

CHAPTER 3

**BORATE DEPOSITS IN THE UNITED STATES: DISSIMILAR IN FORM,
SIMILAR IN GEOLOGIC SETTING**

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BORATE DEPOSITS IN THE US

NO. ON FIG. 1	MINE OR DISTRICT NAME	PRODUCTION PERIOD	GEOLOGIC AGE(1)	GEOLOGIC REFERENCE(S)
COLEMANITE DEPOSITS, TERTIARY				
1	Calico	1890-1907	13-17 my(a)	Wright & others, 1953, p. 223-225; Ver Planck, 1956, p. 280-281; Dibblee, 1967, p. 6
2	Callville Wash	1921-1928	13-16 my(d)	Callaghan & Rubey, 1936, p. 106-113
3	Frazier Mountain	1899-1907, 1911-1913	15 my?(b)	Gale, 1913a
4	Furnace Creek	1915-1928, 1928-1970 <small>(small)</small> , 1970-now	6 my(c)	McAllister, 1970; Fleck, 1970; Barker and Wilson, 1975; Evans and Anderson, 1976; Wendel, 1978
5	Gerstley	1920-now	6 my(c)	Noble, 1926a; Barker and Wilson, 1975, p. 32
6	Hector	None	19-23 my(a)	Madsen, 1970
7	Kramer Junction	None	18-20 my?(b)	Benda and others, 1960; Evans and Anderson, 1976
8	Lang	1908-1923	20 my(b)	Gay and Hoffman, 1954
9	Lila-C	1907-1914	6 my(c)	McAllister, 1973
10	White Basin	1920-1922	13-16 my(d)	Callaghan & Rubey, 1936, p. 106
BORAX DEPOSITS, TERTIARY				
11	Kramer (Boron)	1927-now	18-20 my(b)	Gale, 1946; Bowser and Dickson, 1966; Barnard and Kistler, 1966
ULEXITE DEPOSITS, QUATERNARY				
12	Amargosa	1884-1890	?	Bailey, 1902, p. 50-55
13	China Lake	1894	?	Ver Planck, 1956, p. 282
14	Columbus Marsh	1870-1882	?	Papke, 1976, p. 22
15	Dixie Marsh	1872 ±	?	Papke, 1976, p. 19
16	Eagle Borax	1881-1882	?	Evans and others, 1976, p. 21
17	Fish Lake	1870-1882	?	Papke, 1976, p. 22
18	Harmony Borax	1882-1890	?	McAllister, 1970
19	Koehn Lake	1873 ±	?	Hanks, 1883
20	Rhodes Marsh	1872-1882	?	Papke, 1976, p. 20-21
21	Saline Valley	1888-1892+	?	Gale, 1913b, p. 24-25
22	Salt Wells	1870-1875 ±	?	Papke, 1976, p. 20
23	Searles Lake	1874-1895	?	Smith, 1979, p. 4-5
24	Teels Marsh	1873-1882	?	Papke, 1976, p. 21-22
BORAX DEPOSITS, QUATERNARY				
25	Borax Lake	1864-1868	?	Hanks, 1883, p. 18023
26	Lake Alvord	1897-1907 ±	?	Dennis, 1902
27	Searles Lake	None?	0.03-0.01 my	Smith, 1979, p. 4-5, 34-37, 59-60
BORATE-BRINE DEPOSITS, QUATERNARY				
28	Lake Hachinama (Little Borax Lake)	1868-1874	?	Hanks, 1883, p. 23-24
29	Owens Lake	1926-1960?	1921	Dub, 1947
30	Searles Lake	1919-now	0.03-0.01 my	Smith, 1979, p. 5
OTHER TYPES OF DEPOSITS				
31	Cave Spring (searlesite)	None	Miocene?	Foshag, 1934
32	Chetko (priceite)	1872, 1891-1892	?	Staples, 1948; Wagner, 1969
33	Silver Peak Range (ulexite)	1938-1939	Tertiary	Papke, 1976, p. 23

(1) Age estimates of Tertiary deposits based on data from following sources, and my geologic correlation of them with the borate deposits: (a) Woodburne and others, 1982, p. 51; (b) C. A. Repenning, U.S. Geological Survey, written and oral commun., 1984; (c) Fleck, 1970; (d) Bohannon, 1983; data obtained after preparation of Figure 2 which portrays an earlier estimate.

Source: Data from indicated references and unpublished information in U.S. Geological Survey files.

Table 1. Borate deposits of the United States.

INTRODUCTION

Nearly 30 sites in California, Nevada, and Oregon have (or have had) sufficient concentrations of borates to be considered deposits (Table 1). Most of these can be assigned geologically to one of five types of settings: (1) Tertiary deposits dominated by colemanite and other calcium-borate minerals, (2) Tertiary deposits dominated by borax and other sodium-borate minerals, (3) Quaternary playa lakes having efflorescences, crusts, or near-surface beds composed mostly of ulexite, (4) Quaternary playa lakes underlain by beds containing borax, and (5) Quaternary salt lakes characterized by surface or subsurface borate-rich brines.

The original borate concentrations appear mostly to have been products of subaerial evaporation of borate-rich waters that were related in some way to contemporaneous volcanic activity, though some concentrations may have originated as products of subsurface replacement by such waters. These concepts are hardly new. In 1857, Veach (in Hanks, 1883) concluded that the borates in Borax Lake were products of evaporation and that thermal springs related to geologically-young volcanic rocks were the source of the boron. Over the next half century, little variation on this concept was developed until Gale (1913a, p. 5-7) and Foshag (1921, p. 211-212) recognized, respectively, that some of the Tertiary colemanite deposits discovered near the end of that century could be products of either subsurface metasomatic replacement of limestone or diagenetic recrystallization of lacustrine deposits of ulexite. Those sets of concepts still constitute our basic geologic framework for most borate deposits.

For convenience in discussion, the processes responsible for presently known borate concentrations are divided here into three conceptual groups, although many deposits clearly represent a sequence of these processes. "Primary" deposits are those masses of borate minerals that resulted from the crystallization of borate-rich waters which were juvenile or at least ascended from great depths; "reworked" deposits are those that resulted from the redeposition of borates derived from older near-surface deposits, apparently involving only meteoric waters; "diagenetic" deposits are those that originated as primary or reworked deposits which then underwent post-depositional changes in the mineralogy, paragenetic relations, and spatial distribution of borate minerals.

TYPES OF DEPOSITS

TERTIARY COLEMANITE DEPOSITS

Tertiary colemanite-type deposits in the United States are known only in California and Nevada (Fig. 1). Though all were originally

developed for their colemanite ores, most also have associated ulexite, probertite, and other borate minerals (Table 2), sometimes in even larger amounts. Many of these deposits appear to be stratigraphically controlled, but textural evidence generally shows that the colemanite itself is diagenetic and somewhat displaced stratigraphically and laterally from the site of the primary mineral mass. In some instances, colemanite is demonstrably a result of post-depositional diagenesis of ulexite, but in many deposits this cannot be satisfactorily proven though it remains likely. Gale (1913c, p. 7-9), however, reached the conclusion, after studying the deposits in Ventura County in which he found no

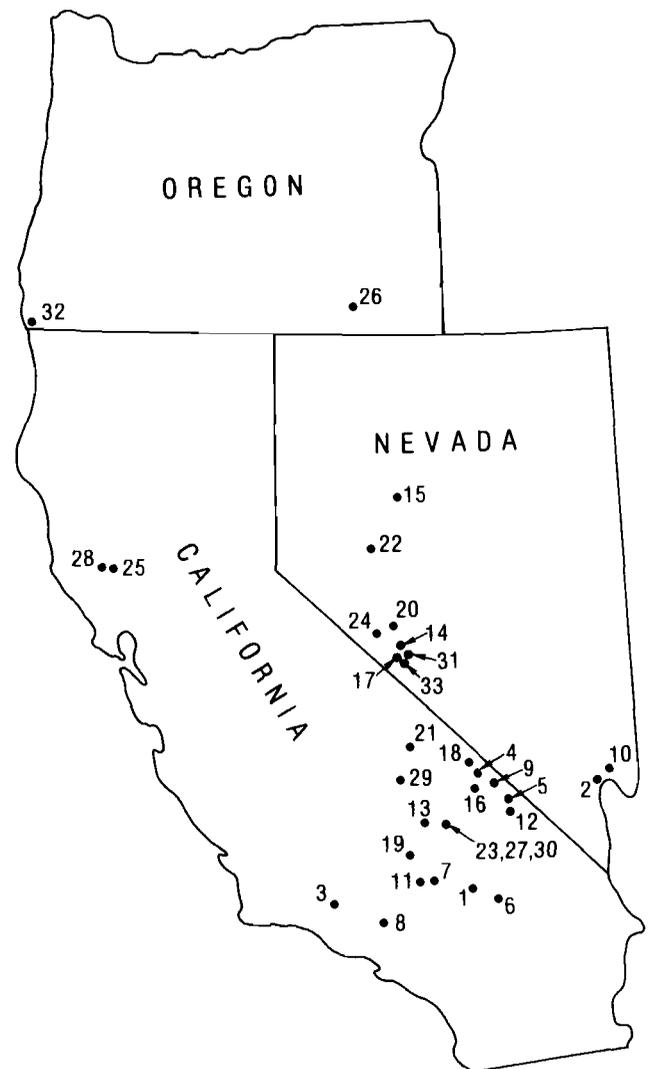


Figure 1. Map of California, Nevada, and Oregon showing locations of borate deposits discussed in text. Numbers refer to those listed to left of mine and district names in Table 1.

Mineral	Chemical Composition ¹	B ₂ O ₃ Content (wt %)
Borax	Na ₂ B ₄ O ₇ ·10H ₂ O	36.5
Colemanite	Ca ₂ B ₆ O ₁₁ ·5H ₂ O	50.8
Howlite	Ca ₂ SiB ₅ O ₉ ·(OH) ₅	44.5
Hydroboracite	CaMgB ₆ O ₁₁ ·6H ₂ O	50.5
Inderite	Mg ₂ B ₆ O ₁₀ ·15H ₂ O	37.3
Inyoite	Ca ₂ B ₆ O ₁₁ ·13H ₂ O	37.6
Kernite	Na ₂ B ₄ O ₇ ·4H ₂ O	51.0
Kurnakovite	Mg ₆ B ₆ O ₁₉ ·15H ₂ O	37.3
Meyerhofferite	Ca ₂ B ₆ O ₁₁ ·7H ₂ O	46.7
Nobleite	CaB ₆ O ₁₀ ·4H ₂ O	62.0
Priceite	Ca ₄ B ₁₀ O ₁₉ ·7H ₂ O	49.8
Probertite	NaCaB ₅ O ₉ ·5H ₂ O	49.6
Searlesite	NaBSi ₂ O ₆ ·H ₂ O	17.1
Ulexite	NaCaB ₅ O ₉ ·8H ₂ O	43.0

1. Compositions expressed as hydrated oxides of the one or more cations. Hypothetical-oxide and structural formulas for these minerals are listed by Erd (1980, table 1).

Table 2. Composition and borate content of minerals most commonly found in borate deposits.

ulexite, that colemanite deposits were vein deposits (and thus primary in the sense defined here), though he later (1946, p. 377) conceded that the colemanite occurrences around and above the ores in the Kramer district were diagenetic, and that ulexite was the first-formed borate mineral. The amounts of ulexite associated with some of the colemanite deposits in the Death Valley are so great, and the technology of utilizing ulexite ore is so improved, that ulexite is locally now the "ore" mineral, and we have the paradox of "colemanite-type" borate bodies now being the major sources of ulexite ore.

Descriptions of most colemanite deposits indicate them to be associated with beds of clay, shale, mudstone, limestone, dolomite, or gypsum. Rocks of these types suggest deposition in lakes, and the dark and greenish hues reported from some suggest that they were products of perennial lakes that maintained reducing conditions in their accumulating sediments. Outcrops of colemanite-bearing beds generally are light tan, but this is a result of near-surface oxidation. In the Furnace Creek area of Death Valley, the change

from oxidized to unoxidized rock in mines and cores occurs at depths ranging from 15 to 45 m (McAllister, 1970; Wilson and Emmons, 1977). Other evidence indicating that the sediments serving as host rocks for colemanite ores were deposited in perennial lakes consists of thin to laminar bedding, well-sorted sediments, beds of clastic-free limestone, dolomite, and gypsum, and the general absence of playa-lake criteria such as mud cracks, root casts, oxidation zones, fossil soils, and channels. However, Baker (1911, p. 351, 358) comments on such playa-lake criteria in a few horizons of the Calico deposits, and a playa may well have been the site of original borate deposition for those--and possibly several other--deposits.

The variety of minerals known in well-studied deposits provides a clue to the chemical character of the waters that were responsible for them. The Furnace Creek area contains the most extensively studied group of colemanite-type deposits and a total of 28 named boron-bearing minerals have been identified (McAllister, 1970, 1976), and several more borate minerals are as yet undescribed (J. F. McAllister, written commun., 1984). The ores are composed primarily of colemanite, ulexite, and probertite, but six other borate minerals are also found in the underground portions of the of the mined deposits (McAllister, 1970). Cations represented in these borate ores are dominated by Ca, Na is next-most abundant, and Mg or Sr borates are found locally, while borates containing only Na as a cation are absent. Among non-borate minerals, calcite, dolomite, and gypsum are very common, and celestite is present (McAllister, 1976). If ulexite, which forms the upper levels in the cores of these orebodies, was the first-deposited borate mineral (McAllister, 1970), cations in the waters responsible for the primary borate assemblage probably consisted of sub-equal amounts of Ca and Na. The waters responsible for diagenesis probably contained less Na, more Ca, some Mg, and unusual amounts (compared to most waters) of Sr. The anion components were evidently mostly carbonates, sulfates, and borates, and the abundance of Ca requires the pH values of the depositing waters to have been near either neutral or slightly acid.

TERTIARY BORAX DEPOSITS

Only one major borax deposit of Tertiary age occurs in the United States, the Kramer deposit at Boron, in the west-central Mojave Desert of California (Fig. 1). Though calcium borates were discovered in this area in 1913, the sodium-borate body was not found until 1925, and production from it commenced in 1927 (Ver Planck, 1956). Most of present United States production of borates comes from this source. The geology of the deposit has been described by many (Noble, 1926b; Gale, 1946; Bowser and Dickson, 1966; Barnard and Kistler, 1966; Dibblee, 1967, p. 125-128); the mineralogy has also been comparably documented (Schaller, 1930; Morgan and Erd, 1969a, 1969b). Fifteen borates and borosilicates

have been confirmed by the 1969 studies as present in the main orebody. Sassolite (boric acid) has been reported as secondary(?) crystals in fringe areas (Smith and others, 1958).

Borax, a primary as well as a diagenetic borate mineral, is the most abundant sodium-borate mineral in the deposit. Where primary, borax is present as both euhedral crystals embedded in dolomitic marl, claystone, and siltstone, and as massive beds; where diagenetic, it is present as veins and irregular masses. Kernite, the other sodium-borate mineral, is in the deeper parts of the orebody and is all diagenetic. The orebody extends over an area of more than 2 sq km, has a maximum thickness of about 60 m, and an average borax-mineral content of about 70% (Smith, 1960). Most of the hydrated Na-Ca, Mg-Ca, Mg, and Sr borates, which occur as accessory minerals, are in a diagenetic zone around the edge of the ore body.

In contrast with many of the colemanite-type deposits, the Kramer deposit is dominated by the primary mineral. Both Bowser and Dickson (1966, p. 124-126) and Barnard and Kistler (1966, p. 149) conclude that borax crystallized on or slightly beneath the floor of a perennial lake that received the discharge from thermal springs whose waters contained large amounts of dissolved borate, and that ulexite grew as pods beneath the surface of the muds when borate concentrations fell below borax saturation levels. Coexisting with the borates are small amounts of realgar, stibnite, and native arsenic and sulfur (Morgan and Erd, 1969a, table 1) which furnish additional evidence of thermal spring activity in the immediate vicinity. Diagenesis, a result of encroaching Mg- and Ca-bearing ground waters, is considered responsible for the peripheral colemanite, ulexite, and most of the other Ca- and Mg-borate minerals in those zones. Burial temperatures above 60°C are responsible for the conversion of primary borax to kernite.

QUATERNARY ULEXITE DEPOSITS

Most concentrations of ulexite in the surface sediments of dry lakes--known as "marsh" deposits to early miners--are similar. The ulexite occurs as an efflorescence on the surface, or within a meter or two of the surface, as discontinuous thin beds or disseminated white pods ("cottonballs"), 1-5 cm across, that have a sharp boundary with the enclosing sediments. The mineral is virtually always in the form of very-fine, randomly oriented needles. Concentrations of the beds or pods in the sediments vary greatly, not only between deposits but from place to place within the same deposit.

In most deposits, ulexite is the only borate mineral. In some though, concentrations of borax and other evaporites coexist with ulexite (Rhodes Marsh, Teels Marsh, Fish Lake). In those deposits, the various assemblages appear zoned in a manner reflecting the source of evaporite components, their relative solubilities, the hydrolog-

ic properties of the playa sediments, and the details of playa-surface topography. The majority of the 35 borate-bearing playas in Argentina, Bolivia, Chile, and Peru contain ulexite as the only borate mineral, but small amounts of borax occur with ulexite in two playas, inyoite occurs with ulexite in another playa, and borax alone characterizes a fourth playa (Muessig, 1966, p. 156-158).

Ulexite is an example of the generalization proposed by Muessig (1959) that borate minerals in modern playa and lake environments are likely to be the highest-hydrate mineral in each compositional series, because those environments are characterized by the lowest temperature, lowest pressure, and highest moisture in which borate minerals crystallize or recrystallize. This generalization is supported by the bulk mineralogy of most lake and playa deposits in California and Nevada, but it cannot be extended to recently-crystallized borate minerals in all near-surface environments. In Death Valley, McAllister (1970, p. 9) reports layers of proberite, the next-lower hydrate mineral in the ulexite series, crystallized on modern playa surfaces where borate-mineral deposition from high-salinity brines occurs in an environment where the sun is capable of producing near-surface sediment temperatures exceeding 60°C (McAllister, 1958). In modern weathering environments, on the surface and near-surface, McAllister (1970) reports 15 borate minerals that document a wide range of hydration levels within their compositional series.

In consulting older descriptions of deposits, care is needed to determine whether the described "borax deposits" actually contained the mineral borax or were deposits composed of ulexite, proberite, or colemanite from which borax was manufactured. For example, the "Harmony Borax Works," so listed in most accounts and identified on USGS topographic maps, processed only ulexite. Even when borax is now known to exist in a deposit, caution is necessary as illustrated by my uncertainty as to the true mineralogy of the borates mined from the surface of Searles (dry) Lake in the late 1800s. All accounts describe it as a borax deposit--in fact, the lake was then called Borax Lake. However, neither published nor unpublished studies of my own record borax crystals on or near the lake surface, and none of the cores described by Haines (1959) encountered borax at a depth of less than 1 m. Ulexite is occasionally found near the present lake surface or in lacustrine sediments cropping out around the lake, and that is why I list Searles Lake in Table 1 as a ulexite deposit that had a production period extending from 1974-1985. However, G. F. Moulton, Jr. (personal commun., October, 1984) brought to my attention the existence of very-near-surface borax concentrations in the northern part of the lake as evidence supporting his conclusion that borax was the mineralogical source of early borate production.

Many Quaternary ulexite deposits are almost certainly reworked borates, inasmuch as we find

exposures of older borate deposits uphill from the ulexite-rich portions of those playas. Other deposits have thermal springs in their drainages that are rich in borate, probably making them primary deposits, but others are fed by non-thermal springs, making them candidates for either a primary or reworked classification. Still others, however, have no obvious source of borate-rich waters. Most playas with deposits of ulexite near surface also have "puffy" surfaces which is evidence for capillary transport of water. This clearly suggests the probable mechanism of ulexite crystallization—by upward transport and evaporation of interstitial borate-rich waters lying at depths of less than 3 m (Thompson, 1929, p. 125)—even though the source of borate remains undocumented.

It has never been determined how much time is required for pods of ulexite to develop. Some early descriptions of ulexite deposits imply that the pods regenerate each year or two, but others describe individual deposits as if permanently depleted after the original concentrations were removed. Curiously, almost none of the ulexite deposits active in the late 1800s seem to have comparable concentrations of the mineral now. Either they require more than a century to rejuvenate, or climate change or groundwater withdrawal has removed the hydrologic balance needed to generate a new deposit.

QUATERNARY BORAX DEPOSITS

The first borate mineral deposit discovered in the western United States was the accumulation of borax crystals in and beneath the surface of Borax Lake in Lake County, California (Veach, in Hanks, 1883, p. 18). Discovered in 1856, the borax occurred as small euhedral crystals in the "soapy" residue of the nearly-desiccated lake in the late summer, as larger crystals on the lake floor, and as crystals as long as 15 cm in the underlying mud at depths of about 0.4 to 1.5 m. Production of borax, started in 1864, required the construction of small coffer dams within which the lake water was pumped out, the lake-floor mud was "mined," and the more-dense borax crystals in it were extracted by washing and elutriation (Ayers, in Hanks, 1883, p. 21). Production ceased in 1868 when an uncapped artesian well diluted the lake waters below borax-saturation levels.

Borax was mined briefly from an area of about 8 sq km on the surface of Lake Alvord, Oregon (Dennis, 1902). It was reportedly a component of the annual crop of surface efflorescences that also contained sodium carbonate, sulfate, and chloride.

Searles Lake is the largest Quaternary borax deposit in the United States, though the average percentage of borax in the saline units is only about 3%, with other evaporite minerals constituting the balance (Smith, 1979, p. 48, 66, 116).

The borax-bearing salt beds were deposited during two episodes of pluvial lake desiccation that extended from 32,000 to 24,000 years before the present (4 bp), and from 10,000 to about 6,000 ybp. Though the borax is not being mined directly, it is in a sense being solution-mined, and its presence in the saline bodies assures that the percentage of borate in the brines (that are the source of borax production) will not fall below phase-equilibrium levels. Borax is present as both euhedral crystals and massive beds, and is found in both the saline layers and the adjoining mud layers (Smith and Haines, 1964, p. P10-P12). Isotopic evidence suggests that much or all of the borax now present is a product of post-Pleistocene diagenesis (Friedman and others, 1982, p. 697-699).

QUATERNARY BORATE-BRINE DEPOSITS

Natural occurrences of borate-rich brines are, in effect, very large and very low-grade ore-bodies. Today, the most significant source of borates produced from brines is Searles Lake. Production of borax and related products has been continuous since 1919 (Moulton, 1981, p. 1920), and currently it represents the second most important source of these materials in the United States. To illustrate the "low-grade" quality of this source, the dissolved borate content (recalculated as the mineral borax) constitutes only about 3% of the brine (Smith, 1979, tables 7 and 16), and this is about 4% of the grade represented by borax in the Kramer deposit. The reason Searles Lake brine is an economic deposit is that the cost of "mining" brines is far less than the expense of mining solid ore, and the brines are also a source of several other industrial minerals that share the cost of processing. The total production of chemicals from this deposit is measured in billions of dollars, and borates account for a substantial part of this total, showing that brine deposits can be economically very significant.

Lake Hachinhama, now called Little Borax Lake, was the first borate-rich brine to be exploited and is the smallest of the three brine deposits listed in Table 1. Crude evaporation techniques, and later enrichment of the lake waters using ulexite from Nevada, represented the total United States production between 1868 and 1873 (but can borax production from the ulexite-enriched brine be considered a product of a natural high-borate brine).

Borax from Owens Lake brines, a byproduct of soda-ash production, was a relatively small source (Dub, 1947). It also is questionable whether these brines represent a "natural" deposit inasmuch as the lake desiccated only after water in the Owens River was diverted into the Los Angeles aqueduct in the early part of this century. Even under these artificially enhanced conditions, the "ore" represented by Owens Lake brines had an average grade that was about 3 or

4% of the Kramer borate ore body.

OTHER DEPOSITS

Three borate deposits do not fit into the above five categories. The Chetko deposit (Oregon) consisted of irregular masses of priceite in serpentine host rock; its age and origin have not been determined. The Cave Spring deposit (Nevada) consists of isolated or pockets of searlesite crystals in thinly-bedded Tertiary lacustrine marls; they were never mined but did provide incentive for borate exploration in 1916 and 1962 (Papke, 1976, p. 23-34). The deposit was also the source of the first crystals of searlesite suitable for crystallographic study (Foshag, 1934). The ulexite deposit of Tertiary age in the Silver Peak Range (Nevada), "uncommon" only because most Tertiary borate deposits contain colemanite and are classified here on that basis, was briefly mined. It also serves as an example of a relatively unaltered Tertiary lacustrine-type deposit (Smith, 1964, p. 184; Papke, 1976, p. 23).

Several borate-mineral occurrences in the United States are associated with marine evaporites. Small blebs of lüneburgite ($Mg_3P_2B_2O_{11} \cdot 8H_2O$) are associated with halite, sylvite, and clay in the Carlsbad, New Mexico, potash deposits (Schaller and Henderson, 1932). Secondary nodules of probertite, ulexite, and priceite are found at several localities in west-central Oklahoma (Ham and others, 1961). The marine evaporite facies at both localities are of Permian age.

ORIGIN OF BORATE DEPOSITS

A satisfactory geologic explanation for borate deposits requires that reasonable geologic processes be identified that fulfill three essential requirements, and also that geologic evidence be found that all three coexisted at the same time and place. The essential requirements are: (1) a source of water must be identified that was likely to have contained anomalous amounts of dissolved borate, (2) a mechanism must be proposed that could have transported that water to a site of deposition which in turn prevented it from escaping to the sea, and (3) the existence of a geological process must be established that was capable of concentrating solutions to the point of borate-mineral crystallization.

HISTORICAL DEVELOPMENT OF CONCEPTS

Considering the demanding appearance of the above criteria, there seems to have been wide agreement, early in the history of borate studies, that one geologic scenario provides an

adequate explanation for the initial geologic setting of most borate deposits. That scenario: (1) the boron in primary deposits came from thermal waters issuing from springs related to volcanic activity, while the boron in reworked deposits came from laterally-flowing meteoric water that had dissolved portions of older borate deposits, and (2) the borate salts formed when the borate-rich waters were trapped in closed-basin lakes or playas where they evaporated.

Q. How was this near-consensus among geologists reached by so many, so soon, and so fast?

A. It helps to have similar deposits forming all around you!

Q. How good is the geologic evidence that similar processes produced concentrations of borates in the past?

A. Not always the best, but the circumstantial evidence is pretty strong!

The concept of basins having internal drainage could hardly have been escaped by early geologists working in the Great Basin, an area defined by such topography. The concept of saline lakes in these basins, as a device to concentrate dissolved salts, was similarly obvious from present examples--in fact, it was suggested as an active geologic process more than a century prior to the discovery of borax in the New World (Halley, 1715)! By the end of the 1800's, the evaporation processes responsible for the borax concentrations in Borax Lake, and the ulexite concentrations in California and Nevada playas, were familiar to all geologists concerned with the topic.

Derivation of borate solutions from thermal springs related to volcanic activity was similarly a matter of early near-agreement. The borate-rich thermal springs at Tuscany, Italy, had been long known to earth scientists, and the relation between volcanic activity, thermal springs, and the borax in Borax Lake was evident to Veach at the time of his first visit to the area in 1856 (in Hanks, 1883, p. 17). Later, Bailey (1902, p. 20), Baker (1911), Eakle (1911), Gale (1913c, p. 8-9), and most other early workers agreed. There were still practitioners, however, of the multiple-hypothesis philosophy: Keyes proposed that the borate deposits in California and Nevada were (1) beds of marine evaporites (1909a; 1910, p. 694), (2) accumulations of aeolian dust (1909b, p. 827), (3) salts from groundwaters that had become concentrated by evaporation after aeolian processes, which he held responsible for the creation of most valleys in the Great Basin, had excavated them down to the level of their water tables (1910, p. 704), and/or (4) remnants of desiccated alkaline lakes (1910, p. 702).

There was a less-rapid understanding of, and less of a consensus on, the details of the post-depositional mechanisms that modify borate depos-

its, making them into diagenetic deposits (but in our argumentative geological profession, the degree of consensus that did exist is rare!). Storms (1893, p. 346) was apparently the first to relate a diagenetic-type Tertiary dolomite deposit (Calico) to deposition of borate minerals in a closed-basin lake of Tertiary age. Bailey (1902, p. 20), Campbell (1902, p. 8), Spurr (1906, p. 21), and many others soon concurred in principle with this element of borate-deposit genesis, yet the abundant field evidence that colemanite was a product of post-depositional recrystallization seems to have been overlooked by those workers, and nearly a decade passed before Gale (1913c, p. 5-9) commented on it. In fact, he concluded that the Frazier Mountain colemanite ore body was composed entirely of veins formed at depth by metasomatic replacement of limestone. This conclusion was partly based on the consistent presence of cross-cutting relations observed in the colemanite ores, and partly on the lack of ulexite or other borate that might have served as a precursor lacustrine source, but he did perceive the inconsistency between his conclusion that the borates were genetically linked to the interbedded volcanic rocks yet were later introduced as vein deposits.

ACTIVE VOLCANISM: REQUIRED OR NOT?

The genetic relation between borate deposits and active volcanism was obvious to even the earliest observer at Borax Lake, but in some primary deposits of Quaternary age there is little apparent connection between the presence of borates and volcanism. In some Tertiary deposits, these two geologic entities are even less satisfactorily tied together by specific geologic relations. Most of the evidence for contemporaneous volcanism consists of a stratigraphic association of borate deposits with volcanic flows, pyroclastics, or tuffs, and in many deposits, the evidence is adequate to make this relation clear. In some instances, though, such as at the Callville Wash deposits, tuffs are almost non-existent in the borate-bearing part of the section, and the first evidence of persistent volcanic activity lies about 70 m higher in the section (Callaghan and Rubey, 1936).

Nevertheless, the following lines of evidence provide strong circumstantial support to the premise that the active volcanism and primary borate deposits are genetically related. In recent years, radiometric dating of volcanic rocks associated with borates, and dating of volcanics bracketing the ages of vertebrate faunas associated with borate deposits, has allowed us to assess the degree of general synchronism between volcanic activity and borate deposition. These techniques also enable us to express borate-deposit formation in terms of absolute time. Plotting the ages listed in Table 2, and viewing them with geologic perspective (Fig. 2), seems to indicate a notable similarity in the ages of the earliest borate deposits, and to

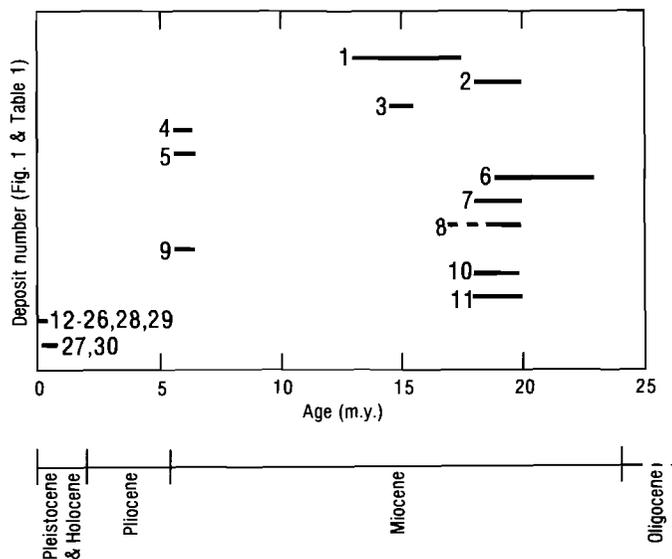


Figure 2. Span of geologic time available, as indicated by radiometric and faunal data, for deposition of sediments now hosts for borate deposits. Numbers refer to list of deposits in Table 1. Assumptions required to make such a diagram significant are that (1) diagenetic deposits (1-11) all started as masses of borate-minerals forming on or near the surfaces of accumulating sediments, and that the borate concentrations were not displaced stratigraphically during diagenesis and (2) most primary and reworked deposits in closed basins (12-26, 28, 29) formed during Holocene time because many of those basins contained perennial lakes until late Pleistocene (an exception, Searles Lake (27, 30), is discussed in text). Numbers 2 and 10 should show age ranges of 13-16 my; see footnote in Table 1.

imply that all of those deposits are primary. This plot suggests, therefore, that about 20 my ago, there began an episode during which unprecedented amounts of borate-rich spring waters reached the surface and flowed into closed basins throughout a large area.

The clustering of borate deposit ages at about 20 my, along a belt extending from southern Nevada to the Coast Ranges of southern California (Fig. 1), also coincides closely in time with the latter part of a brief but intense period of tectonic and volcanic activity over the region. These events appear to have been related to the creation of widespread detachment faults and deep-seated core complexes, probable indications of intraplate extension (Dokka, 1980; Hamilton, 1982, p. 21-25). In the central Mojave Desert, that activity extended from 23 to 20 my ago (Dokka and Glazner, 1982), and to the east, along the Colorado River and 200 km south of the Nevada

borate deposits, it extended from 26 to 17 my ago (Hamilton, 1982, p. 21). A large volume of boron-rich waters, from deep sources that first were tapped during these profound events, seems a reasonable explanation for the time and space relations suggested by Figure 2.

The ages of subsequent deposits (except modern ones) are more scattered, and some or all of them may be "reworked" sources of borates. Among them are the Tertiary deposits near Death Valley (Furnace Creek, Gerstley, and Lila-C) in the Furnace Creek Formation. Although volcanic activity in the area extended from about 8 my until 4 my ago (Fleck, 1970; McAllister, 1973), the unit containing borates is underlain by volcanic rocks having ages as young as 6.3 my and overlain by rocks having ages as old as 5.9 my. These deposits, therefore, do not fit the generalization made above that most primary borate deposits are near 20 my in age, yet the Furnace Creek borate deposits appear to be too extensive and stratigraphically controlled to be reworked deposits, products of the solution and redeposition of older borates. This conclusion stems partly from the fact that there are no known older deposits in the area. Also, it seems that borate solutions generated by a mechanism requiring the solution of older deposits would introduce them in relatively small amounts over a long period (as tectonics and erosion exposed new bodies) rather than in large amounts over a geologically-short period (as their stratigraphic and temporal restriction in the Furnace Creek Formation would imply). If they are not reworked, then their existence suggests that the Death Valley region underwent a crustal event that produced a period of active volcanism about 6 my ago, and that episode was comparable to the disturbance 20 my ago in the central and eastern Mojave Desert. The intensity of tectonic deformation in the Death Valley area during and after the deposition of the Furnace Creek Formation, and the abundance of volcanic rocks that are both older and younger than that formation, clearly supports this possibility.

The section below outlines evidence indicating that Quaternary volcanism and caldera formation in the easternmost Great Basin are genetically related to the borates and other unusual salts in Searles Lake.

THERMAL SPRINGS: REQUIRED OR NOT?

The evidence linking thermal springs and primary borate deposits of Tertiary age is locally strong, but it is not present everywhere. Arsenic- and antimony-bearing minerals in the Kramer ore beds strongly imply hydrothermal springs in the immediate area; some of the colemanite ore bodies in the Furnace Creek area also could be interpreted as borate-spring conduits responsible for the primary deposit.

The Owens Lake and Searles Lake deposits of

late Quaternary age may offer the most-documented examples of primary deposits whose borates and other uncommon dissolved components came from thermal springs that reached their maximum development 0.3 my ago, the delayed consequences of the 0.7-my-ago eruption of the Long Valley caldera (Smith, 1976). Although those springs would still discharge into Owens Lake, if the Los Angeles Aqueduct had not diverted the Owens River water, their discharge reached Searles Lake only during pluvial periods of the Pleistocene when Searles was the third in a chain of lakes that was fed by that river. That lake was the terminus of the chain much of the time, allowing saline concentrations to build up, and it partly or totally desiccated during two periods, 32,000-24,000 mybp and 10,500-6,000 ybp, allowing borax and other salts to crystallize, and the residual borate-rich brines to fill their interstices (Smith, 1979).

Springs known or thought to be borate-rich are credited for deposits in some lakes (e.g. Borax Lake, Lake Hachinham) and playas (Amargosa, China Lake, Eagle Borax, Koehn Lake, Saline Valley). Concentrations of borates along one or more edges of other playas suggest that borate-rich groundwaters migrating from those directions are percolating into the lacustrine sediments, though the waters may not reach the surface and become springs. However, the borates in some Quaternary playa deposits (Fish Lake, Harmony Borax) are clearly reworked--that is, the borate-rich waters that produced them were derived by solution of older borate minerals exposed in the present drainage areas, and thermal springs are not required as a source. As noted above, excepting deposits in the Death Valley area, several of the bedded Tertiary deposits having ages less than 20 my old may be reworked, but it is difficult to distinguish reworked Tertiary deposits from primary deposits with any certainty because the paleodrainages cannot be reconstructed.

LACUSTRINE DEPOSITION: REQUIRED OR NOT?

In North America, virtually all Quaternary borate deposits lie within the bounds of a saline or dry lake. Some lakes are (or were) perennial and some are playas, and the borates in some are primary while others are reworked, but all of the deposits would be described geologically as occurring in a lacustrine setting. Several types of evidence suggest that a lacustrine setting also characterized the primary concentration of borates in a majority of the Tertiary deposits. Permissive evidence is provided by observations that ulexite in the "cottonball" form, similar to the habit found in modern playas, is present in and around many Tertiary colemanite deposits, suggesting that Tertiary deposition of borates was also in a playa or lake. Stronger evidence that Tertiary deposits are diagenetic after lacustrine borate concentrations may be the statistical argument, based on numerous reports, that

virtually all ulexite, probertite, and colemanite concentrations lie in the lacustrine facies of Tertiary formations--even though many of those formations also contain large volumes of nonlacustrine deposits.

It is not possible, though, to eliminate subsurface hydrothermal processes as an alternative means of creating primary colemanite deposits. Many descriptions of colemanite deposits in lacustrine sediments comment on the limited lateral extent and lenticular outline of the mineralized rock, whereas the fine-grained facies of lacustrine deposits are renowned for the pronounced continuity of beds dominated by both clastic and chemical components; hydrothermal deposition seems a more likely explanation of lenticular ore bodies. In fact, starting with the knowledge that borate-rich springs exist, and that those waters travelled extensively underground prior to emerging, perhaps the question should be asked: "What effect would high-borate spring waters have on the soluble components of sedimentary rocks, such as limestone and gypsum, as the waters percolate upward en route to the surface?" The answer almost has to include the probability that reactions do occur.

The few reported observations of colemanite ores in conglomerate (Lang, Furnace Creek) are similarly inconsistent with a lacustrine model for the initial form of borate deposition. Muesig (1966), in his study of South American borate springs and lakes, describes several borate-spring aprons as sites of primary borate deposition. He describes large masses of ulexite (and other minerals) that crystallized almost immediately after the borate-rich waters emerged from hillside springs, producing wedge-shaped aprons downhill from the springs. Their horizontal dimensions are measured in tens to hundreds of meters and their vertical dimensions in meters. Most of the springs are on hillsides, and any sediments interbedded with those borate masses are likely to be gravel. This depositional environment presents a plausible explanation, therefore, for the few borate deposits that coexist with coarse, non-lacustrine, sediments. In fact, the occasionally-reported association of borates and conglomerate may provide one of the more direct methods of inferring the existence of such springs.

DIAGENESIS: PRESSURE, TEMPERATURE, OR WATER CHEMISTRY

Theoretical studies provide an opportunity to gain a semiquantitative insight into the processes responsible for the mineralogical and textural changes observed in diagenetic borate deposits. Most of the minerals present in major deposits are hydrated borates that are combined with oxides of Na, Ca, and Mg. Because of this limited range in compositions, the relations between most of them can be diagrammatically expressed by a small number of ternary diagrams

that relate the borate mineral compositions on the basis of the number of moles of H_2O and the number of moles of two of the several series of Na-, Ca-, and Mg-bearing borates. Similarly, a few schematic isothermal-isobaric plots can relate the relative chemical activity of water (a_{H_2O}) to the relative activities, or ratios of activities, of the cations (a_{Na} , a_{Ca} , and a_{Mg}) that are combined with the borate. Christ and Garrels (1959) and Christ and others (1967) constructed such diagrams, and use of them permits a more systematic approach to understanding diagenetic borate deposits.

Unfortunately, few numerical values are available to define the boundaries and junctions which encompass the stability fields of mineral phases present in the activity diagrams applicable to calcium-bearing borate bodies. Christ and others (1967, p. 320) note experimental studies of Na-Ca-, Ca-, and Mg-borate systems at 25°C, a temperature too low to be very useful except for studies of primary or reworked deposits. In considering diagenetic colemanite deposits, though, we need a basis for estimating the relative importance of increased salinity in the reacting solutions vs. increased temperature and pressure caused by burial, all three of which promote the stability of lower-hydrate borate minerals. This is possible for sodium-borate deposits. Bowser (1964) shows that a sodium-borate solution in equilibrium with borax and kernite, when saturated with halite (thus lowering the value of a_{H_2O} to about 0.7), has its triple point equilibrium temperature lowered from 58.5°C to 36.8°C, more than half of that needed to reach atmospheric temperatures. Christ and Garrels (1959, fig. 3) calculate burial effects for this mineral pair by showing that the triple point would be reached at some depth between about 0.3 km and 0.8 km, depending on rock density, thermal gradient, and hydrostatic vs. lithostatic pressure assumptions. The magnitude of the reduction in a_{H_2O} brought about by increased salinity, and the combined effects of pressure and temperature on the stability fields of this mineral pair, suggest that diagenetic colemanite bodies, or any other of the lower-hydrate diagenetic mineral suites, could be produced by many combinations of these processes. All are geologically reasonable in this area, one that has been characterized since at least middle Tertiary time by tectonic basins several kilometers deep whose sediments were commonly saturated with saline groundwater.

It is also clear that most diagenetic ore bodies document a series of transformations, each a product of different sets of pressure (P), temperature (T), and solution composition (X). As pointed out by Christ and others (1967, p. 318-323), under any one set of P-T conditions, equilibrium assemblages of borates should consist at most of mineral pairs. Under one set of P-T-X conditions, meaning that a_{H_2O} and the component cation ratios are also fixed, most equilibrium conditions favor a single mineral as the stable phase. The presence of an additional mineral under either condition generally indicates an

incomplete reaction.

In the Furnace Creek deposits, nine hydrous borate minerals (three of which are dominant) are known from the underground bodies (McAllister, 1970, p. 8). These include the cations Na, Ca, Mg, and Sr, and several boron-oxide ratios. Excluding the two Sr-bearing minerals (tunellite and volkovite), and using the diagrams of Christ and others (1967, figs. 1, 2, and 3), it is evident that only the colemanite-meyerhofferite-inoite and the probertite-ullexite assemblages individually record variations solely in a_{H_2O} . The existence of two series, however, records at least two different a_{Na}/a_{Ca} ratios in the solutions that interacted with the primary deposit. The presence of nobleite (but not gowerite) and hydroboracite (but not inderborite) records values of a_{H_2O} indicative of no contact with a brine phase and of local differences in the values of a_{Ca} and a_{Mg} in the solutions responsible for their precursors. If ullexite, one of the nine borate minerals in these deposits, was the primary borate mineral, and if ullexite physically still co-exists with each of the other eight minerals, a minimum of eight different P-T-X environments is documented, and the actual number is probably greater.

Mineral assemblages at Kramer (Morgan and Erd, 1969a, p. 146) indicate a less complex diagenetic history for the "sodium borate facies" where borax and kernite, with rare ullexite and probertite, constitute the mineable orebody (Christ and others, 1967, fig. 2). Variations solely in a_{H_2O} can account for the borax-kernite assemblage. Minerals in the "upper ullexite facies," a product of post-burial encroaching groundwaters, document alteration of the primary borate minerals by those waters. Some waters were characterized by higher values of a_{Ca} that produced first probertite and ullexite (before the Na from the primary mineral was entirely dissolved and removed), and then colemanite, meyerhoffite, and inyoite; other waters were characterized by higher values of a_{Mg} that produced hydroboracite, inderite, and kurnakovite (Christ and others, 1967, figs. 2 and 3).

CONCLUSIONS

Borate deposits in the western United States have several geologic characteristics in common: All primary deposits are about 20 my or less in age, and they are observed or inferred to be stratigraphically associated with volcanic activity and thermal springs. Most of them lie at least partially in the lacustrine facies of their host formations which implies the existence of closed basins created by contemporaneous tectonic activity. The preservation of the borate and other dissolved salts requires the climate to have been sufficiently arid for evaporation to offset most of the inflow and prevent the loss of salts by overflow. These are the considerations that justify the title: "Borate deposits...similar in geologic setting."

All but one Tertiary deposit has undergone post-burial diagenetic change as a result primarily of altered hydrologic environments, and/or higher temperatures. These factors, in varying combinations, recrystallized many of the borate minerals, generally replacing the primary minerals with diagenetic minerals having different cation elements and higher borate/water ratios. They also redistributed the borate concentrations in directions and for distances that are now difficult to reconstruct. Even the primary-appearing borax in Searles Lake has undergone diagenesis and redistribution in the few tens-of-thousands of years since its deposition. Primary deposits that are still forming have not yet passed through these stages, and thus they are unlike deposits that have. These are the considerations that justify the remaining part of the title: "Borate deposits...dissimilar in form."

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