes. When Searles Lake received water from upstream, it received quantities that were disproportionately large for its drainage area, and the lake expanded rapidly into a relatively large body of water. When it was cut off from its upstream supply, it was reduced to a minute fraction of its previous supply and quickly became a small saline lake or salt pan.

The fine-grained mineral assemblages in the Searles Lake deposit appear to have formed as primary deposits on the bottoms of those lakes and can thus be regarded as indicators of the conditions in existence at those times. The coarse-grained assemblages are composed mostly of recrystallized minerals, and interpreting them requires some basis for judging whether or not the changes in surrounding physical conditions have permitted the recrystallization of the same species as those in the original deposit.

The pressure changes that took place after burial were relatively small and probably did not produce any changes in the suite. The deepest sample from a depth of 875 feet was under a load pressure of only about 50 bars or an unconfined hydrostatic pressure of about

30 bars, and changes of this magnitude are not likely to have a significant effect on the positions of phase boundaries. (See Mac-Donald, 1953, p. 885–886; Garrels, 1960, p. 193–194; Eugster and Smith, 1964.)

Changes in temperatures probably were more effective. Temperatures at which the deposits were formed may have ranged from lows near 0°C to highs near 40°C, or even more, because of seasonal and long-term changes. Temperature changes produced by postburial adjustments to the present thermal gradient, which probably maintains temperatures between 20°C and 25°C in all but the top 20 to 30 feet (where seasonal changes are pronounced), may thus be 20° or more. Mineral alterations that are produced by temperature changes within this range must be considered possible.

Changes in the activities of water and carbon dioxide were potentially also very effective (Eugster and Smith, 1964). The salinity of the pore waters and the partial pressures of carbon dioxide trapped in the sediments are the main controls of these variables, and whenever mechanisms were available to change them after burial, changes in the mineral suite were possible.

Although some of the mineral aggregates in the saline layers are fine grained and probably primary, most are coarse grained and were probably formed later. Halite, trona, burkeite, and borax are most commonly found in megascopic form, but all are also bound in bedded or fine-grained form. Where both forms are in the same layer, this is interpreted to mean that the recrystallization processes that produced the large crystals are incomplete and that the changes underway are in fact repeating phases found in the original deposit. Because of an abundance of such relations, megascopic crystals of halite, trona, burkeite, and borax are generally interpreted as representative of the primary suite. A nearly complete lack of pseudomorphs in the deposit supports this interpretation. The hanksite crystals in this deposit are probably all secondary. All are in megascopic form and probably none crystallized until after the host layer was deposited, even though the compositions of the depositing solutions may have been in the hanksite field; this temporary inequilibrium is possible because of the very slow crystallization rate that permits aphthitalite, burkeite, and thenardite to form as the primary assemblage (Gale, 1938, p. 896).

Mineral relations have been noted in the muds, however, that show that the megascopic mineralogy does not always accurately reflect the related fine-grained mineralogy. The best examples are provided by units M–5, M–6, and M–7 (in samples taken from the central facies), where megascopic crystals of either pirssonite (M–6 and M–7) or gaylussite (M–5) are embedded in muds containing both species in

microscopic form.  As the compositions of gaylussite and pirssonite differ solely in the quantity of water in the crystal lattice, environmental conditions that cause a change in the chemical activity of water will cause one species to recrystallize into the other.  The presence of only one species of megascopic crystal shows that the activity of the water after burial definitely favored the recrystallization of one over the other.  The presence of two species in the microscopic fraction means either that at the time of original deposition the seasonal range of water activities permitted deposition of both species or that the microscopic crystals of the species found also in megascopic form are simply in an early stage of recrystallization from a homogeneous mud composed of the other mineral.

### MINERALS IN THE SALINE LAYERS

A fairly detailed record of the lake history can be deduced from the distribution of evaporite components in the deposit.  Even though mineral species may have changed in some layers as a result of post-depositional recrystallization, the bulk chemical composition of each stratigraphic unit is probably about the same as it was at the time of deposition because the vertical migration of chemical components through the enclosing mud layers was very slow or absent.

The saline layers are composed chiefly of combinations of sodium with bicarbonate, carbonate, sulfate, and chloride.  The phase relations between these components plus water are illustrated diagrammatically in three dimensions on figure 16 for temperatures near 14°C (below which burkeite does not exist in this system) and 20°C.  Of the fields labeled, only trona, burkeite, mirabilite, thenardite, and halite are present in the Searles Lake deposit.  The field of trona occupies a wedge-shaped volume above a part of the burkeite, mirabilite, thenardite, and halite fields.  The field of nahcolite occupies all the area above these fields.  At temperatures below 14°C the mirabilite, natron, and nahcolite fields expand at the expense of the halite, thenardite, and trona fields.  At temperatures above 20°C, the trona, burkeite, and thenardite fields expand at the expense of the halite, mirabilite, nahcolite, and natron fields.

The mineral relations described in this report show that of the minerals related by figure 16, only trona, halite, burkeite, and thenardite coexist in appreciable quantities and that trona constitutes the first precipitated saline in most units.  Nahcolite is sparsely represented in a few layers, and mirabilite is found only in a few monomineralic beds within the Bottom Mud.  This means that when the saline units began to form, the composition of the brine was generally in the trona field.  Once trona began to precipitate, the composition of the solution moved away from the compositional point represented by trona

(*tr* on the near edge of the tetrahedrons in fig. 16) ; whether it moved toward the mirabilite, thenardite, burkeite, or halite fields depended on the original composition of the water and on the temperature which controlled the positions of the boundaries of the fields toward which it was headed.

These relations allow the history of the saline lakes to be inferred from the mineral suites of the saline layers, their stratigraphic arrangement, and the evidence provided by the interbedded mud layers which is given below.

### MIXED LAYER

In the Mixed Layer, the saline layers are composed almost entirely of combinations of sodium with chloride, carbonate, and bicarbonate. Magnesium- and sulfate-bearing minerals are nearly absent. Borate- and potassium-bearing minerals have not been noted at all. This evidence, combined with the fact that the nonclaustic minerals in the mud layers are almost solely combinations of sodium, calcium, and magnesium with carbonate, shows that besides being low in potassium and borate, the lake waters from which these mud and saline layers were deposited were very low in sulfate. Because of this, the initial composition of the brines was very close to the $Na_2CO_3$-$NaHCO_3$-$NaCl$ face of the tetrahedron (fig. 16). As trona precipitated, the composition of the solution traveled a path nearly parallel to this face, and approached and finally touched the halite field. Evaporation ceased before the coprecipitation of halite and trona could shift the brine composition to a point where it touched the natron, thenardite, or burkeite fields.

### SALINE LAYERS IN LOWER SALT

In the Lower Salt, the mineralogy of the saline units shows that S–1, S–2, S–3, and S–4 represent successively more highly saline lakes and that unit S–5 probably represents desiccation. It also shows that the percentages of potassium, borate, and sulfate in the lake waters had increased over those that produced the Mixed Layer. The lower three saline units—S–1, S–2, and S–3—are composed almost solely of trona. The near lack of other minerals means that as those units were deposited, the crystallization path in figure 16*A*—the path followed by the series of points that represented successive compositions of the remaining brines—moved directly away from the point *tr* on the near edge of the tetrahedron, but did not reach any of the boundary surfaces of the trona field. Units S–4 and S–5 represent salines deposited as the crystallization path reached the boundary surface between the trona and burkeite fields, moved along it, and finally reached the boundary line between the trona, burkeite, and halite fields (the line labeled
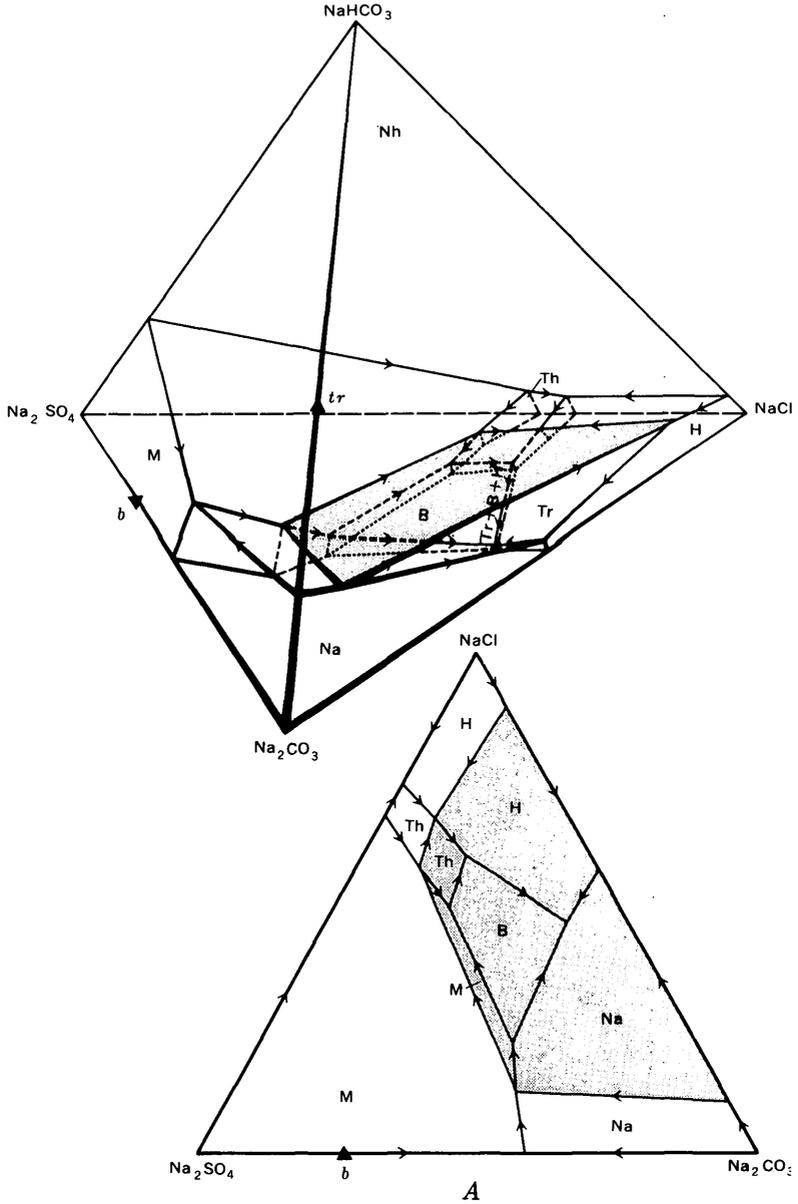
A. SYSTEM AT 20°C, CONSTRUCTED FROM DATA OF TEEPLE (1929)

FIGURE 16.—Phase diagrams of the system NaHCO₃–Na₂CO₃–Na₂SO₄–NaCl–H₂O. Solid phases indicated as follows: B, burkeite (2Na₂SO₄·Na₂CO₃); H, halite (NaCl); M, mirabilite (Na₂SO₄·10H₂O); Na, natron (Na₂CO₃·10H₂O); Nh, nahcolite (NaHCO₃); Th, thenardite (Na₂SO₄); Tr, trona (Na₂CO₃·NaHCO₃·2H₂O). In the tetrahedron diagrams, shaded areas represent tops of trona fields which occupy wedge-shaped volumes between overlying nahcolite fields and parts of underlying natron, mirabilite, thenardite, halite, and burkeite fields. The triangle diagrams are projections of tops of labeled fields onto
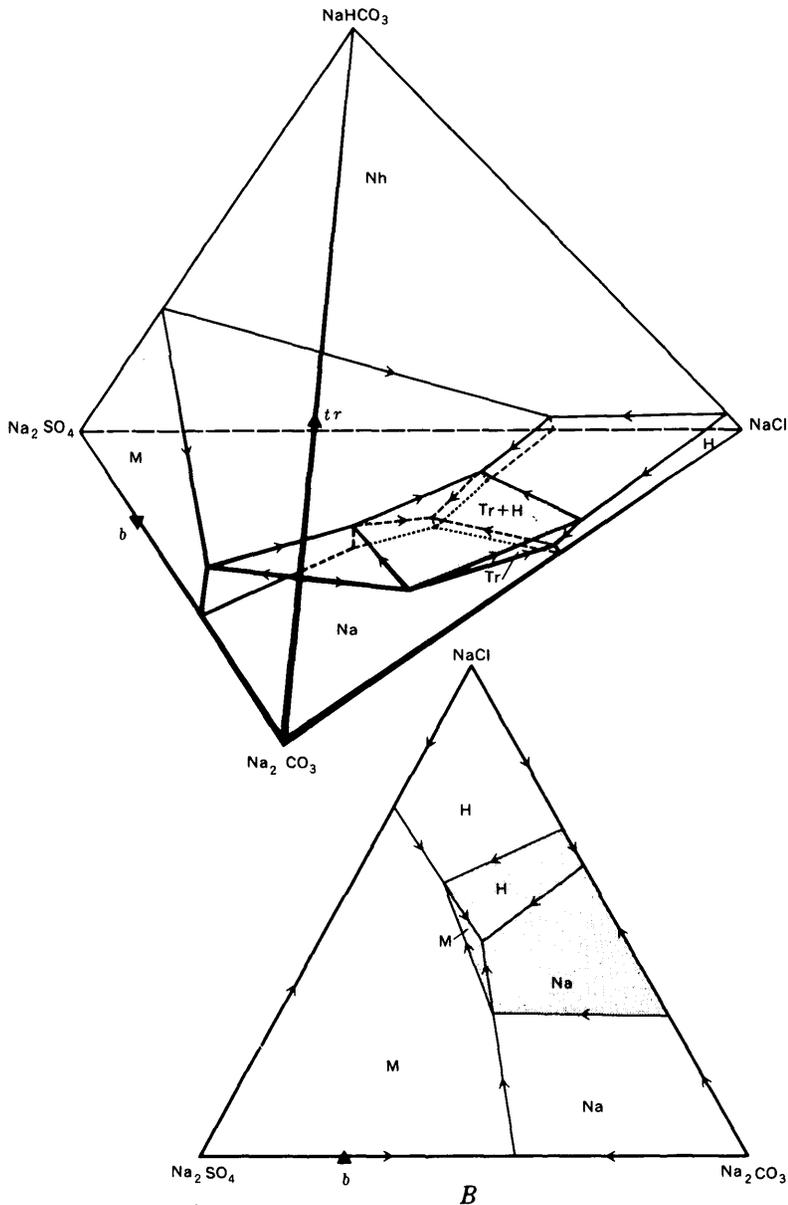
B. SYSTEM AT ABOUT 14° C, CONSTRUCTED FROM DATA INTERPOLATED
FROM CASPARI (1924), FREETH (1923), MAKAROV AND BLIDEN
(1938), AND TEEPLE (1929)

base of the tetrahedron; all points within shaded areas are saturated with trona,
and all points outside these areas are saturated with nahcolite. Boundaries of
stability fields are plotted in terms of weight percent of the four solid compo-
nents in the equilibrium solutions. Arrows show directions of slope toward
base of the tetrahedron. Compositions of double salts burkeite (b) and trona
(tr) are shown on edges of the tetrahedrons.

Tr + B + H on fig. 16*A*).   The small amount of thenardite in the edge facies of S–5 shows how local variations in the temperature or water composition were able to cause the crystallization paths followed by brines in some parts of the deposit to touch other nearby boundary surfaces instead.

The upper two saline units in the Lower Salt—S–6 and S–7—consist chiefly of trona and halite.   This is interpreted to mean that the lake did not dry up to form a salt pan, because that probably would have produced appreciable amounts of a third solid phase.   The presence of halite instead of burkeite probably means that the temperatures of these saline lake waters were so low that the burkeite field had shrunk or disappeared from the system (as shown on fig. 16*B*).   Under these conditions, the crystallization path, which started in the trona field, moved directly away from the composition *tr* and finally reached and traveled along the halite-trona boundary surface (labeled Tr + H on fig. 16*B*).   The uprecipitated sulfate in the residual brine was apparently incorporated into the lake that formed the Parting Mud and subsequently desiccated to form the Upper Salt; otherwise, secondary deposits of burkeite would be found because the present temperature of these two saline layers is well within its stability range.   It is possible that the composition of the waters that flowed into the basin to form M–6 and M–7 were lower in sulfate than previous and subsequent waters, or that the sulfate was largely converted to sulfur dioxide by bacteria and lost; but it seems unlikely that such conditions would exist in this basin only within the time represented by these two units and not before or after.

### UPPER SALT

In the Upper Salt, a thick bed of fine-grained trona grades upward into beds containing halite.   Hanksite and aphthitalite are most common near the top of this layer.   It is probable that the brine that produced this layer started out higher in sulfate than the brine that produced the Lower Salt because of the disproportionate quantity that remained in solution during formation of S–6 and S–7 of the Lower Salt; mapping in progress shows that the basin did not overflow during deposition of the Parting Mud, and all the components that remained in solution after deposition of the Lower Salt were added to the saline components introduced during the long period of inflow that followed.   Clearly, however, this initial difference in brine composition was not enough to move the starting point of the crystallization path out of the trona field.

Hanksite, aphthitalite, borax, and northupite are not represented in the sodium bicarbonate-carbonate-sulfate-chloride-water system

shown in figure 16, although they are locally important components in the saline layers. As discussed below, though, the distribution of these minerals, combined with available phase-equilibrium data, supports the lake history based on an interpretation of the simpler system.

W. A. Gale (1938, fig. 1) shows that at 20°C, hanksite and then aphthitalite represent stables phases in solutions having successively higher percentages of potassium; the required percentages of sulfate are about the same. It thus appears that hanksite is rare and aphthitalite missing in the Lower Salt because the concentration of potassium was too low. However, by the time the upper part of the Upper Salt was deposited, its concentration had apparently been raised, relative to sodium, by the extensive precipitation of trona and halite in the underlying saline layers. Gale also notes (p. 869) the very slow crystallization rate of hanksite, showing that burkeite, thenardite, and aphthitalite are generally the primary precipitates of solutions with these compositions and that these minerals recrystallize to hanksite if kept in contact with the parent brine; this supplies an explanation to the fact that all the hanksite in the Searles Lake deposit is in the form of megascopic crystals that are probably secondary.

Phase data for borax in complex saline systems are rare, but those available make it clear that cool temperatures strongly favor its crystallization (Teeple, 1929, p. 128–130; Bowser [3]).

Experiments on the crystallization of northupite (Wilson and Ch'iu, 1934, table 4) show that it is formed when magnesium-bearing water is introduced into a solution having a high percentage of sodium carbonate and chloride; the required percentage of carbonate and chloride relative to magnesium is much higher than that attained by simple evaporation of a normal water, suggesting that mixing of two waters is most likely responsible for natural deposits of this mineral. De Schulten (1896) and Watanabe (1933) had previously shown that high temperatures accelerate northupite's crystallization, though they did not determine a lower temperature limit for successful crystallization of the mineral.

## MINERALS IN THE MUD LAYERS

The most abundant primary minerals in the mud layers are gaylussite, pirssonite, aragonite, and dolomite. Gaylussite has been reported by Bury and Redd (1933) to form at about 15°C from solutions saturated with calcium and containing more than about 14 percent sodium carbonate. They report pirssonite forming at about 37.5°C

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[3] C. J. Bowser, 1959, Geochemical and petrographic study of the system $Na_2B_4O_7$–NaCl–$H_2O$ : California Univ., B.A. thesis, 78 p.

from solutions containing more than 22 percent sodium carbonate. Bury and Redd did not demonstrate that these limits were based on eqiulibrium assemblages, and more recent work (Eugster and Smith, 1964) shows this temperature to be too high. However, theoretical studies show that the relative positions of the two fields with respect to temperature and salinity are correct (Milton and Eugster, 1959, p. 136–137; Eugster and Smith, 1964.) Phase equilibrium data for precipitation of these minerals from solutions also containing appreciable percentages of sodium chloride and sulfate have not been published, but they would show that the minimum temperatures and sodium-carbonate percentages required for each field are reduced below those of the simpler system.

Aragonite and calcite form in solutions lower in sodium carbonate than gaylussite and pirssonite (Bury and Redd, 1933). The carbonate in the mud layers of Searles Lake is generally aragonite rather than calcite. Aragonite is a metastable mineral and is commonly formed instead of calcite where precipitated rapidly from solutions with high pH and salinity (Zeller and Wray, 1956; see summary by Ingerson, 1962, p. 827–829). In the environment represented by Searles Lake, these conditions were most likely to be satisfied when calcium-bearing "fresh" waters were introduced into the basin and mixed with saline waters that were already there, probably along the zone of mixing between a dense saline lower layer and a lightweight fresher upper layer. Extensive areas of aragonite laminae are thus interpreted as an indicator of periodic inflow of fresh water into a lake that was stratified. Such stratification presumably resulted from a certain sequence of events; namely, a period of moderately high salinity that was followed by a period of rapid inflow during which an upper layer of fresh water accumulated before wind action could mix the new water with the old. During those periods in which the introduced calcium was precipitated as fine-grained aragonite, it is assumed that the salinity of this underlying layer was low; during those periods the calcium was precipitated as gaylussite or pirssonite, it is assumed that the salinity of the lower layer was high.

The conditions under which dolomite forms at near-room temperature is not known. It occurs in the muds of Searles Lake chiefly near their contacts with salines. This fact plus the observations of others (for examples, see Alderman and Skinner, 1957, p. 566; Graf and others, 1961, p. 221; Fahey, 1962, table 6 and fig. 7; Jones, 1961, p. 201; and the review by Ingerson, 1962, p. 830–837) show that much of the dolomite in young sediments may be the result of a depositional or diagenetic environment with high pH and with total salinity intermediate between that producing aragonite (or calcite) and trona, and

this environment is assumed to be responsible for the deposits in Searles Lake.

Applying these criteria to the mud layers in the deposit, the following conclusions are reached about the character of the depositing lake.

### MIXED LAYER

Virtually every mud layer in the Mixed Layer contains secondary gaylussite or pirssonite; gaylussite is predominant in units A and B, and pirssonite is predominant in the mud layers of units C, D, E, and F. Laminae of aragonite are noted sporadically throughout the Mixed Layer but are more common in units A, B, and F. Dolomite has not been noted, although it probably exists locally in the muds.

The mud layers containing gaylussite or pirssonite apparently indicate periods in which solutions high or saturated with calcium flowed into a stratified lake containing a high percentage of sodium carbonate. During the periods represented by mud layers also containing aragonite, solutions saturated with calcium were intermittently mixed with more dilute solutions. Aragonite deposition occurred more commonly during the periods represented by units A, B, and F than by units C, D, and E. This evidence is compatible with that from the interbedded saline layers; in units A, B, and F these layers are composed chiefly of moderately soluble trona or nahcolite; and in units C, D, and E they are composed chiefly of highly soluble halite. In other words, aragonite formed during lake expansions that followed periods of moderate salinity, and gaylussite or pirssonite formed during expansions that followed periods of high salinity or desiccation.

The prevalence of megascopic pirssonite in the mud layers of units C, D, and E shows that the activity of the water in the muds is relatively low. This probably results from a combination of slightly higher temperatures at those depths, and higher salinities in the pore brines derived from the bottom waters of the depositing lake. These mud layers are interbedded with saline layers, and it seems likely that the bottom waters in the expanded lakes were also very saline. The prevalence of megascopic pirssonite in unit F, which is virtually free of saline layers, is probably almost completely a result of temperature.

### BOTTOM MUD

The Bottom Mud contains gaylussite throughout. Aragonite laminae in the lower 40 feet of the unit indicate the periodic introduction of calcium-bearing fresh water which formed a layer on top of more saline water. Dolomite has been noted near the top and in the middle and is common in the lower 40 feet of this section. The sporadic occurrence of northupite near the top indicates an increas-

ingly saline lake and possibly higher temperatures. The beds of mirabilite 10 to 30 feet below the top indicate periods of temporary lake shrinking during extremely cool periods; they probably also mean that the percentage of sulfate in the lake water had built up to a higher level than at any time represented by the underlying sediments.

### MUD LAYERS IN LOWER SALT

The mud layers M-2, M-3, M-4, and M-5 of the Lower Salt consist of megascopic and microscopic crystals of gaylussite and laminae of aragonite in dark-green mud. Each of these layers represents a temporary period of lake expansion that intervened between the deposition of saline layers S-1 to S-5 of the Lower Salt. That the volume of water introduced during each of these periods of expansion was less than that of previous expansions is shown by the steady reduction in the quantity of introduced calcium as reflected by falling percentages of gaylussite and aragonite. A simultaneous increase in the salinity that characterized each of these lakes is shown by the upward decrease in the abundance of aragonite laminae, the calcium in the younger units being precipitated entirely as gaylussite, or, locally in M-4 and M-5, even as pirssonite. The interstitial waters in these four mud layers also became progressively more saline, as shown by the upward increases in the percentages of the more soluble minerals northupite and borax that crystallized from them after burial.

The mud layers M-6 and M-7 of the Lower Salt contain major percentages of both gaylussite and pirssonite, a minor and upward-decreasing percentage of northupite, a slightly increasing percentage of borax, and very little aragonite. The saline lakes that deposited the interbedded layers S-6 and S-7 were highly saline but probably did not evaporate to dryness, so it is probable that the deeper lakes that followed had layers of dense brines along their bases. The concentration of pirssonite in the central facies of these muds may have resulted from the lowering of the water activity by this salinity. Average temperatures that were lower than those of the lakes that deposited the mud layers M-2, M-3, M-4, and M-5 are probable in view of the lower temperatures indicated by the mineralogy of the interbedded saline layers, but there is no direct evidence.

### PARTING MUD

The Parting Mud contains megascopic crystals of gaylussite and, in the top and bottom few feet of the central facies, some pirssonite. Microscopic crystals of gaylussite, pirssonite, and halite occur throughout. Dolomite is generally abundant near the top and bottom contacts. Aragonite laminae are normally present in the upper third of the unit.

The aragonite laminae in the upper third of the unit are interpreted to mean that calcium-bearing waters were introduced periodically into the expanded lake to form a relatively fresh layer on top of a slightly saline layer.   The salinity of this lower layer was probably less than that of the lakes in which M–6, M–7, and the lower part of the Parting Mud were formed, where the calcium was instead precipitated as gaylussite or pirssonite, because of the dilution that ultimately resulted from the large volumes of water that entered the basin at the beginning of this period.   The formation of these aragonite laminae might have started after mixing broke down the density layering during a partial recession of the lake; this recession is suggested by variations in the pollen content (Roosma, 1958; Estella B. Leopold, written commun., 1957, 1958) and by an increase in clastic material in cores from this horizon, and is definitely indicated by interbedded sand layers in equivalent horizons of the exposed lake sediments. These criteria also indicate one or more expansions of the lake during the period represented by the remainder of the Parting Mud.   The increases in gaylussite and pirssonite near the top, and in dolomite at the top, indicate a final shrinking of the lake that culminated in the deposition of the Upper Salt.   The borax crystals at the very top of the Parting Mud indicate a brief very cool period just prior to the deposition of the basal layer of the Upper Salt.

### OVERBURDEN MUD

The Overburden Mud differs from all underlying mud units in that it was deposited largely in intermittent or shallow saline lakes.   It consists chiefly of dark-brown mud in the edge facies and interbedded halite lenses and brown mud in the central facies.   The mud consists chiefly of clastic materials.   The bottom few inches of the unit contain pirssonite or gaylussite crystals, and small quantities of salines are locally interbedded.   Halite crystals from some horizons are waterworn and rounded.   These crystals, together with the lenslike character of the salines and the lack of fine-grained evaporite minerals in the muds, make these sediments strongly resemble others being deposited today on the surface of shallow or seasonal saline lakes, and the depositing environment is so interpreted.

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