BORON AND BORATES

ROBERT B. KISTLER AND CAHIT HELVACI

Borates are defined as “salts or esters of boric acid; a compound containing the radical $\text{B}_2\text{O}_3^-$” (Bates and Jackson, 1987). Borates are defined by industry as any compound that contains or supplies boric oxide. A large number of minerals contain boric oxide, but the three that are the most important from a worldwide commercial standpoint are: borax, ulexite, and colemanite. These are produced in a limited number of countries (Fig. 1), dominated by the United States and Turkey, which together furnish about 90% of the world’s borate supplies (Lyday, 1991). Production in the United States originates in the Mojave Desert of California; borax and kernite are mined by US Borax from its large deposit at Boron. Borate containing brines are pumped from Searles Lake by North American Chemical Co., and a limited amount of colemanite is mined by Newport Mineral Ventures from Death Valley. Turkish production originates in the Bigadic and Emet Districts, plus borax from the Chemical Co., and a limited amount of colemanite is mined by Etibank, the national mining enterprise, which supplies most of the commercially traded ulexite and colemanite from mines in the Bigadic and Emet Districts, plus borax from the huge deposit at Kirka.

Borate minerals have been employed in a wide range of uses for many centuries, dating from at least the 8th century when they were used primarily as a flux for assaying and refining gold and silver. Their valuable properties and relative rarity soon stimulated international trade in borates; Marco Polo claimed to have transported Chinese borate minerals from Tibet to Europe, and his home port of Venice was the center for borate imports and use throughout the Middle Ages (Travis and Cocks, 1984).

Borates were traded at relatively high prices for highly specialized applications into the late years of the 19th century. At that time they were being used for medicines, food preservatives, ceramic glazes, and in expanded applications as metal fluxes. It was in that era that borax was discovered in Clear Lake, CA, and more significantly, the playa deposits of western Nevada were found and exploited by F.M. “Borax” Smith and others. Research and development by Smith’s company began the evolution of borates from a high priced commodity with a few specialized uses to the relatively low priced chemical raw material used in large tonnages on a worldwide scale today.

Borates are often defined and sold by their boric oxide or $\text{B}_2\text{O}_3$ content, and most statistical data are listed in tons of $\text{B}_2\text{O}_3$. Of the products sold by the industry, borax pentahydrate or 5 mol and boric acid are the most commonly traded commodities. Boric acid plants are operated by all of the major borate producers. Glass fiber insulation is the major end use in the United States followed by textile glass fiber and borosilicate glass, detergents, and ceramics. Detergent usage continues to be a major end use in Europe.

GEOLOGY

Mineralogy

Over 150 minerals are known to contain the element boron (B). These minerals may be divided for convenience into three broad groups according to their origin and geological environments: A) skarn minerals related to intrusives, mainly silicates and iron oxides; B) magnesium oxides related to marine sediments; and C) hydrated sodium and calcium borates related to continental sediments and volcanic activity.

In groups A and B are the source minerals for the Russian and some of the Chinese production, the major ones being datolite and szaibelyite. In group C are borax, kernite, colemanite, and ulexite which provide the source for most of the world’s production from Turkey, South America, and the United States. Table 1 provides a more complete list of the common borates.

For description of minerals in detail, readers are referred to mineralogy texts. Here, mineral names and compositions are taken from Dana’s System of Mineralogy (Palache et al., 1951). Some names of long standing are persistently used in the borate industry, such as tincal, an old name for borax which is often used to distinguish the naturally occurring mineral from the identical manufactured compound; others are indicated by parentheses on Table 1.

Borax is by far the most important mineral for the borate industry. It crushes freely and dissolves readily in water; its solubility and rate of solution increases with water temperature. Borax in large tonnages is present in the deposits at Boron, CA, Kirka, Turkey, and Tincalayu, Argentina. Kernite, the metamorphic phase of borax, is present in minor amounts at Kirka and Tincalayu, but it makes up about a third of the total reserve at Boron. Kernite has a higher $\text{B}_2\text{O}_3$ content than borax, but its excellent cleavage causes it to form into fibers that mat and clog handling equipment, and being slowly soluble in water, it requires autoclaves or pre-refinery hydration for efficient conversion into refined products. It is currently used primarily as feed for the boric acid plant at Boron.

Colemanite is the preferred calcium-bearing borate used by the non-sodium fiberglass industry. It has low solubility in water, although it dissolves readily in acid. Some colemanite is used in Europe in chemical plants to produce boric acid because the supply from Turkey provides $\text{B}_2\text{O}_3$ at lowest cost. Turkey is the world’s major source of high grade colemanite. The United States has important reserves in the Death Valley area, but only limited amounts are produced there at this time. Colemanite is not known to occur in major deposits outside Turkey and North America, although the higher hydrate, inyoite, is mined on a limited scale in Argentina and in eastern Europe.

Ulexite is the usual borate found on or near the surface, in playa-type lakes and marshes of Recent to Quaternary Age throughout the world, where it occurs as soft, often damp, masses of fibrous crystals. These “cotton balls” or “papas” are collected in major amounts in South America and China. Ulexite of Neogene Age, which is mined and produced in Turkey and which occurs at Boron and Death Valley in the United States, is well lithified and is, therefore, harder, more dense, and commonly well-bedded.

Szaibelyite (ascharite) is a major source of both Chinese and Russian borate material. It is a magnesium borate and, like colemanite, has low solubility in water. Although it is less satisfactory,
Table 1. Common Borate Minerals

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Empirical Formula</th>
<th>B₂O₃ Content, Wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sassolite</td>
<td>B(OH)₃ or B₂O₃·3H₂O</td>
<td>56.4</td>
</tr>
<tr>
<td>Borax (Tincal)</td>
<td>Na₂B₂O₅·10H₂O</td>
<td>36.5</td>
</tr>
<tr>
<td>Tincalconite</td>
<td>Na₂B₂O₅·5H₂O</td>
<td>48.8</td>
</tr>
<tr>
<td>Kernite</td>
<td>Na₂B₂O₇·4H₂O</td>
<td>51.0</td>
</tr>
<tr>
<td>Ulexite</td>
<td>NaCaB₂O₅·2H₂O</td>
<td>43.0</td>
</tr>
<tr>
<td>Proberite</td>
<td>NaCaB₂O₅·2H₂O</td>
<td>49.6</td>
</tr>
<tr>
<td>Priceite (Pandermite)</td>
<td>Ca₂B₂O₇·7H₂O</td>
<td>49.8</td>
</tr>
<tr>
<td>Inyoite</td>
<td>Ca₂B₂O₇·19H₂O</td>
<td>37.6</td>
</tr>
<tr>
<td>Meyerhofferite</td>
<td>Ca₂B₂O₇·7H₂O</td>
<td>46.7</td>
</tr>
<tr>
<td>Colemanite</td>
<td>Ca₂B₂O₇·5H₂O</td>
<td>50.8</td>
</tr>
<tr>
<td>Hydroboracite</td>
<td>CaMgB₂O₇·6H₂O</td>
<td>50.5</td>
</tr>
<tr>
<td>Inderborite</td>
<td>CaMgB₂O₇·11H₂O</td>
<td>41.5</td>
</tr>
<tr>
<td>Kurnakovite</td>
<td>Mg₂B₂O₇·15H₂O</td>
<td>37.3</td>
</tr>
<tr>
<td>Indenite</td>
<td>Mg₂B₂O₇·15H₂O</td>
<td>37.3</td>
</tr>
<tr>
<td>Szaibelyte (Ascharite)</td>
<td>Mg₂B₂O₇·15H₂O</td>
<td>41.4</td>
</tr>
<tr>
<td>Suanite</td>
<td>Mg₂B₂O₇</td>
<td>46.3</td>
</tr>
<tr>
<td>Kotoite</td>
<td>Mg₂B₂O₇</td>
<td>36.5</td>
</tr>
<tr>
<td>Pinnoite</td>
<td>Mg₂B₂O₇·3H₂O</td>
<td>42.5</td>
</tr>
<tr>
<td>Boracite (Strassfurite)</td>
<td>Mg₂B₂O₇·Cl</td>
<td>62.2</td>
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<tr>
<td>Datolite</td>
<td>Ca₂Si₃O₆·H₂O</td>
<td>21.8</td>
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<td>Cahmite</td>
<td>Ca₂AsBO₄·2H₂O</td>
<td>11.7</td>
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<tr>
<td>Danburite</td>
<td>CaB₂Si₂O₇</td>
<td>28.3</td>
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<td>Howlite</td>
<td>Ca₂Si₃B₁₂O₆·5H₂O</td>
<td>44.5</td>
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<tr>
<td>Vonsenite (Paigeite)</td>
<td>(Fe,Mg)₂FeBO₃</td>
<td>10.3</td>
</tr>
<tr>
<td>Ludwigite</td>
<td>(Fe,Mg)₂Fe₆B₂O₇</td>
<td>17.8</td>
</tr>
<tr>
<td>Tunellite</td>
<td>SrB₂O₆·4H₂O</td>
<td>52.9</td>
</tr>
</tbody>
</table>

due to its magnesium content, for most uses than either borax or colemanite, substantial tonnages are utilized in eastern Europe, Russia, and Asia; it is not traded internationally as a mineral concentrate on a major scale.

The Russians also produce substantial amounts of borates utilizing the skarn borosilicates, mainly datolite, with some reports of minor amounts of danburite, ludwigite, and tourmaline. These minerals must first be liberated, concentrated, and then dissolved in acid to make a usable product because their natural melting points exceed those of the other minerals used in common glass furnaces. They also usually contain iron and manganese, which must be removed because they color glass.

The list of boron minerals in Table 1 includes some that were utilized in the past even though they are difficult to treat. Priceite (pandermite) was mined in Turkey and hydroboracite was mined in Russia and Argentina. Other minerals such as inyoite, howlite, meyerhofferite, and kurnakovite occur intimately associated with the major ores. Boracite was used in Germany prior to 1945 where it and minor magnesium borates were recovered as a byproduct of potash mining.

A large number of silicates contain boron in their lattices in varying amounts. Axinite, suanite, kotoite, and others are listed in the literature as occurring with the Russian borosilicate ores. Sassolite has only mineralogic interest at most occurrences, for the quantity found is generally very small. In the Lardarello region of Italy, however, natural steam carries boric acid recoverable as sassolite, and for a long period prior to 1965, several thousand tons per year were produced.

Chemistry

Boron is the fifth element of the periodic table and is the only electron-deficient nonmetallic element. Thus, boron has a high affinity for oxygen, forming strong covalent boron-oxygen bonds in compounds known as borates. Boron is also the only light element with two abundant isotopes, B⁰ and B¹¹; the former has a large capture cross-section that makes it an excellent neutron absorber.

The chemistry of borates is somewhat analogous to, but more
complex than silicates. The boron atom in borates can be either three or four coordinate-bonded to oxygen, forming either planar trigonal $\text{BO}_3$ units or negatively charged tetrahedral $\text{BO}_4^{3-}$ units; crystalline sasolite or boric acid, $\text{B(OH)}_3$, has only $\text{BO}_3$ units. Other borate minerals are typically salts containing a mixture of $\text{BO}_3$ and $\text{BO}_4^{3-}$ units.

The nomenclature for borates can be confusing because three different formula systems are in common use. For example, ulexite can be described by an empirical formula, $\text{NaCa}_{2}\text{B}_2\text{O}_5\cdot 8\text{H}_2\text{O}$, an oxide formula, $\text{Na}_2\text{O}\cdot 2\text{CaO}\cdot 5\text{B}_2\text{O}_3\cdot 16\text{H}_2\text{O}$, and a crystal structure formula, $\text{NaCa}(\text{B}_2\text{O}_3\cdot \text{OH})$ $\cdot 5\text{H}_2\text{O}$. Only the latter formula conveys information about how atoms are organized in the crystal. Empirical formulae are used to describe the borate minerals listed in Table 1.

Many borate minerals contain waters of hydration and, with the exception of borax, are stable at ambient conditions. Borax dehydrates to tincalconite under ambient conditions unless the relative humidity is high. Upon heating, borates lose their attached water molecules before fusing to a melt. The common borate salts melt at low temperatures; the melts are excellent fluxes or solvents for dissolving other more refractory oxides.

Only alkali-metal borates, ammonium borates, and boric acid have appreciable solubility in water. In dilute aqueous solutions, borates exist as an equilibrium mixture of two species, un-ionized molecular boric acid molecules, $\text{B(OH)}_3$, and the monoborate, $\text{B(OH)}_4^{-}$. For example, borax dissolves in water giving a 1:1 mixture of $\text{B(OH)}_3$ and $\text{B(OH)}_4^{-}$ and is a good buffer system at pH 9.4.

$$\text{B(OH)}_3 + 2\text{H}_2\text{O} \rightleftharpoons \text{B(OH)}_4^{-} + \text{H}_2\text{O}^+ + \text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O} (\text{borax})$$

Most borate minerals dissolve in strong mineral acids to liberate the weaker boric acid; for example, boric acid can be produced by mixing ulexite with sulphuric acid. Boric acid is a weak Lewis acid, electron pair acceptor, with a solution pH of about 5.

Crystalline borate minerals are made up of both trigonal and tetrahedral borate units. These borate units can link through B-O-B bonds to form chain polyborates or they may join into rings which can contain three or four boron atoms, that is, tri- and tetraborates. These rings can in turn link together to form pent-α-, hexa-, and higher borates.

Non-borate boron-containing compounds (those containing no boron-oxygen bond) are not found in nature. These include elemental boron, borides, boron halides, boranes, and organoboron compounds. In general, these manmade materials are either stable inert solids, or they hydrolyze in the presence of moisture or oxidize in the presence of oxygen to form the more stable borates (Smith, 1992).

Borates are widely distributed in nature in low concentrations as alkali-metal and alkaline-earth borate and borosilicate minerals, and less commonly as boric acid. They are typically found in soil and rock in concentrations of up to about 450 ppm total boron, distributed in over 150 minerals primarily as salts of sodium, calcium, and magnesium. The average concentration of boron dissolved in land surface water is about 0.1 ppm and, in sea water, about 4.6 ppm (Sprague, 1972).

At low levels, water soluble boron is an essential micronutrient for the growth and viability of plants; the range between insufficient and excess boron is narrow (0.25 to 15.0 ppm boron) and most soils are usually within this range (Mass, 1986, Sprague, 1972). Borate has been found in animal tissues at about 1 ppm, resulting from ingestion of fruits and vegetables; it is not known to have an essential biochemical function, although it may play a role in the body’s ability to use calcium. Borate is transported in plants and animals usually complexed with polyalcohols in the aqueous phase (Smith, 1992).

**Origin**

Major borate deposits throughout the world are found in terrigenic acid volcanic associated with plate boundaries (Ozol, 1977, Alonso et al., 1988). Most of the commercial borate deposits in the United States, South America, and Turkey are thought to be associated with continental sediments and volcanism of Neogene Age. Many of the older skarn deposits also appear to be related to continental volcanic sources. Marine borate deposits are apparently the product of evaporation of seawater in a restricted basin, probably associated with a sea floor borate source and/or progressive decanting that preferentially concentrated the borates many times above natural seawater values. Borates associated with igneous and some metamorphic rocks are thought to be an end phase of specialized magmatic segregation, or leached from the intruded rocks by associated hydrothermal fluids. Boron isotope studies indicate that most borates are derived from crustal sources (Swihart et al., 1986, Ol et al., 1989).

**Borate Deposits in Nonmarine Basins:** The largest known borate deposits originated as chemical precipitates and are found interbedded with clays, mudstone, tuffs, limestones, and similar lacustrine sediments. There is evidence that most of these deposits were closely related in time to active volcanism. Thermal springs and hydrothermal solutions associated with this volcanic activity are therefore regarded as the most likely source of the boron (Warin, 1965, Alonso et al., 1988). As examples, several South American springs in volcanically active areas are depositing borates (Muesing, 1966), and the first borax discovered in the United States was found in the muds associated with warm springs at Clear Lake, CA, a volcanically active area (Hanks, 1883). The Italian (Tuscany) steam vents from which sasolite was recovered also represent an active volcanic source.

In addition to the concentrated source of the borates and a “basin” in which they can collect, an arid to semiarid climate also seems to be an essential requirement during deposition and concentration of economic amounts of the soluble borates. These soluble borates can, in the long run, only be preserved by tectonics; however, the lack of deposits of soluble borates older than mid-Tertiary may indicate that even burial is not adequate for their preservation over long periods of geologic time.

Hydrated borates may accumulate in several ways within a nonmarine basin. They may be deposited in layers in a spring or as a spray borate deposit, with ulexite, borax, or inosite as the primary borate mineral (Muesing, 1966). Borates may also form in a pool dominantly fed by a borate spring, with borax crystals formed in bottom muds or at the intermittently dried margins as at Clear Lake, CA (Hanks, 1883, White 1957), and at Salar de Surire, Chile (Fig. 2). If the spring flow is low or intermittent, evaporation develops a surface efflorescence or precipitate, or an accumulation of crystals just below the surface; these are in turn playa deposits of early mining in California and Nevada and some of the salt deposits of

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**Fig. 2.** Warm spring borate source, Salar de Surire, Chile (photograph: R. Kistler, May 1987).
South America (Papke, 1976). Finally, there are lake deposits, whose occurrence required much more than seasonal flooding; these are the borax deposits such as Boron and Kink, formed by chemical precipitation in a closed basin. There is some disagreement as to whether the thicker ulexite deposits, such as those in Turkey and Death Valley, for example, are spring apron or lake deposits. In fact, there is probably a complete gradation between spring apron and small lake deposits. These borate lakes are essentially *mono mineralic* in the sense that no other salts occur in major quantities. There is, however, another type of borate lake deposit, with mixed salts and/or brine containing borates in sufficient quantity to justify recovery. These are becoming increasingly important on a worldwide scale. Searles Lake, CA, has been cited as a type example of a multicomponent lake formed by evaporation of lake waters (Smith, 1966, 1979). Numerous studies of Searles Lake have concluded that boron and the other dissolved constituents originated along the eastern front of the Sierra Nevada, were concentrated and decanted in a series of updrainage lakes, and finally were precipitated and preserved in Searles Lake itself. This scenario seems to fit several of the Chinese and Tibetan lakes as well, although they are far less studied (Lock, 1991). The borates found in the large South American salars, such as Uyuni and Atacama, may also have formed by leaching of surrounding rocks and subsequent evaporation, although the role of local mineralized spring waters containing boron has not been fully evaluated at this time.

**Marine Evaporites:** Borates of marine origin have been found in commercial quantities only in eastern United States. These are magnesium borates associated with Permian salt deposits. They were produced in Germany as a byproduct of potash mining, and in the Inder region of Kazakhstan. The Inder deposits, where the borates occur as veins in the cap of a very large salt dome complex, are reported to be remobilized and concentrated from the salt during the intrusion of the salt dome itself. The source of the unusual amount of marine boron, however, remains a problem. Some of the Chinese deposits of the Liaoning Peninsula may be of similar origin although they occur as veins in metamorphosed limestone and magnesite of Precambrian Age.

The Inder Lake brines which are also a source of Kazakhstan production appear to be simply a sump accumulation of borate values leached from the huge Inder salt dome complex. These would be similar in occurrence to the complex lake brines, referred to above, although leached from marine salts rather than continental rocks. The Kara-Bagaz-Gol Lagoon borates on the east shore of the Caspian Sea would appear to be leached from marine brines as well (Lyday, 1991).

**Magmatic Sources:** Pegmatites and contact metamorphic rocks contain assemblages of various boron-containing minerals such as datolite, ludwigite, paigeite, and tourmaline. These represent concentrations of boron that relate more or less directly to the crystallization of intrusive granitic magma. Analyses show that granites average about 10 ppm boron with a few exceptions ranging up to 300 ppm. However, boron does not enter readily into the crystal structure of the common rock-forming minerals; hence, when magma crystallizes, the boron is thought to leave with the released water. The conditions of high temperature, 300 to 400°C, and fluids under high pressure at an intrusive contact also provide the possibility that some of the boron may be extracted from the adjacent country rocks. In either case, borate skarn deposits may be developed. These deposits, some associated with iron ores and magnesite deposits of commercial grade, are mined in both eastern Russia and China (Zhang and Jin, 1991, Lisitsyn and Pastushenko, 1983).

**Major Deposits**

**United States:** In 1856, J.A. Veach discovered borax in the muds associated with a mineral spring at what is now Clear Lake, in Lake County, CA. Small-scale production began there in 1864. Prospecting soon led to the discovery of larger deposits in the desert areas of western Nevada and southeastern California. The first 63 years of domestic production saw several changes in both the type and location of the mineral deposits mined, but in general, production increased and the price of borax decreased as larger and better deposits were found and refinery techniques improved. The year 1927 was a benchmark in US borate history as both the large borax deposit at Boron and the Searles Lake brines with their recoverable borax content were brought into large scale production and soon replaced most of the other domestic sources. Borates are presently produced at three locations in Southern California: Boron, Searles Lake, and, to a lesser extent, the Death Valley area (Fig. 3).

**Boron, CA (Kramer)**—The Boron (Kramer) deposit is located between the towns of Mojave and Barstow in the northwestern Mojave Desert, about 145 km northeast of Los Angeles. Geologically, the deposit lies near the edge of a large Tertiary basin. The "basement" rocks consist of Jurassic and Cretaceous granitics and metavolcanics. These are overlain by a lower Tertiary sequence consisting of continental sediments, primarily arkosic sands and silts apparently derived from the earlier granites, with occasional freshwater limestones and volcanics. The borates are immediately underlain by a Tertiary basalt flow and overlain by a series of continental arkosic sands, Fig. 4 (Siefke, 1991). The Boron deposit has been dated as upper Middle Miocene on the basis of mammalian fossils found above the borates (Whistler, 1984) and from tuffs within the ore.

The Boron deposit consists of a lenticular mass of borax, kerinite, and interbedded montmorillonite-illite clays, dipping about 10°S. It is approximately 1.6 km long, 0.8 km wide, and up to 100 m thick. Outward from this central borax core, there is a facies change to ulexite and clay, which also exists above and below the borax. The deposit is thought to have formed in a shallow "permanent" lake fed by sodium- and boron-rich thermal (volcanic) springs which accompanied late stage volcanic activity. Several tuff and tuffaceous clay beds, some of which exhibit ripple marks and other evidence of shallow water deposition, occur interbedded with the borax.

The original lake basin was controlled by faulting contemporaneous with the deposit. Continued fault movement tilted and dropped the lake sediments; they were then buried under at least 762 m of late Miocene and Pliocene arkosic sediments (Christ and Garrels, 1959). The more deeply buried portions of the borax deposit were metamorphosed to kerinite at this time. Renewed movement in late Pliocene-Pleistocene uplifted the deposit, removed a portion of it by erosion, and caused the outer portions of
the kernite facies to rehydrate to borax. The deposit was then covered by 9 to 21 m of Pleistocene and Recent sands and gravels (Barnard and Kistler, 1966, Sieffke, 1991).

Over 80 minerals have been reported as occurring in the Boron deposit (Morgan and Erd, 1969) including at least 15 borates (Puffer, 1975). Of these, borax comprises about two-thirds of the ore body with kernite and clays, mainly montmorillonite, comprising most of the remainder. The ulexite and claystone facies which envelops the ore body contains most of the 80 minerals mentioned in the literature, including minor amounts of colemanite which occurs at the upper ulexite-clay contact.

Five faults cut the borax body in a NNW direction. Most of these exhibit both late Tertiary strike-slip movement and evidence of movement contemporaneous with the deposition of borax. Borax crystals in the main portion of the ore body are commonly euhedral to sub-euhedral, and range in length from less than 0.5 to over 2.5 cm (Barnard and Kistler, 1966).

The Boron deposit did not crop out; it was discovered in 1913 by Suckow, a homesteader, who struck colemanite accidentally while drilling a water well on the northwest fringe of the deposit. The sodium borates were first detected by exploration drilling in 1925, and production of kernite and borax began in 1927. Mining, soon entirely in borax, continued by large scale underground methods until 1957, when production began from the present open pit. US Borax presently mines both borax and kernite by methods with the ore being removed from the pit by conveyor and processed in the adjacent sodium borate refinery and boric acid plant. Reserves of the Boron deposit were estimated by the US Bureau of Mines at 140 Mt (Norman, 1991).

**Fig. 4.** Stratigraphic section, Boron, CA.

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**BORON AND BORATES**

**Fig. 5.** Stratigraphic section, Searles Lake, CA.

—decanntation, in a series of late Quaternary lakes which extended along the east front of the Sierra Nevada. The boron contained within the salt bodies probably originated in the hot springs along the Sierra Nevada frontal faults in Long and Owens Valleys (Smith, 1979, Mumford, 1954, Gale, 1914). There are two main salt producing horizons: the “upper salt,” which ranges from 9 to 27 m thick, averaging 15 m, with a brine content averaging 1.0% B₂O₃, and the “lower salt,” which is 8 to 14 m thick, averaging 12 m, with a brine content averaging 1.2% B₂O₃. The upper salt is overlain by a recent surficial mud and salt crust about 7 to 9 m thick and is separated from the lower salt by 3 to 6 m, averaging 4 m, of relatively impervious clays called the “parting muds.” The interstitial multicomponent brine, which makes up almost 45% by volume of these salt horizons, is pumped from a series of wells and treated in two adjacent refineries. A relatively constant brine content is maintained by natural recharge and dilute refinery effluent which dissolves additional salts. The two producing salt horizons are pumped separately as they differ somewhat in chemical makeup and therefore require different plant treatment.

Playa-type borax was discovered on the shores of Searles Lake by D. Searles and others perhaps as early as 1863. Small amounts of borax were produced from the playa surface until 1919 when, after extensive potash exploration drilling during World War I, borax along with trona and various other salts began to be recovered from brine wells sunk into the central portion of the lake, with large scale production beginning in 1927. At the present time, North American Chemicals Co. is the only company producing borates from the lake. Reserves in Searles Lake have been estimated to contain 40 Mt of sodium borates (Norman, 1991).

**Death Valley, CA**—Death Valley is a long, north-trending valley near the Nevada border with Southern California. It is fault-bounded on both the east and west sides by recently active faults which have lowered the area near Badwater to 86 m below sea level while raising the adjacent Panamint Range to 3 367 m. The valley contained several lakes during the Pleistocene and over 300 m of salts, mainly halite and gypsum, accumulated in the Badwater area at that time. Minor amounts of the playas borates, borax and ulexite, which occur with these salts, accumulated in the surface muds and seeps and were gathered in the early 1880s. The more productive
playa area near Harmony, 32 km north of Badwater, near the present National Park headquarters, was the source for the famous 20 Mule Team borates (1883–1897). This area of the Valley floor appears to be enriched by fluids derived from the leaching of the adjacent borate-containing Tertiary beds.

In the late Neogene, over 2130 m of lake sediments were deposited in what is now Furnace Creek Wash, in and adjacent to the east side of Death Valley. It is these lake sediments of the Furnace Creek Formation which contain the bedded borates that were the main source of domestic borates from 1907 to 1927 and that are currently being mined.

The area has undergone several periods of faulting since the Tertiary borates were deposited. Many deposits are fault-bounded and bedding dips of up to 45° are common. Geologic mapping indicates that the deposits are elongate parallel to the old shore lines of the Tertiary lake. Laterally, the deposits grade into shallow water limestones or limy mudstones and tuffaceous clays.

‘The main deposits (Tertiary colemanite-ulexite deposits) are low in the Furnace Creek Formation, starting at the top of the lowest conglomerate and continuing to about 152 m higher. The deposits form elongate lenses as much as 61 m thick in which the borates are interlayered with mudstone, limestone, conglomerate, and gradational variations of these lithologies. The three minable borate minerals, where found in the same deposit, are distributed in three zones in the following order of increasing abundance: proberite in the core or deepest zone, ulexite next, and colemanite in the surrounding outermost zone. The boundaries of the zones are generally transitional, but colemanite veins sharply transect some of the ulexite. Proberite is a significantly large part of only one of the deposits, whereas ulexite is a large part of many, and colemanite is predominant in most’ (McAllister, 1970). A generalized stratigraphic section based on more recent mapping and drill data is shown on Fig. 6.

The 16 deposits that were commercially worked in the Death Valley area range in size from 181 kt to over 13.6 Mt, averaging 18 to 24% B₂O₃; all but four were underground operations. Production is presently from the Billie underground mine, operated by Newport Mineral Ventures (formerly American Borate Company) and from the Gerstley underground mine of US Borax located near Shoshone, CA, about 50 km to the southeast of the Billie.

**Turkey:** The borate deposits of Turkey occur in Western Anatolia, south of the Marmara Sea within an area roughly 300 km east-west by 150 km north-south. The main borate districts are Bigadic, Kestelek, Sultancayiri, Emet, and Kirka (Fig. 7).

These borate deposits were formed in lacustrine environments during periods of volcanic activity which commenced in early Tertiary time and continued at least to the beginning of the Quaternary. Although the lithologies of the borate deposits show some differences from one to another, they are generally interbedded with conglomerate, sandstone, tuff, tuffite, claystone, marl, and limestone, and are usually enveloped by, or grade into, limestones or claystones (Fig. 8). Sediments in the borate basins often show clear evidence of cyclicity and exhibit both lateral and vertical facies changes.

Volcanic rocks in the vicinity of the playa-lakes in which the borate deposits were formed are extensive. The volcanic rocks are generally represented by a calc-alkaline series of flows ranging from acidic to basic and by pyroclastic rocks which are interbedded with the sediments.

**Bigadic—**The Bigadic borate deposits are located in two different zones of Neogene playa-lake sediments within a northeast trending basin. Volcano-sedimentary sequences in the Bigadic district consist of, from bottom to top: basement volcanics, lower limestone, lower tuff, lower borate zone, upper tuff, upper borate zone and olivine basalt. The Neogene sequence in the region rests unconformably on a Paleozoic and Mesozoic basement complex (Helvaci, 1983, Meixner, 1965, Özpeker 1969). The Bigadic borate deposits were formed in two separate but interconnected lacustrine playa-lakes, fed by thermal springs associated with local volcanic activity and under arid climatic conditions. The borates are interbedded with tuffs, tuffites, clays, and limestones (Helvaci and Alaca, 1984, Helvaci, 1989).

The borate minerals formed in two distinct zones, lower and upper, separated by thick tuff beds transformed during diagenesis to montmorillonite and chlorite and to zeolites with heulandite being most common. Colemanite and ulexite predominate in both borate zones, but other borates include howlite, proberite, and hydroboracite in the lower borate zone; inyoite, meyerhoffierite, priceite, terschite, hydroboracite, howlite, tunellite, and rivadavite are found in the upper borate zone. Calcite, anhydrite, gypsum, celestite, potassium feldspars, analcime, heulandite, clinoptilolite, quartz, opal-CT, montmorillonite, chlorite, and illite are the associated minerals. These are the largest colemanite and ulexite deposits known in the world (Helvaci, 1989).

**Sultancayiri—**In the Sultancayiri borate deposit, the sequence consists of, in ascending order: basement conglomerate, tuff, limestone, borate zone, gypsum zone, and limestone units. The borates are interbedded with gypsum, claystone, limestone, and tuff. Priceite is abundant, but other borates include colemanite and howlite. Gypsum exists abundantly and calcite, zeolite, smectite, illite, and chlorite are the other associated minerals in this deposit. Howlite, which has apparently grown in the clays alternating with thin priceite and colemanite bands, indicates a period of increasing silica concentration. As a result of diagenetic events, some small howlite nodules are also embedded in the priceite and colemanite nodules. In the Sultancayiri deposit, the initial solutions must have had abundant boron, calcium, and sulfate (Helvaci, 1990).

**Kestelek—**The Neogene sediments which contain borates in the Kestelek region rest unconformably on the Paleozoic and Mesozoic basement complex. The sequence consists of, from bottom to top:
basement conglomerate and sandstone, claystone with lignite seams, marl, limestone, tuff, and agglomerate; the borate zone consists of clay, marl, limestone, tuffaceous limestone, tuff, and borate. These sediments were deposited during a tectonically stable period with extensive volcanic activity. During this period, the volcanic activity gradually increased and produced tuff, tuffite and agglomerate, and andesitic and rhyolitic volcanics that are interbedded with the sediments. This sequence is capped by loosely cemented conglomerate, sandstone, and limestone (Helvaci, 1990, Özpeker, 1969).

The borate minerals occur interbedded with clay as nodules or masses and as thin layers of fibrous and euhedral crystals. Colemanite, ulexite, and probertite predominate, with hydroboracite occurring rarely. Calcite, quartz, zeolite, smectite, illite, and chlorite are the associated minerals. Secondary colemanite occurs as transparent and euhedral crystals in the cavities of nodules, in cracks and in vugs. Proberrite, which forms in the same chemical environment with ulexite in the Kestelek deposit, indicates a period of higher temperature within the playa lake. The initial solutions crystallizing the borates in the Kestelek deposit are deduced to have had a very low concentration of chloride, low concentrations of sulphate and high concentrations of boron and calcium, with some sodium. Reserves here are about 10 Mt (Helvaci, 1990).

Emet—The Neogene sequence in the Emet region rests unconformably on Paleozoic metamorphic rocks that consist of marble, mica-schist, calc-schist, and chlorite schist. The Neogene consists of the following sequence in ascending order: conglomerate and sandstone; thin bedded lower limestone with lenses of marl and tuff; intermediate and acid volcanics, tuff, and agglomerate; a red bed containing conglomerate, sandstone, clay, marl, limestone with coal, and gypsum bands; clay, tuff, tuffite, and marl containing the borate deposits; an upper limestone containing clay, marl, and chert layers; and a capping basalt (Helvaci, 1977). The unit of clay, tuff, tuffite, and marl containing the borate deposits has abundant realgar and orpiment at some horizons indicating that arsenic and boron have a genetic relationship and volcanic origin at Emet (Helvaci, 1984).

The borates are interlayered with tuff, clay, and marl with limestone occurring above and below the borate lenses. The principal borate mineral is colemanite, with minor ulexite, hydroboracite, and meyerhoffierite. The Emet borate deposits are the only Turkish deposits known to contain any of the minerals veinachtite-A,
tunellite, teruggite, and cahnite. Montmorillonite, illite, and chlorite are the only clay minerals that have been identified; montmorillonite is the dominant clay mineral in all the samples and occurs as Al-, Mg-, or Al-Mg-Fe montmorillonite. Illite is only a minor component and is distributed randomly. Chlorite is widely distributed within the deposits and is relatively abundant near or within the horizon of tuffs and tuffites. Zeolites are abundant along the tuff and tuffite horizons. Native sulfur, realgar, orpiment, and celestite occur in the borate zone throughout the area. Gypsum associated with borate minerals has been observed in the southern deposits. Calcite is found in outcrops and adjacent to faults as a result of modern weathering (Helvaci, 1984). Reserves are extensive, estimated at 110 Mt of 45% B₂O₃ (Helvaci and Firman, 1976).

Kirka—The Neogene volcano-sedimentary sequence in the Kirka Basin rests unconformably partly on Paleozoic metamorphics, a Mesozoic ophiolite complex, and Eocene fossiliferous limestone. The Neogene sequence consists of, from bottom to top: volcanic rocks and tuffs; lower limestone with marl and tuff interbeds; borate zone; upper claystone; upper limestone containing tuff and marl with chert bands; and basalt (Helvaci, 1977, Inan et al., 1973, Sunder, 1980).

The principal mineral in the Kirka borate deposit is borax with lesser amounts of colemanite and ulexite. In addition, inyoite, meyerhoffelite, tincalconite, kernite, hydroboracite, inderborite, inderite, kurnakovite, and tunnelite are found (Inan et al., 1973, Helvaci, 1977, 1978, 1983). This is the only deposit in Turkey that contains the sodium borates (borax, tincalconite, and kernite), together with inderborite, inderite, and kurnakovite. The borax body is enveloped by a thin ulexite facies, followed outward by a colemanite facies. The whole is enclosed by calcite and limestone.

The borate layers contain minor amounts of realgar, orpiment, gypsum, celestite, calcite, and dolomite, and the clay partings contain some tuff layers, quartz, biotite, and feldspar. The clay is made up of smectite-group minerals and, less frequently, illite and chlorite minerals. Zeolites occur within the tuff horizons (Helvaci, 1983).

This deposit is distinct from similar borax deposits at Boron and Tincalayu in having very little intercrystalline clay; the clay at Kirka is very pale green to white and is high in carbonate. The borax crystals are fine, 10 to 20 mm, and quite uniform in size. The ore body has an indicated thickness of up to 145 m, averaging 20 to 25% B₂O₃ with reserves of plus 100 Mt (Wendel, 1978).

South America: There are over 40 borate deposits located along an 885-km trend in the high Andes near the common borders of Argentina, Bolivia, Chile, and Peru, of which at least 14 are currently in production (Fig. 9). This is an arid segment of the Andean tectonic-volcanic belt, characterized by compressional tectonics and many closed basins with playas or salt flats, called salars. Reserves are said to total millions of tons of B₂O₃, but the figures lack supporting data. For many years (1852–1967), Chile was a
major producer of borates, but the industry gradually shifted to adjacent areas of Argentina. Recently, Chile has again become a major borate producer.

Borate spring deposits are better developed in South America than anywhere else in the world. These deposits consist of cones and aprons of ulexite and in one case borax, built up around vents from which warm to cool waters and gas are still issuing in some cases (Fig. 10).
Most deposits are associated with calcareous tufa which occurs as a late-stage capping over the borates, and sometimes with halite and gypsum as well. Recent volcanic activity is indicated by basaltic to rhyolitic flows in adjacent areas, and a volcanic source for the borates is presumed. Older rocks in the vicinity of the deposits range from Precambrian to Tertiary and appear to have no genetic relationship to the deposits. The deposits currently forming are quite small, ranging from a few hundred to approximately 9 kt of borates averaging 20% $\text{B}_2\text{O}_3$ (Muessig, 1966).

The salar deposits of South America consist of beds and nodules of ulexite with some borax or inyoite, associated with Recent playa sediments, primarily mud, silt, halite, and gypsum. The borate-bearing playas occupy individual basins which range in size up to several hundred km$^2$. Springs and seeps appear to be the source of the borates. The brines of Atacama, Chile, and Uyuni, Bolivia, contain borates of possible commercial interest.

Argentina—Argentina produces about 200 ktpy of boron minerals and compounds, mostly from the Tincalayu borax deposit (Lyday, 1991). The borax there occurs as a lens of very fine crystalline borax about 100 m in diameter and more than 30 m thick, which was apparently pushed upward along with associated playa sediments by a plug of massive halite (Alonso, 1986). The borax rests on gypsum and halite, and it is partially overlain by about 60 m of reddish, salty, detrital sediments that include thin layers containing, separately, ulexite, inyoite, kurnakovite, and some kernite. The deposit and the surrounding sediments are complexly folded into an anticlinorium and truncated by a fault. The deposit is mined by open pit methods with relatively modern equipment by Borax Argentina S.A. (Fig. 11), and the ore is transported by truck and rail some 400 km to the refinery near Salta. Reserves are about 10 Mt (Alonso and Helvaci, 1988).

The Pastos Grandes (Sijes) area north of Tincalayu contains a number of borate deposits that are located east and south of the Salar de Pastos Grandes. The borates are found in the Sijes Formation of upper Miocene Age. There are at least six small open cut mines in the area which produce colemanite, inyoite, and hydroboracite. Reserves are on the order of 20 Mt (Sureda et al., 1986). In addition, at least six Argentinian salars currently produce ulexite and occasionally borax crystals. The ulexite occurs as “papas” or large cotton balls and as irregular bedded masses, some with a high sulfate and chloride content. The crude ulexite is dried and bagged for shipment to local and Brazilian boric acid plants.

Chile—Ulexite from Chile currently enters the world market from at least five salars. About half of the total production, estimated at 31 ktpy, comes from the Salar de Surire, a relatively small salar situated near the border with Bolivia. The ulexite occurs 6 to 14 cm below the surface as irregular masses and in beds that attain up to a meter in thickness and averaging perhaps 30 cm. The surface muds and salts are removed by a small front end loader, but the ore is mined by hand; it is then stacked to drain and dry, and finally trucked to a boric acid plant near Arica. Other salars currently in production are Ascotan, Aguas Calientes Sur, Atacama, and Quisquiro (Diabolique).

Peru—Peru exported ulexite from about 1883 until the 1920s; production of 4 to 6 ktpy is again reported (Lyday, 1991). The source is Laguna de Salinas, which occupies a large mountain basin east of Arequipa, reached by 56 km of mountain road that crosses a mountain pass at nearly 5 200 m. The basin, at an altitude of 4 328 m, has a seasonally flooded floor, and the ulexite is recovered from shallow pits along the lake margins in the dry season. Ulexite occurs as irregular masses and lenses 25 to 130 cm thick in fine, sandy detritus and green muds, 0.6 to 2.9 m thick, which lie below a surface layer of black to green muds with disseminated ulexite, sulfate, and halite. Reserves are estimated at 9 Mt of ulexite (Norman and Santini, 1985, Muessig, 1958).

Bolivia—Very limited production of borates is reported from Bolivia. Reserves of playa borates and brines containing borates in the giant Salar de Uyuni have been known for many years, but supply and transport difficulties have hindered production (Anon, 1991c).

China: China produces about 27 ktpy of borate minerals and compounds (Lyday, 1991) from deposits in Liaoning, Xizang (Tibet), and Qinghai Provinces. There are few published data on the sources of this production, but the output appears to be rising rapidly. The Liaoning production comes from a number of relatively small, open pit and underground mines on the Liaodong Peninsula of northeast China. There are reported to be more than 55 operations on some 112 separate deposits of which 12 contain 98% of the reserves. The ores are magnesium borates, saibelyite (ascharite), with ludwigite and suanite associated with magnesite, magnetite, and rare earths (Dongming, 1988). The ores occur as veins in early Proterozoic (2.3 Ga), magnesium marbles of the middle Liaoji suite. The ore bodies are closely related to, and conformable with, the Liaoji granites (Zhang, 1988). Average grades are low by western standards, 5 to 18% $\text{B}_2\text{O}_3$, and many of the smaller deposits are mined by labor intensive methods.

The Qinghai production comes from three playa lakes in the Tsaidam Basin of south-central China: Da Qaidam, Xiao Qaidam, and Mahai. The main borates there are ulexite, pinnoite, hydroboracite, and borax. Recent reports indicate that the surface crusts of ulexite and pinnoite are mainly worked out and that most production
is now from the brines, which are associated with mirabilite (Na₂SO₄·10H₂O) that is also produced. In addition, China has substantial reserves on the Tibetan Plateau where 57 lakes have been identified as containing borates. These are not believed to be in large-scale production at this time due to transport and supply difficulties (Lock, 1991).

**Other:** There are few data in English on the sources for borate production from the former USSR, which is estimated to be about 200,000 tpy (Norman, 1991). For many years, the Inder (Guryev) District of Kazakhstan was considered the principal source (Anon, 1989). Borates, mainly szalbelyite and hydroboracite, occur there as veins and fracture fillings in a large (250 km²) Permain marine salt dome associated with gypsum, carbonate, and clay, and in the nearby brine lakes. Reserves of up to 7 Mt of 20% B₂O₃ are reported. However, recent (1990) exchanges with Russian geoscientists indicate that 95% of the Russian supply now comes from the Bor deposit at Dalnegorsk in Primorsk near the Sea of Japan. The ore is a datolite skarn assemblage formed in Triassic limestones and siltstones intruded by a large porphyry dike swarm. The borosilicate skarns occur over a length of 2 km and are up to 500 m wide; they have drilled ore grade material to 1,000 m. Ore grade is estimated at 8 to 10% B₂O₃ (30 to 45% datolite). The ore is mined by open pit methods and trucked to an adjacent refinery.

Minor production of ludwigite has been reported from small pipe-like bodies in North Korea at Khod-on (Hol-Kol) and Raitakuri, southwest of Pyongyang during the 1950s (Kurmen, 1958). There have been no recent reports that these deposits are currently in operation.

The colemanite body at Magdalena, Sonora, owned jointly by US Borax and Vitro (Mexico’s major glass producer) remains on standby status pending an upturn in the market. The development of this deposit has been hampered by processing problems and the relatively high arsenic content of the ore.

The occurrence of low grade borates, predominantly howlite and colemanite, has been reported from the Jarandol Basin of Yugoslavia. The borates here apparently lie above the commercial salt dome associated with gypsum, carbonate, and clay, and in the nearby brine lakes. Reserves of up to 7 Mt of 20% B₂O₃ are reported. However, recent (1990) exchanges with Russian geoscientists indicate that 95% of the Russian supply now comes from the Bor deposit at Dalnegorsk in Primorsk near the Sea of Japan. The ore is a datolite skarn assemblage formed in Triassic limestones and siltstones intruded by a large porphyry dike swarm. The borosilicate skarns occur over a length of 2 km and are up to 500 m wide; they have drilled ore grade material to 1,000 m. Ore grade is estimated at 8 to 10% B₂O₃ (30 to 45% datolite). The ore is mined by open pit methods and trucked to an adjacent refinery.

**Exploration**

Borate exploration consists of detailed prospecting of favorable areas followed by drilling and utilizes all the tools available to the exploration geologist. The recognition of trends of favorable host rocks and structures is an important guide to areas that are of possible interest. Satellite imagery, both real and false color, and standard photo interpretation can be successfully used under certain conditions.

In most parts of the world, the identification of a Cenozoic suite of non-marine fine-grained sediments and tuffs is the usual starting point for the field geologist, because most commercial borates are found associated with these rocks. Any accumulation of salts in these sediments is examined closely. Because many borates are associated with volcanic rocks, volcanic centers, flows, ash deposits, and tuffs, particularly if zeolite-bearing, may also be favorable guides to borate prospecting (Barker and Lefond, 1979).

The skarn borates of eastern Europe and Asia were found by careful prospecting in geologically preserved fold belts where limy sediments are in contact with potassic to alkaline volcanics. Datolite and danburite occur in skarns where the limestone was originally rich in calcium and silica; axinite, kotoite, and ludwigite skarns are hosted by dolomitic limestones. The magnesium borates and those associated with iron ores are generally of low grade. Marine borates are sought in tectonically stable areas with shallow to outcropping salt structures, with gypsum caps, where near surface borate deposits are identified by whitish soil cover and scanti vegetation (Lisitsyn and Pastushenko, 1983).

In arid regions, ulexite often accumulates at, or just beneath, the current surface of salt flats and playas, indicating that boron is moving in the system. These recent crusts may also indicate brine deposits containing boron values of interest. In either case, additional prospecting is usually justified; playas are usually prospected by pitting on a 100 to 500 m grid. Springs and recent spring deposits containing anomalous borates may also be used as a guide to ore in certain areas.

**Geological surveys** are useful methods of narrowing down prospect areas to a drill target. Both soil and rock chip sampling techniques are utilized in exploration programs with boron, strontium, arsenic, and lithium as a common suite of elements. Beryllium is also used in the search for skarn borates in Russia, as are complex B-Mg-Ca-Cl ratios. Water sampling, both surface and well (subsurface), may be useful. Certain plants are boron sensitive and vegetation surveys might prove interesting, but only the Russians have done much work in this area.

**Geophysical surveys,** particularly gravity and magnetics, are used to outline target basins or structures beneath sedimentary basin fill. Resistivity and seismic surveys have been used to define basin structures and formations which may be associated with the borates in that area. Various downhole well logging techniques, including natural gamma and neutron probes will indicate the approximate percentage of borates and clay in zones of special interest.

**Geologic mapping** followed by drilling is still the definitive test in most areas of the world. While rotary drill methods may be used, cores are generally taken of the most prospective zones. Assays of B₂O₃ and other associated elements (arsenic, lithium, strontium) are then run on the horizons that appear favorable for borates. Because the saline borates are water soluble, short core runs are used, but the common borates generally core well with recoveries above 90%.

In areas of doubt, two easy field tests are available to determine the presence of borates. The original flame test, where the mineral is soaked with sulfuric acid and alcohol and ignited (“she burns green, Rosie. . . .”), is still one of the most diagnostic. The tumeric test where hydrochloric acid and tumeric solution turns the specimen red-brown is also used. As chemical tests performed in the laboratory are more diagnostic and accurate, most field samples are sent there for analysis.

Under current economic conditions, bedded deposits of borax, colemanite, and ulexite are not generally sought at depths greater than 500 m. Brines with a high boron content, particularly those associated with other salts of value, might be extracted from greater depths under certain circumstances. The skarn and magnesium borates are economical only from surface and near surface excavations at this time.

**Mining/Processing**

Most commercial borate deposits in the world are mined by open pit methods (Fig. 12). The world’s major borate operations, the Boron mine of US Borax at Boron (Kramer), CA, and the Kirka mine of Etiбан in Turkey are huge open pit mines utilizing large trucks and shovels and front end loader methods for ore mining and overburden removal. Ores and overburden are drilled and blasted for easier handling. The Boron operation uses a belt conveyor to move ore from the in pit crusher to a coarse ore stockpile from which
it is reclaimed by a bucketwheel that blends the ore before it is fed to the refinery. Kirka utilizes trucks which haul to a crusher near the refinery which is about 0.5 km from the current ore faces.

Smaller operations in Argentina, Chile, China, Turkey, and Russia use similar methods, but on a scale down-sized to the scale of the operation. Some of the South American and Chinese salar operations utilize hand labor to mine the thin salar borates, generally after stripping of overburden with a small dozer or front end loader (Fig. 13).

Borates are mined by underground methods in the Liaoning area of northeast China, at the Billie and Gerstley mines in Death Valley, CA, and in Turkey at Emet and the Simav mine at Bigadic. Borate brines are recovered at Searles Lake, CA, and in the Qinghai Basin of China; brines may also be utilized in the Inder region of Kazakhstan. Borate containing brines are being considered for production from several salars in South America, but there have been no borates produced there as of late 1991. Also under study is the recovery of low grade borates by in-place acid leaching, producing a crude boric acid for subsequent refining. This latter methodology is being pilot-tested by Fort Cady Minerals just east of Barstow, CA.

Processing techniques are related to both the scale of the operation and the ore type, with either the upgraded or refined mineral (borax, colemanite, ulexite) or boric acid as the final product for most operations (Fig. 14).

Borax-kernite ores (Boron, Kirka, Tincalayu) are crushed to -2.5 cm and then dissolved in hot water/recycled borate liquor. The resultant strong liquor is clarified and concentrated in large countercurrent thickeners, filtered, fed to vacuum crystallizers, centrifuged, and then dried. The final product is refined borax decahydrate or pentahydrate, or fused anhydrous borax, or is used as feed for boric acid production.

The ulexite from most of the South American salars is air dried, screened, and bagged. It is then combined with locally available sulfuric acid to produce a relatively low grade boric acid or exported as feed for boric acid plants elsewhere.

Colemanite concentrates are used directly in specific glass melts or used as a feed for boric acid plants. The magnesium borates are generally concentrated, dissolved in acid to remove the magnesium, and then converted to boric acid or sodium borates. The borosilicates of the Bor deposit in eastern Russia with their relatively low B₂O₃ grades, are crushed, and then run through a complex plant, which includes magnetic separators, heavy media separators, and flotation cells. The concentrates are then dried, leached, and calcined before being converted to boric acid or to a sodium borate.

Brines from Searles Lake, and presumably the Chinese sources, are recovered by either controlled evaporation or carbonation. In the latter process, carbon dioxide produced from lime kilns or flue gas is bubbled through the brine to crystallize sodium bicarbonate; borax is then crystallized in vacuum crystallizers. In the “evaporation” process, a rapid, controlled cooling selectively crystallizes the various salts. The remaining borate liquor is fed to tanks containing borax seed crystals which aid in the recovery of borates from the liquor. The resultant slurry is filtered, washed, redissolved, and fed to vacuum crystallizers that produce dehydrated borax products or boric acid.

Boric acid is one of the final products produced from most of the processes. The world’s largest boric acid facility is located adjacent to the Boron pit. It utilizes either refined borates or hydrated kernite as feed, with sulfuric acid as the reacting agent. Other facilities around the world make use of smelter acid or other locally available acid feed-stock to produce products acceptable to their local markets.
The principal uses of borates have not changed much in the past decade, although sales have declined slightly since the peak year of 1987. The current market breakdown is shown in Fig. 15. Major domestic markets include fiberglass insulation, textile or continuous-filament glass fibers, glass, detergents and bleaches, enamels and frits, fertilizers, and fire retardants. In Europe, bleaches and detergents are the major end use; however, sales for glass and glass fibers, including fiberglass, are increasing.

Boron fiber-reinforced plastics continue to be utilized in quantity for aerospace frame sheathing where they combine flexibility and light weight with strength and ease of fabrication. Relatively minor uses that are expected to increase in the near future include those in fertilizers, wood preservatives, alloys and amorphous metals, fire and flame retardants, and insecticides. However, the promising field of boron-iron-silicon electrical transformers has not developed as rapidly as predicted due to various cost factors.

As noted in Table 2, “miscellaneous” is a sizable portion of total US sales. It includes pharmaceuticals, cosmetics, anti-corrosion compounds, adhesives, abrasives, insecticides, metallurgical processes, and nuclear shielding, to name but a few. Research is continuing in many areas. One of the more publicized is in supermagnets, where borates, combined with rare earths, nickel and iron, produce an alloy that can be used to make electromagnets for computer drives, high fidelity speakers, automobile starter motors, and various household appliances. Another new field is biological growth control agents.

Borates can be utilized to protect the environment by aiding in converting heavy metals in industrial waste streams into recoverable free metals and by removing impurities from polymers used in bleaching wood pulp for paper production. Borates also aid in the control of the refractive index in optical fibers for medical research where precise control is needed. Other medical applications include cancer research where the B\(^{10}\) isotope reacts with low energy neutrons to give off short range alpha particles that can be used for microsurgery in previously inoperable areas of the brain (Barth et al., 1990). Current tests on boron analogues indicate they may be effective in reducing serum cholesterol and other disease-causing proteins.

![Fig. 15. Borate end uses 1990 (United States only).](image)

<table>
<thead>
<tr>
<th>Borate End Use</th>
<th>Percent of Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Fiber Insulation</td>
<td>30</td>
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<tr>
<td>Textile-grade fiber</td>
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</tr>
<tr>
<td>Enamels Borosilicate Glass</td>
<td>9</td>
</tr>
<tr>
<td>Soaps and detergents</td>
<td>8</td>
</tr>
<tr>
<td>Fire and flame retardants</td>
<td>4</td>
</tr>
<tr>
<td>Enamels and glazes</td>
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</tr>
<tr>
<td>Agriculture</td>
<td>2</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>27</td>
</tr>
</tbody>
</table>

**ECONOMIC FACTORS**

Borates have become a relatively modestly priced industrial mineral commodity in recent years following the development of the large deposits at Boron, and more recently, Kirk. Prices are directly related to the costs of production, of which the major cost is fuel for drying, dehydrating, and melting the refined ore into the products desired by industry. Industry prices for most products have held steady with the rate of inflation despite added costs imposed by government regulations.

Both Western Europe and Japan, neither of which have local borate sources, are major markets for US and Turkish production. South America is largely self sufficient with an increasing amount in excess of their needs which is exported mainly to Europe and Japan. Russia and China both appear to be self sufficient in borates at this time, although their costs of production per ton of B\(_2\)O\(_3\) are thought to be relatively high.

Borates are a lightweight commodity and are generally sold in bulk by carload lots, in IBC's (Intermediate Bulk Containers) or “super-sacks,” and by palletized bags. In the United States, about a third of the production now moves to market by truck, a major change from the recent past when most moved by rail. Overseas shipments are made mostly in bulk from special terminals at Los Angeles, CA, and from Bandirma on the Bosphorus Strait in Turkey, to similar terminals in the Netherlands, Belgium, and the United Kingdom, from where it is moved by barge, as well as rail and truck. Other imports to Europe arrive in Italy and Spain. Imports to the Far East are generally sold in small bag lots. Bulk imports to the United States (mainly colemanite) usually land in Charleston, SC, where there are grinding facilities; this colemanite is then shipped to eastern fiberglass manufacturers. There is no import duty on borates brought into the United States.

**GOVERNMENTAL CONSIDERATIONS**

Newly discovered deposits of borax and kernite, as well as brines that contain sodium borates in the United States can be exploited on federal lands only under the provisions of the Mineral Leasing Acts of 1917 and 1920 applicable to sodium minerals. The federal government’s position is that these borates are “sodium minerals.” Other borates can be claimed under the mining law. Borate minerals carry a 14% depletion allowance.

Most of the known colemanite reserves in the United States are within Death Valley National Monument with stringent controls on development. Most of the favorable prospects for borates are located in the adjoining California Desert Conservation Area, portions of which are being considered for permanent withdrawal under bills currently in Congress. In addition, laws and regulations protecting various endangered species, such as the Mojave ground...
squirrel and desert tortoise, also affect where and when exploration and development can take place (Anon, 1991b).

In Turkey, only Etibank, the Government mining company, can sell borates, effectively limiting participation by others. South American governments are generally favorable in their treatment of foreign mining enterprises. The situation in both China and Russia is in a state of flux at this time. It is believed that, while both countries will eventually permit exploration by foreign concerns, development and subsequent export of products and profits may be somewhat difficult.

In all countries, pollution control has become a major concern. With regard to borates, this concern relates mainly to fugitive dust control and disposal of trace elements contained in the tailings.

With regard to borates, this concern relates mainly to fugitive dust control and disposal of trace elements contained in the tailings. In the United States, the National Institute of Occupation Safety and Health and a research team sponsored by US Borax conducted studies of employees at Boron who were exposed to borate dust in the work place. Both studies, comprised of almost 800 employees of US Borax, showed slightly healthier lung functions than predicted by the national averages. These results confirm that there are no respiratory or lung effects from even long term exposure to borate dust. In general, naturally occurring boron compounds have relatively low toxicity for man and other mammals. Boron in medium to large doses can be toxic to plants and is used in nonselective herbicides. It is also toxic to certain insects and prevents bacteria from forming.

FUTURE TRENDS

Boron consumption is directly related to the usage of glass, glass fibers, and ceramics. These materials, along with certain plastics that contain borate products, are seen as having a steady consumer demand in the construction and housewares markets well into the next century. Other major uses, detergents, plant foods, wood preservation, etc., are expected to show a slowly rising demand. Specialty uses are expected to increase, but these will probably have only a minor affect on total borate sales. Total world borate demand is expected to grow at about 3% in the near future, based on industry forecasts.

Known reserves of borate minerals are large, particularly in Turkey, South America, and the United States, and production from Turkey and the United States will continue to dominate the world market. However, borates from other areas will probably take up an increasing share of the world market. This trend is already evident with boric acid from Chile reaching the Far East and Europe, and both Russia and China beginning to export. The latter two countries may or may not become major players depending upon what role “real world economics” play there, because it appears that their sources are inferior in grade and recovery to those now in production elsewhere.

There are few substitutes for borates. In most applications, they provide unique chemical properties at a reasonable price; this is particularly true in glass fibers and in the field of heat and impact resistant glass. Borates are an essential part of certain plant foods. Their use in nuclear reactor shielding and control is well documented.

As with many products in the mineral industry, there are two somewhat opposing borate trends: 1) toward less refined and therefore less expensive borates for some users, 2) toward super refined, very pure, and more expensive products. Both trends are at the expense of those borates currently produced.

Future markets are difficult to predict. Based upon recent history, the major world consumers of borates will continue to be the developed countries of North America, Europe, and Japan. The large populations of China, India, and Russia would appear to want an ever-increasing amount of borates. The markets for borates in the less developed countries are predicted to remain relatively minor at least for the near term.

REFERENCES

of Interior, National Park Service, Mining and Minerals Division, Apr., 139 pp.


