A new Tertiary borax deposit in the Andes


Abstract. The Loma Blanca borate deposit was formed in the muds of playalake environments during the Late Mioce ne and is the fourth Tertiary commercial borax deposit discovered within the borate districts of the world. It is the only South American deposit known to contain any of the minerals colemanite, inyoite, ulexite, borax, tincalconite and teruggite with a unique and characteristic mineral sequence among the other Argentinian borate deposits. The Loma Blanca deposit is characterized by abundant Ca, Na and B, very low CI and relatively high As, S and Mg concentrations compared with other borate deposits. Thermal springs and hydrothermal solutions associated with local volcanic activity are thought to be the source of the borates. The early colemanite, inyoite, ulexite, borax and teruggite nodules and crystals appear to have been formed directly from brines penecontemporaneously within the unconsolidated sediments, and they continued to grow as the sediments were compacted. Later generations of borate minerals occur in vughs, veins and as thin layers. Diagenetic alterations include the partial replacement of borax by ulexite and tincalconite; when weathered, borates are often almost completely replaced by calcite.

The newly discovered Loma Blanca Tertiary borax deposit in the northern part of the Puna high plateau region is situated in Jujuy province, Argentina, approximately 70 km southeast of the point where Argentina, Bolivia and Chile meet. The Loma Blanca deposit lies between 23°03′S and 66°27′W, at an elevation of approximately 4150 m.

The deposit was formed in a playalake environment during the Neogene (Late Miocene time). It is the fourth recognized Tertiary deposit in the world, after Kirka (Turkey), Boron (United States) and Tincalayu (Argentina), where borax minerals occur in commercial quantities. The principal minerals in the Loma Blanca deposit are borax, inyoite and ulexite, with minor colemanite and trace teruggite.

Aristarian and Hurlbut (1968, 1972) provided the only published account on the geology and mineralogy of the deposit, and described a new mineral species, teruggite, from it. Recently, Alonso (1986) studied Tertiary sediments in the region and mentioned the first occurrence of borax beds in the deposit. In addition, it has been shown for the first time, by his study, that the Loma Blanca deposit formed within a playalake environment during the Late Miocene, and is not a recent spring deposit as indicated by Aristarian and Hurlbut (1968, 1972).

Since the discovery of borax beds in 1982, the deposit has been mined by opencast mining methods at Loma Blanca; principally borax, inyoite and ulexite are extracted by the Industrias Quimicas Baradero S.A. The results of subsequent exploration by Baradero have been made available to the writers, and access to opencast workings has been freely granted. Although there is no exploratory drilling at present, geological reserves of the Loma Blanca deposit are estimated at approximately 1 million metric tons with 16% B₂O₃, average ore grade.

The aim of the present paper is to report and discuss the geology, mineralogy and genesis of the newly discovered borate deposits and also to compare the Loma Blanca deposit with other known borax deposits in the world.

Geological setting

The borates of the Loma Blanca area are part of the Neogene playalake volcano-sedimentary sequence which rests unconformably on Lower Ordovician sedimentary greywackes, pelites and black shales, which represent the oldest rocks in the region (Fig. 1).

The sediments of the Loma Blanca area consist of the following, predominantly pyroclastic, sequence in ascending order: (a) lower pyroclastic rocks, yellowish in colour, predominantly ignimbrites and surges, ca. 50 m; (b) lacustrine sediments, green in colour, predominantly tuffite, claystone and tuff with borate deposits and travertine overburden, ca. 113 m; (c) upper pyroclastic rocks, generally grey in colour, ca. 106 m (Fig. 2).

The red conglomerate and sandstone in the lower part of the section do not outcrop in the Loma Blanca area, but intervene between ignimbrites of the lower pyroclastic rocks and the Ordovician basement outside the study area. Above the base of the section, facies changes are frequently observed over short distances, indicating that the lacustrine deposition in Loma Blanca occurred in a small basin. Borate facies intercalating with Neogene rocks are present in a restricted area within the extensive volcanic flows and pyroclastic rocks of the Coyahualma volcanic chain (Vira-
monte et al. 1984). Much of the sediments in the borate basin seems to have been derived from volcanic terrain.

On the eastern side of the Loma Blanca area, the Salta Group rocks, which are Late Cretaceous–Early Eocene in age (Salfity 1982), have tectonic contacts on each side with Tertiary and Ordovician rock units and occur in a narrow belt that strikes NE–SW.

In the Loma Blanca area, a sequence of volcanic rocks is well displayed. Volcanic activity began in the Middle Miocene, reached its climax in the Late Miocene, decreased in the Pliocene and ended during Pleistocene time (Viramonte and Seggiaro 1987). A tuff sample collected from the base of the borate zone gives an age of 6.99 m.y. (Watson, personal communication). The earliest lava flows and pyroclastic rocks are rhyolitic and dacitic in composition, and the younger volcanic rocks are of intermediate composition.

The thickness of the Tertiary sediments in the region varies from one place to another, probably because of deposition in separate or interconnected playa-lake environments. The volcaniastic sediments have been moderately folded any faulted and the total thickness reaches 500 m in the region, but it is only 300 m in the Loma Blanca deposit as the lower red conglomerate and sandstone units occur only locally.

The borate zone reaches up to 30 m thick in the Loma Blanca creeks, and the depositional basin is aligned NE–SW. The sedimentary formations also strike in a roughly NE–SW direction and their dip ranges from nearly horizontal to over 20°, due to moderate tectonic action. Often, steeply dipping beds are present near principal faults. The general north–south alignment of the mineralized ore body is conditioned by NE–SW oriented limit of the travertine and overburden rocks. Estimates of the sub-
surfaces extent of the borate-bearing horizons is based on information from altered outcrops of the mineralized body and on the distribution of underlying rocks exposed at the surface.

The Loma Blanca borate deposit and associated sediments are dislocated by NE–SW trending faults and are gently folded with small anticlines and synclines which also trend in the same direction. The sediments and the deposit appear to be eroded along the small creeks (Fig. 1).

Stratigraphic and structural evidence shows that the Loma Blanca borates were deposited in a small basin that was elongated in a north–south direction and limited by the basement Ordovician rocks. The age of one tuff sample from Loma Blanca (6.99 m.y.) permits it to be correlated with other borate deposits formed in the Neogene rocks of the Puna region. The Sijes hydroboracite–colemanite deposits and Tincalayu borax deposit, both in Salta province, have ages of 6.8 m.y. and 5.8 m.y., respectively (Alonso 1986). As a result, all Tertiary borate deposits in the Puna accumulated 6 ± 1 m.y. before the present.

Mineralogy

Borate and other minerals from the Loma Blanca deposit were determined by X-ray camera analysis with standard powder and oriented-sample techniques. Mineralogical studies have shown that the borate deposit is far more complex than was first thought by Aristarain and Hurlbut (1968), who recorded only tergurite, inyoto and ulexite, with non-borate minerals calcite, aragonite and realgar.

Borax, tincalconite, colemanite, orpiment, sulphur, montmorillonite, illite and chlorite have been found during the present investigation, in addition to the minerals previously recorded (Aristarain and Hurlbut, 1968) (Table 1). New exploration and mining indicate the district to be the second major Na-borate deposit in Argentina. Borax, inyoto and ulexite are the dominant minerals in the deposit.

As shown in Fig. 1 and 2, assemblages of minerals in the borate zone differ at different levels in the sequence (Fig. 3). Borate minerals in the Loma Blanca deposit are found to occur as: (a) euhedral disseminated crystals in the claystones, mudstones and tuffite matrix; (b) thin layers interbedded with claystones, mudstones, tuff and tuffites; (c) small nodular forms with radiating structures; (d) cauliflower-like nodules, and often “cotton ball” textures in a clay matrix; and (e) vein and vugh fillings.

Borax ($\text{Na}_6\text{B}_2\text{O}_7\cdot 10\text{H}_2\text{O}$) is the most abundant mineral found in the deposit, and for this reason the Loma Blanca deposit is referred to as a borax deposit in the remainder of this paper. The highest concentrations of borax are in the central part of the sequence (Figs. 2 and 3).

Fresh, pure borax is colourless and transparent, but often, in most places where it is mixed with clay and tuffite, it is light green, grey and pale brown due to fine inclusions of foreign material. Borax occurs at two different levels, within zones 3 and 1 meters thick, separated by ulexite mineralized horizons, and forms mainly as euhedral and subhedral crystals 0.5–4.0 cm long; but most common are 1- to 2-cm-long crystals with dominant (100) and (101), subordinate (001), and rarely (110) and (021) crystallographic faces (Fig. 4). Similar occurrences of borax crystals are also present in the known borax deposits else-

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Primary borate</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Inyoite</td>
</tr>
<tr>
<td></td>
<td>Ulexite</td>
</tr>
<tr>
<td></td>
<td>Borax</td>
</tr>
<tr>
<td>30 meters</td>
<td>Inyoite</td>
</tr>
<tr>
<td></td>
<td>Ulexite</td>
</tr>
<tr>
<td></td>
<td>Borax</td>
</tr>
</tbody>
</table>

Fig. 3. Mineral assemblages variation with depth in the Loma Blanca deposit

Table 1. Borate and non-borate minerals occurring in the Loma Blanca deposit

<table>
<thead>
<tr>
<th>Mineral name</th>
<th>Oxide formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Borax*</td>
<td>$\text{Na}_3\text{B}_2\text{O}_7\cdot 10\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Tincalconite*</td>
<td>$\text{Na}_3\text{B}_2\text{O}_7\cdot 5\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Ulexite</td>
<td>$\text{NaCaB}_2\text{O}_7\cdot 8\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Inyoto</td>
<td>$\text{Ca}_3\text{B}_2\text{O}_7\cdot 13\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Colemanite*</td>
<td>$\text{Ca}_4\text{B}_2\text{O}_7\cdot 5\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Terugrite</td>
<td>$\text{Ca}_3\text{MgAs}<em>2\text{B}<em>2\text{O}</em>{22}\cdot (\text{OH})</em>{12}\cdot 14\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Realgar</td>
<td>AsS</td>
</tr>
<tr>
<td>Orpiment*</td>
<td>$\text{As}_2\text{S}_3$</td>
</tr>
<tr>
<td>Gypsum*</td>
<td>$\text{CaSO}_4\cdot 2\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Sulphur*</td>
<td>S</td>
</tr>
<tr>
<td>Calcite</td>
<td>$\text{CaCO}_3$</td>
</tr>
<tr>
<td>Aragonite</td>
<td>$\text{CaCO}_3$</td>
</tr>
<tr>
<td>Montmorillonite*</td>
<td>$(\text{Mg, Al})_2\text{SiO}_4\cdot (\text{OH})_2\cdot n\text{H}_2\text{O}$</td>
</tr>
<tr>
<td>Ilite*</td>
<td>$(\text{K, Na})\text{Al}_2(\text{Si}_3\text{O}_9)\cdot (\text{OH})_2$</td>
</tr>
<tr>
<td>Chlorite*</td>
<td>$\text{Si}_8\text{(Mg, Fe)}<em>6\text{O}</em>{20}\cdot (\text{OH})_4$</td>
</tr>
</tbody>
</table>

* New occurrence of minerals found by the authors in the deposit for the first time

where (Inan et al. 1973, Helvaci 1978, Barnard and Kistler 1966, Muessig 1966, Alonso 1986); and, at present, in the deposits of Turi Lari, Lina Lari, Rincon, Cauchari and Hombre Muerto salars (Muessig 1958, Alonso and Vi-ramonte 1985), some euhedral borax crystals are developing under the surface of the mud flats. Borax is mainly observed as disseminated individual crystals in the clay-tuffite matrix, with a 2:1 borax/matrix ratio, and occasionally as borax-clay or tuffite breccia (Fig. 5). Borax occurs chiefly in almost mono-mineralic zones interbedded with volcanosediments. Above and below the main borax zone, borax always co-exists with ulexite; in some parts and near the surface, tincalconite forms as a thin film on the exposed part of borax crystals and borax shows a transformation into ulexite at or near the surface. On the surface outcrops of
Fig. 4. Well-developed borax crystals from Loma Blanca deposit

Fig. 5. Disseminated borax crystals in the clay-tuffite matrix. Diameter of camera objective cover is 5.7 cm

Fig. 6. Calcite, pseudomorphous after borax crystals, occurring at or near the surface

Fig. 7. Cauliflower-like ulexite nodules occurring in the clay-tuffite matrix

Fig. 8. Aggregates of perfect euhedral inyoite crystals

Fig. 9. Stellate colemanite crystals in a clay matrix showing radiating groups of colemanite crystals

Fig. 10. Pure-white and powdery potato-shaped teruggite nodule
the borax zone, especially 100 m north of the main exploration, calcite is often found as pseudomorphs after borax crystals (Fig. 6).

_Tincalconite (Na₂B₄O₇·5H₂O) does not form independent crystals in the deposit, but occurs only as an alteration product of borax at near-surface outcrops. The microscopic crystals of tincalconite develop very rapidly on borax crystals in contact with the atmosphere in a matter of days, depending on the humidity and temperature, similar to occurrences elsewhere._

_Ulexite (Na₂CaB₅O₉·8H₂O) is the only mineral of the Na–Ca borate series found in the Loma Blanca deposit. It occurs at four different levels in beds of 3, 1, 0.75 and 0.5 m thickness and always as cauliflower-like nodules in the deposit. Fibrous and “cotton ball” textures are also observed in the clay and tuffite matrix. Sometimes, very thin fibrous ulexite crystals growing on top of the massive and cauliflower-like ulexite nodules are composed of randomly oriented crystals, 1.0–0.5 mm long. The ratio of the ulexite nodules and clay-tuffite mixtures varies from 2:1 and 1:1, with 15% B₂O₃ the average grade (Fig. 7). Ulexite is commonly associated with borax and inyoite in the deposit. It is usually very soft and the purest forms of ulexite are white, but many are grey due to the nodule growing in the clay. Secondary recrystallization of ulexite occurs in the upper part of the deposit. This ulexite in the borax-clay mixture is pseudomorphic after borax on the surface; as a result of Ca⁺⁺-bearing surface water and groundwater affecting the borax, ulexite formed as a secondary mineral in the deposit. A possible source for the Ca⁺⁺ could be the travertine overburden._

_Inoyite (Ca₄B₄O₁₁·13H₂O) is the most abundant mineral of the calcium borate series found in this deposit and occurs, predominantly, at three different levels within zones that are 2, 2 and 3 m thick, and the thickness of the inoyite ore beds varies between 0.1 and 0.4 m. It is usually found as discrete tabular crystals and crystal groups, intergrown crystal masses, reaching up to 10 cm in length but generally 2–4 cm, with spathic habit (001) dominant (100) subordinate forms, colourless, grey and brown in colour (Fig. 8). Coalescent non-orientated aggregates of inoyite crystals are generally present, although parallel tabular aggregates and veins can also be found with less frequency (Fig. 8). The parallel aggregates of the thin tabular crystals are usually colourless and show structural zoning due to the diagenetic recrystallization, and the crystals probably continued to grow as the sediments were compacted. Sometimes it occurs as clear, coarse-grained euhedral aggregates with perfect crystals, and it is clearly associated with ulexite in the deposit. After the burial of the deposit by younger sediments, B- and Ca-bearing solutions were responsible for precipitation of later generations of inoyite as veins and thin layers._

_Colemanite (Ca₃B₂O₇·5H₂O) occurs in the lowermost part of the deposit, where it is found both as small individual nodules with radiating crystals and geodes a few centimetres to 3 cm in diameter and as continuous layers which exceed up to 20 cm in thickness. The individual crystals which make up the nodules and aggregates are colourless transparent, rarely grey. There is a tendency for the smaller nodules to be spherical and the larger ones to be ovoid. Some, irrespective of size, contain vughs; others have a core of granular colemanite which is coarsely crystalline and second-generation in origin. Later generations of cole- 

[Fig. 11. Calcite occurring frequently in surface outcrops, pseudomorphs after borax crystals]
disseminated crystals in a clay matrix have been considered as early-formed minerals penecontemporaneously with the clastic sediments. Thin layers, vein and vugh fillings of borate minerals are believed to be late diagenesis products, as similar observations made for the Kramer, Emet and Sijes deposits by different authors (Bowser 1965, Helvaci 1984, Barker and Barker 1985, Alonso 1986).

From the field and textural evidence it is clear that all early-formed borate minerals, such as borax, ulexite, inyoite, colemanite and teruggite, were deposited penecontemporaneously with the unconsolidated sediments. It is likely that they were formed within the clays and tufts below the sediment/water interface and probably continued to grow as the sediments were compacted. Whether early-formed colemanite was formed by the breakdown of ulexite as suggested by Foshag (1921) and Noble (1926); by the dehydration of inyoite as proposed by Rogers (1919), Hanshaw (1963), Christ et al. (1967), Christ (1972) and Inan (1973); or by direct precipitation from solutions as concluded by Nikolaev and Chelischeva (1940), Kurnakova and Nikolaev (1948), Bowser and Dickson (1966), Bowser (1965) and Helvaci (1984) is problematic.

The genesis of colemanite by the breakdown of ulexite was suggested by Foshag (1921) for deposits in California, but does not appear to be applicable to the Loma Blanca for the following reasons: nowhere is colemanite found with colemanite beds in the Loma Blanca, similar to the Kramer and Emet deposits studied by Bowser (1965) and Helvaci (1977), respectively. Arsenic sulphides and sulphur, although present in minor quantities, are as widely distributed as borates and hence it may be assumed that the initial brines at all times were fed an abundance of boron, sodium and calcium with minor amounts of arsenic, sulphur and antimony. The evidence indicates that some of the late ulexite in the borax zone formed during diagenesis after borax as a result of the Ca-rich solutions.

On weathering, all borate minerals are altered, especially borax crystals which are readily replaced by tincalcanite and calcite, and realgar which is replaced by orpiment.

The geochemical association of boron, arsenic, antimony and sulphur suggest a common origin for all elements in Loma Blanca, similar to the Kramer and Emet deposits. Arsenic sulphides and sulphur, although present in minor quantities, are as widely distributed as borates and hence it may be assumed that the initial brines at all times were fed an abundance of boron, sodium and calcium with minor amounts of arsenic, sulphur and antimony. The evidence indicates that some of the late ulexite in the borax zone formed during diagenesis after borax as a result of the Ca-rich solutions.

| Table 2. Partial chemical analyses of tuffitic mudstones containing disseminated evapocrystals of ulexite, inyoite and borax |
|--------------|---|---|---|---|---|---|
| % Oxide      | 1  | 2  | 3  | 4  | 5  | 6  |
| B₂O₃         | 14.24 | 12.28 | 10.75 | 16.58 | 23.19 | 19.49 |
| CaO          | 6.06  | 4.80  | 6.82  | 6.87  | 6.82  | 6.82  |
| Na₂O         | 3.42  | 3.29  | 3.72  | 2.42  | 2.36  | 3.72  |
| Cl            | 1.02  | 0.28  | 0.22  | 0.29  | 0.36  | 0.22  |
| Fe            | 0.05  | 0.10  | 0.15  | 0.04  | 0.02  | 0.15  |
| Insoluble     | 66.07 | 60.04 | 66.38 | 53.66 | 34.74 | 66.38 |

1, 2 and 3: tuffitic mudstones containing ulexite
4 and 5: tuffitic mudstones containing inyoite
6: tuffitic mudstones containing borax
Conclusions

From the foregoing discussion it is concluded that the Loma Blanca borates were formed in a playa-lake, in a seismically active area, fed partly by streams draining the catchment areas. The bulk of the interbedded clastic sediments appears to be derived from volcanic terrain.

Since Ca, Ca–Na and Na borates make up over 95% of the deposit, it is reasonable to assume that the original brines were enriched in sodium, calcium and boron. Arsenic sulphides and native sulphur, although present in minor quantities, are as widely distributed as the borates and hence it may be assumed that the initial brines, at all times, concentrated to allow borate precipitation until the lakes partially or wholly dried up. Brines were evidently rich in Ca and B in the basin; and Na borate (borax) did not crystallize from solution until Ca borates (colemanite and inytoite) and Na–Ca borate (ulexite) had been precipitated. Field and textural evidence clearly indicates the sequence Ca borate→Ca–Na borate→Na borate. Arsenic-bearing borate (teruggite) occurs with Ca borates.

The proposed history of the Loma Blanca may, therefore, be tentatively summarized as follows:

1. Establishment of a playa-lake in a seismically active area fed by thermal springs and surface streams.
2. In this playa-lake, clay and volcanic ash were deposited and borate nodules and crystals developed within the unconsolidated sediments during periods of evaporation. Small amounts of realgar and sulphur were also formed within the sediments penecontemporaneously with the borates.
3. After burial, the borate nodules and crystals continued to grow. Diagenetic minerals formed and recrystallization took place in vughs and veins.
4. Reaction between Ca-rich brines and borax led to its partial replacement by secondary ulexite.
5. Solution and re-precipitation of borates in veins, around earlier crystals and nodules.
6. Uplift and erosion led to the weathering of borates and their replacement by calcite in surface outcrops.

Acknowledgements: Field work was supported by the Baradero Company in the local mineral production division in Loma Blanca, and we thank Dr. Luis De Rito and Mr. Carlos Elias for their assistance. We also thank Mualla Gürel for considerable drafting assistance and Erol Şanlı for photographic assistance.

References


Christ, C.L., Truesdell, A.H., Erd, R.C.: Borate mineral assemblages in the system Na₂O·CaO·MgO·B₂O₃·H₂O. Geochimica et Cosmochimica Acta 31:313–337 (1967)


Foshag, W.F.: The origin of the colemanite deposits of California. Econ. Geol. 16:199–214 (1921)


Helvaci, C.: Geology, mineralogy and geochemistry of the borate deposit and associated rocks at the Emet Valley, Turkey, Ph.D. dissertation, University of Nottingham, England (1977)


Noble, L.F.: Note on a colemanite deposit near Shoshone, California, with a sketch of the geology of a part of Amargosa Valley, U.S. Geol. Survey 785:63–73 (1926)


Received: January 19, 1988
Accepted: May 10, 1988