Chemical Zonation of the Borates of Kramer, California[1]

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ABSTRACT

A marked zonal relationship exists among borax (sodium borate), ulexite (sodium-calcium borate), and colemanite (calcium borate) in the lake beds at Kramer, California. A central borax body is surrounded above and laterally by beds containing ulexite and colemanite and below by beds containing only ulexite. Most thin-bedded borax and part of nodular ulexite may be first-formed or synsedimentary minerals. Therefore, the existing mineral distribution may be a reflection of an earlier chemical zonation that developed during or shortly after deposition of the Kramer lake beds.

In several localities nodular (cottonball) ulexite similar to Kramer ulexite has formed by replacement of muds of modern playas. The ulexite at Kramer shows identical textures. In contrast, the borax at Kramer was deposited on lake muds in response to evaporation of saturated $Na_2B_4O_7$ *brines.*

Two mechanisms may explain the separate occurrences of the borate phases. Subsurface reaction of calcium-bearing ground water with the sodium borate ore body or with sodium borate-rich brines entrapped in the lake muds may have produced with relatively less soluble ulexite and colemanite, a mechanism compatible with preliminary experimental findings of other workers. Another possible, although less probable, mechanism is the formation of ulexite and colemanite by ion exchange of sodium and calcium with the montmorillonitic claystones interbedded with the borates. Textural and structural data, together with the spatial distribution of the borates in the lake beds, suggest that the first mechanism was more important.

INTRODUCTION

The nonmarine evaporite deposit at Kramer, California, consists almost exclusively of borax, ulexite, colemanite, and kernite, with minor amounts of other borate minerals such as inderite, kurnakovite, inyoite, meyerhofferite, and probertite. The deposit is unusual in that many of the minerals usually found in typical salt deposits, such as halite, trona, gypsum, and thernardite are not present. Although the deposit contains unusually large amounts of sodium borate, borax appears to have accumulated under normal evaporitic conditions in ways that are compatible with mechanism proposed for saline deposition in other evaporite environments. The specialized gross composition of the evaporite minerals at Kramer reflects the unusual chemical nature of waters entering the basin. However, details of the mineralogical distribution may

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reflect environmental differences within the former lake basin that existed during or after the existence of the lake.

Borax ($Na_2B_4O_7 \cdot 10H_2O$) and ulexite $NaCaB_5O_9 \cdot 8H_2O$) are the two most abundant borates held by Gale (1946) and Obert and Long (1962, pp. 66-67)[4] to have formed as early phases at Kramer, that is, at the time the lake existed or shortly thereafter. The borax layers, interbedded with montmorillonitic claystone layers, form a moderately thick, tabular body (maximum thickness 345 feet, Obert and Long, 1962). Scattered nodules and veins of calcium-bearing borates (ulexite and colemanite, $Ca_2B_6O_4 \cdot 5H_2O$) occur in claystones both immediately above and peripheral to the borax body (Gale, 1946, p. 342). Ulexite also occurs in the claystone beneath the sodium borate beds. Some ulexite is associated with borax, but most of the ulexite is in zones separate from the borax.

The precise details of the spatial relationships of colemanite and ulexite are imperfectly known, but most, if not all, of the colemanite occurs in the claystone that surrounds the borax. Recently Barnard and Kistler (1966) presented evidence indicating that most of the colemanite and ulexite occur separately from one another; the colemanite-bearing claystones form beds that both laterally surround and overlie the more central cottonball ulexite and borax beds. In other words the borate occurrence at Kramer is formed of a central borax body, surrounded by claystone beds containing cottonball ulexite, with colemanite occurring in beds to the side of, and above, the ulexite-bearing rocks. Knowledge of processes leading to the deposition of these borate minerals is needed to better understand the origin of the Kramer deposit.

The purpose of this paper is to examine some of the problems bearing on the modes of deposition of the sodium, sodium-calcium, and calcium borates (borax, ulexite, and colemanite respectively) at Kramer. Evidence concerning the origin of "cottonball" ulexite at Columbus Marsh, Nevada and Airport Dry Lake, California, is used to help evaluate the conditions of formation at Kramer. The geologic features are interpreted in the light of chemical and mineralogical data presented by Bowser (1965), Kemp (1956), and Kurnakov and Nikolayev (1948).

ACKNOWLEDGMENTS

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Dr. S.W. Bailey and Dr. S. Muessig critically read the manuscript, although responsibility for any conclusions found in this article rests solely with the authors. Mr. Karoly Fogassy kindly prepared the line drawings. Financial support for the project was provided by the National Science Foundation (Grants G-11345 and G-23932).

DEPOSITION OF BORATES

Ulexite

Ulexite at Kramer, commonly referred to as "cottonball" ulexite, occurs in massive green claystones as rounded, lumpy masses that generally range in size from a fraction of a centimeter up to several centimeters in diameter. The aggregates are composed of fine fibrous ulexite in both parallel and radial arrangements. Texturally the Kramer ulexite is identical to the "cottonball" ulexite that occurs in many other borate deposits of the world. For example, cottonball ulexite appears to be forming today at Columbus Marsh (approximately 35 miles west of Tonopah, Nevada), and Airport Dry Lake (10 miles north of China Lake, California).

[4] To date there has been insufficient evidence presented to argue whether some of the colemanite, inyoite, meyerhofferite, kurnakovite, and inderite may have also formed at or nearly the same time that the enclosing sediments were deposited, but, with the exception of colemanite, these other borates are not abundant, and, consequently, they will not enter into the discussion presented in this paper.

Ulexite at Columbus Marsh occurs on the southern margin of the salt flat, immediately adjacent to the highway leading west from Coaldale junction. The area is covered with numerous "phreatophyte mounds." Minor efflorescent crusts cover the intervening low ground. In clayey and silty sands underlying the marsh, ulexite is forming approximately ten centimeters below the surface above a conspicuous boundary that separates finer grained sediments below from coarser grained sediments above. The ulexite occurs in a moderately thin (2-3 cm.) and regular horizon in most places, but beneath the phreatophyte mounds the ulexite horizon thickens, with the upper surface of the ulexite horizon tending to conform to the topographic rise. Since the ulexite appears to be controlled by present-day surface it is probably forming at the present time. The ulexite is now growing <u>in</u> the sediments, probably by precipitation from dilute runoff waters, which are prevented from percolating deeper into the sediments by the low permeability of the underlying finer grained sediments. The precipitation of ulexite is probably caused by evaporation of solutions standing below the surface. Regardless of the mechanism of precipitation, however, ulexite is growing <u>in</u> the enclosing sediments, very likely by replacement of the sediments, as is the case with celestite nodules at Bristol Dry Lake (Durrell, 1953, p. 13).

The occurrence of ulexite at Airport Dry Lake is similar to that at Columbus Marsh except that at Airport Dry Lake the boundary separating finer and coarser grained sediments is deeper, nearly one meter below the dry lake surface (see Fig. 1). The nodules, slightly larger than those at Columbus Marsh, are distributed through a thicker layer and are higher above the coarse- to fine-sediment boundary. Growth of the ulexite by replacement of the enclosing sediments has apparently taken place at Airport Dry Lake as well as at Columbus Marsh.

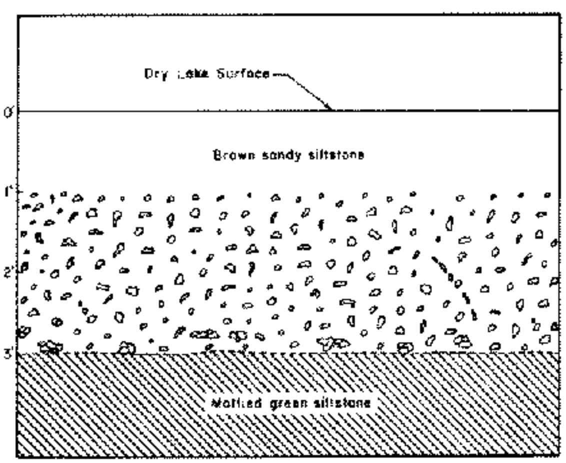

Figure 1. Sketch showing distribution of "cottonball" ulexite at Airport Dry Lake (rounded, irregular masses). Many ulexite masses are multiple, that is, composed of two or more fibrous "cottonballs."

The "cottonball" ulexite at Kramer is sufficiently similar in most important respects to the two occurrences at Columbus Marsh and Airport Dry Lake to allow the working hypothesis that first generation ulexite at Kramer also grew <u>in</u> muds. Thus, the ulexite formed distinctly after mud deposition. This is in accord with the conclusions reached by Gale (1946, p. 377) and by Godlevsky (1937, p. 358), in his studies of the Inder borate district of Russia, and by Muessig (1959, p. 496).

<u>Borax</u>

Evidence that the first formed[5] borax at Kramer was precipitated from lake water was presented in abstract form by Bowser and Dickson (1963) and in a manuscript now in preparation. A summary of the data pertinent to the topic of this paper is presented in the following paragraphs.

The bedding relationships between the primary borax and the claystone are different from place to place, but one of the most common and most significant is the type illustrated in Fig. 2. The borax occurs in thin, relatively pure layers, about one to three cm. thick, interbedded with thinly laminated claystone beds of about the same thickness. Individual borax layers show the following characteristics:

1. Numerous crystals at the base and fewer and larger crystals at the top.
2. Crystals at the top of the layer with upward facing euhedral terminations.

[5] The term "first formed" borax is used in this paper to mean the borax that was precipitated directly from the lake water at the lake-sediment interface. The terms primary and syngenetic have been used to describe the timing of some of the borate minerals, but useage is avoided here because of uncertainties in the timing of some minerals and the number of different ways in which these terms have been used.

3. Many large crystals at the top of the borax layer that taper downward, thus showing fan-shaped cross sections.

4. Large borax crystals at the tops of the beds with preferred crystallographic orientation, with the b-axis vertical (see Fig. 3), but numerous small borax grains along the base of the layer without preferred orientation.

5 Borax crystals with internal zones, that reveal variations in the amount of clay within the crystals. The zones are parallel to existing external crystal faces.

Figure 2. Primary borax bed showing prominent development of clay zoning. Cross-cutting white veinlets and unzoned white areas between zoned borax crystals are secondary borax. Black areas at the base of the borax bed are crystals of kernite ($Na_2B_4O_7 \cdot 4H_2O$) that formed during later alteration of the ore body. Maximum thickness of borax bed is approximately two centimeters.

The clay zones within borax crystals probably were formed by variations in the rate of clay sedimentation relative to the rate of borax crystal growth. The variations in borax growth rates probably reflects diurnal variations of lake water temperature and evaporation rate.

From the field and textural observations we conclude that the first generation borax at Kramer formed <u>on</u> bottom muds, in contrast to ulexite, which formed <u>in</u> muds. Borax grown in the laboratory in beakers through evaporation of saturated $Na_2B_4O_7$ solutions developed identical features to those of natural crystals (Fig. 4), thereby strengthening the argument that borax crystals at Kramer grew on the bottom of the lake in response to components being supplied from above.

The montmorillonitic claystone interbedded with the first-formed borax was deposited during times when the lake was undersaturated. Corrosion observed on the tops of some borax layers provided visible evidence of the transition to conditions of lake undersaturation from lake saturation.

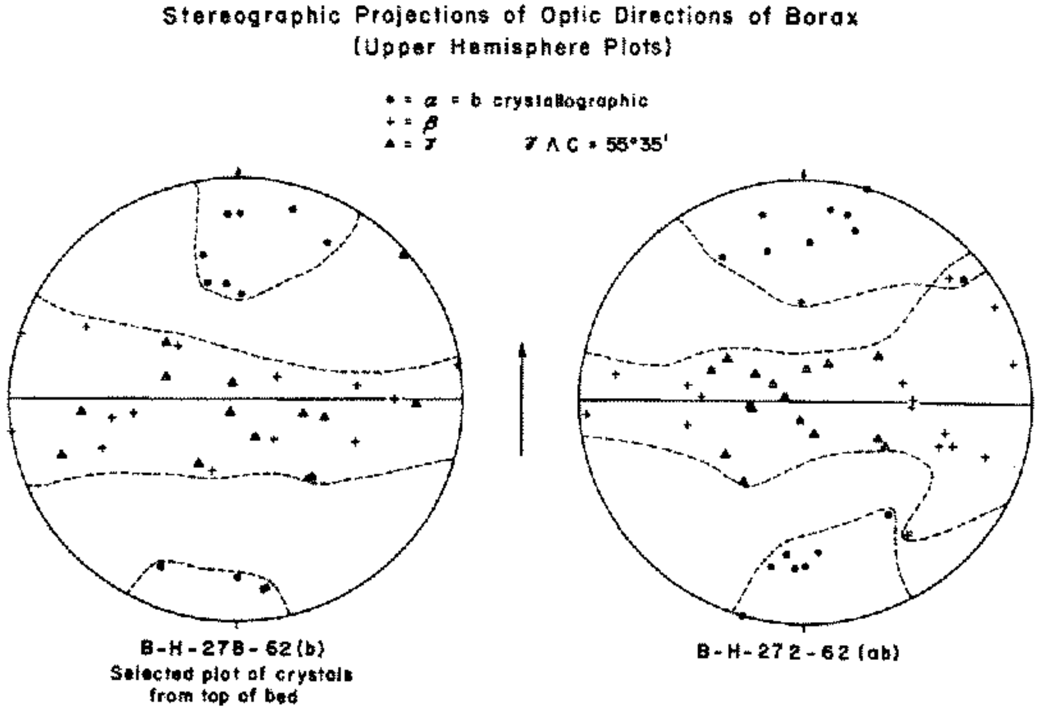

Figure 3. Stereographic projections of optic directions of borax crystals from the tops of primary borax beds. The pole of the bedding plane is indicated by the arrow. The dashed lines are roughly drawn to illustrate the grouping of the α and β - δ optic directions, and have no quantitative significance. Similar plots of crystals from the base of the bed show considerably less preferred orientation.

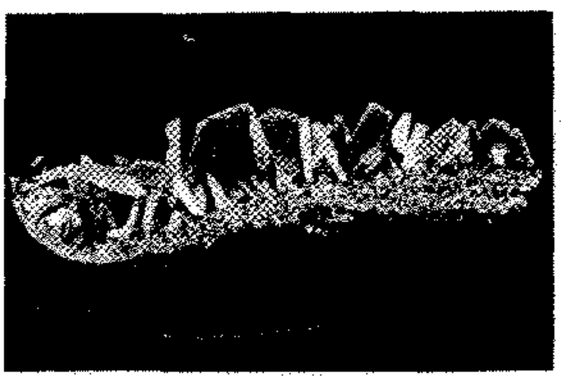

Figure 4. Artificial borax crystals grown on the bottom of a beaker from a $Na_2B_4O_7$-H_2O solution by evaporation. Note the similarities to the natural primary borax shown in Figure 2. Length of specimen is approximately three centimeters.

The borax beds described previously are common throughout the borate beds at Kramer. They are therefore a major type. Two deductions have an important bearing on the conditions attending deposition of evaporites at Kramer. First, zoned crystals that grew on the bottom of the lake in response to diurnal temperature fluctuations require the lake to have been relatively shallow, probably less than 10-20 meters, in order for temperature variations to have affected the growing crystals. Second, the borax beds are monomineralic and were produced by monomineralic[6] precipitation of borax. Such borax layers scattered throughout the deposit imply that the lake brines at Kramer never were sufficiently rich in constituents such as NaCl, Na_2SO_4, or Na_2CO_3 to allow precipitation of salts other than borates. Inferences drawn from solubility studies in the system $Na_2B_4O_7$-NaCl-H_2O (Fig. 5) suggest the concentrations of other salts in the former lake at Kramer were unusually low; otherwise these salts would have precipitated at some stage during the existtence of the lake. Borax appears to have grown in a relatively simple chemical environment (Bowser, 1965, pp. 180-200).

[6] By monomineralic precipitation it is meant that other minerals that are common in many other evaporite deposits, such as halite, trona, or gypsum, were not coprecipitated with borax. Minor amounts of minerals such as calcite or dolomite could have been coprecipitated without affecting the primary borax textures.

INTERPRETATION

In the previous discussion it was concluded that "cottonball" ulexite grew <u>in</u> the lake muds hereas first generation borax grew <u>on</u> the muds. However, some borax and ulexite occur at the ame stratigraphic levels, (Obert and Long, 1962, p. 15; and Gale, 1946, p. 377) a fact generally aken to indicate closeness in times of formation of the minerals. Is it possible that while the orax was being precipitated from solutions within the lake, ulexite was growing by replacive rocesses in muds surrounding the lake? "Cottonball" ulexite also occurs in zones both above and elow the borax beds; did this ulexite have the same mode of origin as the ulexite that occurs at he same stratigraphic levels as the borax beds?

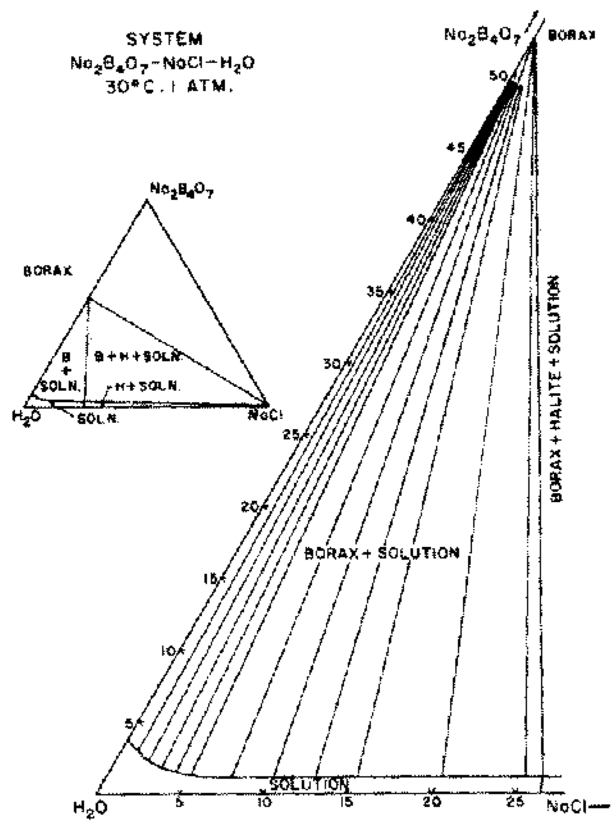

Figure 5. Water rich corner of the 30°C isotherm for the system $Na_2B_4O_7$-NaCl-H_2O. Inset shows complete isotherm and the stability fields of borax (B) and halite (H).

It may be that all the "cottonball" ulexite at Kramer has the same mode of origin, however, since each type of occurrence involves slightly different lines of evidence, the following discussion is subdivided according to mode of occurrence and mechanism of formation suggested from that occurrence.

Of principal concern in this discussion is the evidence on the timing of ulexite deposition relative to that of the adjacent borax. "Cottonball" ulexite is forming at present in many modern playas, however this does not offer conclusive proof of the earliness of ulexite formation at Kramer. It only indicates that it can form any time after deposition of the enclosing muds; from penecontemporaneous to much later. In the following discussion an attempt is made to take this problem into account, realizing, however, that other evidence is necessary before definite conclusions can be reached on the relative timing of some of the different borate phases at Kramer.

Claystone interbedded with first-formed borax

The claystone that is interbedded with the borax probably was originally permeated with solutions containing chemical components essentially identical to those in the lake brine from which the borax deposited. Much of the claystone was deposited when the lake was undersaturated, and the brines trapped in the clay were probably of lower salt content. Claystone interbedded with the borax does not contain significant amounts of "cottonball" ulexite. However, there is some minor ulexite pseudomorphic after borax that occurs in the borax-claystone interbeds. This ulexite probably formed by some process that involved interreaction with the solutions trapped in these muds. Obviously, more than simple dehydration of the claystone was involved; some calcium had to be present or introduced for the sodium borate components in the mud to react to produce ulexite rather than borax.

Cation exchange of sodium and calcium with the clays possibly could modify the composition of the interstitial solutions enclosed in these claystones. According to Gates (1959) the claystones at Kramer are largely montmorillonite with subordinate illite. The relatively high exchange capacity of most montmorillonites is well known (Grim, 1953, p. 130). It is generally accepted that Ca^{++} replaces Na^{+} in the clays more readily than Na^{+} replaces Ca^{++}. Grim (1953, p. 145) points out, however, that replaceability is a function of the concentration of Na^{+} and Ca^{++} in the exchanging solution. The concentration of Na^{+} in the solutions trapped in the Kramer lake muds may have been high enough to allow exchange of Na^{+} for Ca^{++} in the clay. The process could be written:

$$Na_2B_4O_7 \text{ solution} + CA^{++}\text{-Montmorillonite} \longrightarrow NaCaB_5O_9 \cdot 8H_2O + Na^{+}\text{-Montmorillonite}$$

This reaction has not been demonstrated experimentally to take place. Even small amounts of Ca^{++} generated by this mechanism would account for the trace amounts of ulexite in the sedimentary layers that alternate with the borax ore body.

Claystones surrounding the bedded, first-formed borax

The origin of the "cottonball" ulexite that occurs in the claystones surrounding the main borax body presents a more difficult problem. Some ulexite may have formed by a cation exchange process as suggested above. Alternatively, the entrapped brines may have been originally of appropriate composition for precipitating ulexite, or Ca^{++} may have been added to the brines by some external source, such as by moving in of ground water of a different composition. A cation exchange mechanism is much less appealing for this type of ulexite occurrence, because the percentage of "cottonball" ulexite in the claystone would seem to demand a large amount of Na-Ca exchange; seemingly much more than could be provided locally. To help decide among these alternatives it is necessary to know the spatial and paragenetic relationships between the first generation borax beds and the "cottonball" ulexite-bearing claystones.

The "cottonball" ulexite-bearing claystone that occurs directly above the borax beds evidently represents a phase of borate deposition that followed deposition of the borax.[7] The lake water composition could have been slightly different during these two periods (i.e., richer in calcium), and, therefore, it is possible that the ulexite in these muds precipitated directly from solution by saturation. However, Obert and Long (1962, p. 15) state that: "Laterally, the bedded sodium borates are generally abruptly lenticular and interfingered with the so-called blue clay and other associated sediments of the Kramer lake beds." More recently Barnard and Kistler (1966) have demonstrated that the upper borax and "cottonball" ulexite-bearing claystones interfinger with one another. Some of the "cottonball" ulexite formed essentially at the same stratigraphic level as laterally adjacent primary borax, a conclusion not compatible with simultaneous equilibrium precipitation of ulexite and borax from the same solution. This ulexite could have formed either penecontemporaneously with the borax or at some much later time.

[7]Ulexite also occurs in the beds that underlie the main borax body, but whether or not deposition of the ulexite had taken place prior to precipitation of borax is not known. Gale (1946, pp. 342 and 345) indicates that this ulexite looks slightly different from the typical "cottonball" ulexite, being a dense form that occurs as seams, veinlets, and irregular patches. This ulexite could have formed much later than the overlying borax.

A possible way in which this ulexite might have formed is suggested by the experiments reported by Kemp (1956, p. 71). "... [ulexite] has... been prepared by the action of an excess of a cold saturated solution of borax on calcium chloride, the first-formed amorphous precipitate being transformed in 5-30 days to a mass of fine crystals." Identical results have been produced by us by mixing saturated borax solutions with solutions of calcium chloride, by adding solid calcium chloride solutions. Menzel and Schulz (reported in Kemp, 1956, p. 71) obtained ulexite by dissolving borax and $CaB_2O_4 \cdot 6H_2O$ in water. Evidently addition of calcium to $Na_2B_4O_7$ solutions causes the solubility product of ulexite to be exceeded, leading to its deposition.

If ground waters containing calcium seeped into sediments at the margins of the lake at Kramer, reaction with sodium borate rich brines in sediments at the margins of the lake basin would have precipitated some ulexite.[8] Alternatively post-lake encroachment by calcium-rich ground water at deeper horizons would encounter $Na_2B_4O_7$ containing-muds surrounding the sodium borate beds, causing ulexite to precipitate in a shell of rocks around the borax. Thus, the formation of "cottonball" ulexite could have taken place penecontemporaneously with borax deposition, or it may have formed considerably later, after the lake ceased to exist. The similarity of the "cottonball" ulexite at Kramer to ulexite forming in modern playas suggests, but does not prove, a syngenetic origin for the Kramer ulexite.

Possible reactions between ground water and entrapped lake waters

If the ulexite formed by interaction of ground water and borax or lake brine, then from mineral associations one might be able to deduce something about the possible compositions of the ground water. The following chemical reactions help illustrate the point.

$$5Na_2B_4O_7 + 4CaCl_2 + 33H_2O \longrightarrow \underset{\text{(ulexite)}}{4NaCaB_5O_9 \cdot 8H_2O} + 6NaCl + 2HCl$$

$$5Na_2B_4O_7 + 4CaSO_4 + 33H_2O \longrightarrow \underset{\text{(ulexite)}}{4NaCaB_5O_9 \cdot 8H_2O} + 3Na_2SO_4 + H_2SO_4$$

$$5Na_2B_4O_7 + 4Ca(HCO_3)_2 + 33H_2O \longrightarrow \underset{\text{(ulexite)}}{4NaCaB_5O_9 \cdot 8H_2O} + 6NaHCO_3 + 2H_2CO_3$$

and

$$Na_2B_4O_7 + Ca_2B_6O_{11} + 8H_2O \longrightarrow \underset{\text{(ulexite)}}{2NaCaB_5O_9 \cdot 8H_2O}$$

In the first three reactions the precipitation of ulexite would produce a solution containing respectively, chloride, sulfate, or bicarbonate of sodium. Solutions of this sort would lead eventually to the deposition of these particular salts that, however, have not been observed. If such solutions were retained in the clays, the salts would have precipitated during later evaporative dehydration of the muds. To date, no significant amounts of salts of this sort have been detected at Kramer, either in the muds or with the borax. However, if entrapped saline water were expelled by mechanical compaction rather than by evaporation, the soluble salt components would have fled from the system.

On the other hand, reaction of a small amount of calcium borate solution with the sodium borate-rich fluids trapped in the muds would precipitate ulexite, as shown in the last reaction, and the composition of the brine in the sediment would have been relatively little altered.

It is possible that, as Dickson and Raab have suggested, that borate-bearing hot springs discharged directly into a lake basin of restricted drainage (Dickson and Raab, 1965, p. 44). Continuation of hot spring activity to a time clearly after accumulation of the sediments could have been accompanied by a shift in the composition of the spring solutions from dominantly sodium-borate components to calcium-borate components. Such solutions, if they attacked the margins of the borax body, could produce the observed distribution of calcium and sodium-calcium borates surrounding the borax.

[8] During periods when the lake was saturated with borax the limits of the lake may have extended only to the present limits of the bedded borax. Consequently the muds surrounding the central borax may have been subaerial at times of lake saturation.

SIGNIFICANCE OF THE NODULAR COLEMANITE AT KRAMER

Because of the replacive aspect of some nodular colemanite with "cottonball" ulexite shown in some localities some workers have suggested that colemanite is a secondary mineral derived from the breakdown of ulexite. Noble (1926) concluded that all the colemanite at the Gerstley Mine, east of Death Valley, California, was derived from ulexite. Foshag (1921) believed that sodium chloride solutions percolating through ulexite-bearing strata could cause the ulexite to convert to colemanite. This reaction was reported to occur at temperatures above 70° C (Kemp, 1956, p. 71). Pure water can extract small amounts of sodium from ulexite and perhaps some colemanite has been formed in this way. The reaction may have been:

$$\underset{\text{(ulexite)}}{2NaCaB_5O_9 \cdot 8H_2O} + AQ = \underset{\text{(colemanite)}}{Ca_2B_6O_{11} \cdot 5H_2O} + [Na_2B_4O_7]\,Aq$$

At Kramer colemanite may have originated by more than one mechanism. Cores of coarse-grained, massive colemanite are found in indurated nodular masses of "cottonball" ulexite. This ulexite apparently has been replaced by colemanite, by a mechanism similar to the one proposed by Noble (1926) for the Gerstley deposit. However, many of the colemanite nodules that occur in the beds overlying the borax and "cottonball" ulexite-bearing beds are similar to ulexite only in their nodular shape (see Figs. 6 and 7). The radiating structure of the colemanite crystals in the nodules suggests that the nodules grew from the center outward. This radiating structure is unlike the structure of the colemanite which is thought to have formed from ulexite in that the crystals of the nodular colemanite are in most places much finer grained. These nodules show centers that contain radiating and concentric veins of clear, crystalline colemanite, (Fig. 6), structurally identical to septaria of carbonate concretions described in Pettijohn (1957, p. 208). Numerous septarian calcite nodules occur with the colemanite nodules in the same stratigraphic horizons. The calcite nodules differ from the colemanite nodules only in their finer grained nature and their preservation of the laminations of the surrounding claystone. Both types of nodules are evidently types of concretions. The relative lack of compaction of laminae in the calcite nodules compared to the more closely spaced laminae of the adjacent claystone indicate an early origin for the calcite nodules. The similar structure and mode of occurrence of the colemanite nodules suggests that they too formed early. The colemanite in these nodules apparently grew from solution in unconsolidated sediments and need not have formed by alteration of pre-existing ulexite.

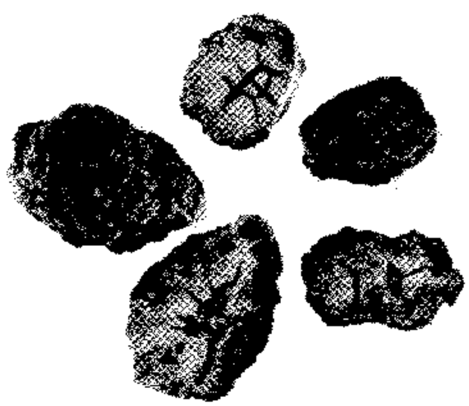

Figure 6. Septarian colemanite nodules from the claystone overlying the borax beds at Kramer, California. The rough surfaced specimen (3, 3 cm, long) shows the typical external surface of the nodules; the other four specimens are medial sections that have been ground smooth and plastic spray coated to show the typical septarian structures.

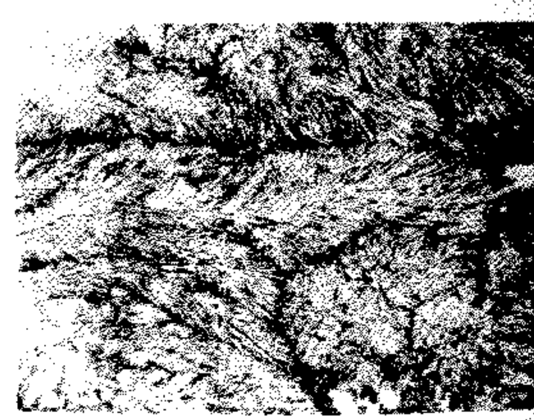

Figure 7. Photomicrograph of the edge of a septarian colemanite nodule. Colemanite crystals radiate away from the central portion of the nodule. The increase in darkness toward the edge of the nodule is caused by an increase in the clay content of the nodule. Width of photograph is four millimeters.

The 25° C isotherm of the system Na_2O-CaO-B_2O_3-H_2O published by Kurnakov and Nikolayev (1948) shows that stability field of the calcium borate (inyoite in their experiments) was separated from the borax stability field by a field of ulexite. Thus mineral associations of borax-ulexite and ulexite-calcium borate would be predicted to occur in borate deposits, but borax-colemanite associations would not be expected as an equilibrium assemblage. Studies of the distribution of colemanite, ulexite, and borax in the borate shales at Kramer by Barnard and Kistler (1966) show that most of the colemanite does occur separately from borax, and hence is in accord with the experimental studies.

CONCLUSIONS

In conclusion, it is proposed that the nodular forms of ulexite and colemanite at Kramer were formed dominatly by subsurface reaction of calcium-bearing ground waters with the sodium borate solutions trapped in the lake muds during sedimentation. Another possible mechanism for deposition of ulexite and colemanite in the lake muds, not held to be important, involves cation exchange of Na^+ in the trapped fluids with Ca^{++} in the enclosing montmorillonite clays.

The separation of the colemanite-bearing claystones from the borax beds by an intervening "cottonball" ulexite-bearing claystone facies suggests that ground water modification of trapped brines is probable. Cation exchange of brines and clays may have been operative on a small scale. Studies of the stability of borate minerals under a variety of conditions in various solutions such as sodium chloride-water solutions, and in clay-water systems, and more detailed studies of the relative distribution and amounts of the borates at Kramer are needed before more definite conclusions can be drawn.

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