SEDIMENTOLOGY AND DIAGENESIS OF MIOCENE COLEMANITE-ULEXITE DEPOSITS (WESTERN ANATOLIA, TURKEY)

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ABSTRACT: The Neogene borate deposits of Anatolia have thin sedimentary covers and have never been deeply buried. The major rock-forming, calcium-bearing borates are colemanite and ulexite. Under progressive evaporation, borate precipitation occurred in a number of settings, from stable playa to perennial lakes, the latter evolving to shallow lakes and playa lakes. In all these lakes, shallowing-upward cyclicity is common. Colemanite facies occupy the margins, and ulexite facies the centers of the basins; this mineral zonation is depositional and cannot be ascribed to diagenetic processes. Colemanite and ulexite formed mainly as interstitial growths under synsedimentary conditions, and cannot be ascribed to diagenetic processes. Colemanite and ulexite facies in colemanite and ulexite.

INTRODUCTION

Borate minerals form sedimentary deposits of economic interest. Many of these deposits in the U.S.A., South America, and Turkey are mainly composed of hydrated borates of Na and Ca, and are related to Neogene nonmarine basins and volcanism. Thermal springs or hydrothermal activity supplied the necessary boron-rich solutions to the evaporitic lacustrine systems. The most important criteria for interpreting these Neogene deposits are: (1) comparison with Holocene borate precipitation and with the mineral paragenesis observed in arid basins; (2) the existence of chemical diagrams of phase relations, in particular for the system Na₂O·2B₂O₃·2CaO·3B₂O₃·H₂O; and (3) the stratigraphy and petrography of the deposits.

Although much mining and mineralogical research has been carried out in these Tertiary deposits, information on the sedimentologic and diagenetic relations between the two major rock-forming borates, colemanite and ulexite, is scant, with the result that some aspects remain poorly understood, e.g., the original distribution and facies associations in the lacustrine basins, the depositional cyclicity between borates and other evaporites, and the genesis of colemanite, for which both a primary and a secondary origin have been proposed.

The Neogene Turkish borate deposits of Anatolia are overlain by a thin sedimentary cover and have undergone limited burial. Thus, they offer an opportunity to verify some of the genetic hypotheses commonly applied to other ancient borate formations that have undergone deep burial diagenesis. On the basis of earlier work on mineralogy, modes of occurrence, and stratigraphy of these deposits (Helvaci 1995), the present paper is focused on the study of lithofacies, textures, cyclicity, lacustrine environments, and diagenetic processes that can affect calcium borates. The aims of this paper are: (1) to determine the depositional settings of the boriferous deposits in Anatolia; (2) to improve our understanding of the genesis of colemanite; and (3) to document the growth conditions and sites of the nodular lithofacies in colemanite and ulexite.

GEOLÓGICO SETTING

The Turkish Neogene sedimentary basins bearing borates are in western Anatolia, within an area 300 km east-west and 150 km north-south. Figure 1A indicates the location of the five major borate areas, and Figure 1B summarizes the sedimentary sections in some of these basins, which are only slightly deformed by tectonic. Active mining operations exist in these districts: (1) Bigadiç (colemanite, ulexite), (2) Kestelek (colemanite), (4) Emet (colemanite), and (5) Kirka (borax). In the past, the Sultançayır district (2) was also exploited (priceite). These borate deposits have lenticular forms, and synsedimentary slump structures are common in all of them.

Volcanic rocks are generally represented by a series of calc-alkaline flows and by abundant pyroclastic layers. Borate deposits display variable concentrations of Mg, Sr, and As. The presence of Sr is demonstrated by celestite, and the presence of A sand S is demonstrated by realgar, orpiment, and elemental sulfur, this supporting a probable volcanic origin for As, Sr, and B. Kistler and Helvaci (1994) postulated that the dissolved ions that concentrated in the basins were supplied by leaching of Tertiary volcanic rocks (enriched with B and Sr) and basement metamorphic rocks, and were transported by thermal springs and hydrothermal solutions associated with volcanism. The lithium content of the clay minerals associated with these borate deposits is high and frequently attains 0.30 % Li (Mordogan and Helvaci 1994).

In the Bigadiç basin, the Paleozoic basement is overlain by a thick Neogene sequence (Fig 1B). The borate deposits form two units (lower and upper borates) separated by thick beds of tuff. Colemanite and ulexite are the dominant minerals in both borate units. Other borates are howlite, probe,ertite, and hydroboracite in the lower borate, and orpiment, meyerhowtite, priceite, hydroboracite, howlite, and tunellite in the upper borate. In the Emet basin, a borate unit is intercalated with clay, tuff, and marl in the Miocene sequence (Fig. 1B). The principal mineral is colemanite, with minor proportions of ulexite, hydroboracite, tunellite, and meyerhowtite. Native sulfur, realgar, orpiment, and celestite are present in this area. In the Kestelek basin, a borate unit is intercalated with clay, marl, limestone, tuffaceous limestone, and tuff in the Miocene sequence (Fig. 1B). Colemanite, ulexite, and probevertite predominate, with hydroboracite rare.

The maximum thicknesses of the Miocene materials overlying the borate units in the various basins are about 100 m in Bigadiç, 200 m in Emet, 250 m in Kestelek, 200 m in Kirka, and 250 m in Sultançayır (Kistler and Helvaci 1994). Overlying these Miocene materials, the Quaternary cover records thickness between 10–150 m. Although a disconformity separates the top of the Miocene deposits and the base of the Quaternary cover everywhere, there is no stratigraphic, geomorphologic (thick erosional sequence), or rapid uplift evidence to suppose that significant thicknesses of Miocene and Pliocene deposits were eroded. Thus, a burial depth of 300–350 m can be assumed for the borate units, although in the Bigadiç and Kestelek districts, where the overburden sediments are very thin, lower values seem to be more realistic.

Moreover, limited subsidence from the middle Miocene affected not only these borate-bearing basins but also the recorded mosaic of variable-sized basins which formed in western Anatolia during the Tertiary. In these basins, Pliocene sediments are unknown and Quaternary cover is poorly developed. Thus, the Neogene-Quaternary fill was not very thick (1000–1200
m) in this part of Turkey (Helvaci and Yagmurlu 1995). In contrast, in those Neogene grabens developed in Anatolia to the south of the area under consideration, at least 400 or 500 m of Pleistocene sediments were deposited above Miocene and Pliocene sequences.

**METHODOLOGY AND MATERIALS**

Field work consisted of study of selected stratigraphic sections in the open-pit mines in the Bigadiç (Tüllü, Acep, Kurtpinari, Simav, Kireçlik), Emet (Espey, Killik, Hisarcık), and Kestelek districts, and sampling of the various borate lithofacies, in particular colemanite and ulexite, as well as the associated host sediment (mainly carbonates). A mineralogic and petrographic study (approx. 100 thin sections) was carried out on all samples to complete the lithofacies study. Attention was given to microscopic identification of traces of precursor phases (pseudomorphs, relics) as a control on diagenetic processes.

**LITHOFACIES AND PETROLOGY OF ULEXITE**

The genetic interpretation of lithofacies (we use this term in the sense of facies or macroscopic textures) and environments of the Neogene borates can be done by comparing them with (1) the Recent lacustrine borate deposits in the world; at present, only borax precipitates within the water bodies, i.e., on a depositional floor, whereas many other borates—and some occurrences of borax also—form within the unconsolidated sediments of playas or shallow lakes, and (2) the lithofacies displayed by common evaporites.

Borates are interbedded with layers of sandstone, tuff, marl, and carbonate. Tuff layers have variable thicknesses, between < 1 mm and several meters; their glassy material is commonly transformed into zeolites. Authigenic minerals currently accompanying tuffs include K-feldspar, quartz, and opal-CT. Claystone and siltstone are present in layers whose thickness ranges from < 1 mm to the meter scale; the mineralogy mostly corresponds to a smectite-group mineral accompanied by illite and chlorite (Ataman and Baysal 1978).

Carbonate layers display the following lithofacies: (1) **Finely laminated** (varve-like; < 1 mm thick). In this lithofacies, some laminae are intercalated with dark, very thin lutitic films resembling euxinic facies in which carbonaceae debris is preserved. (2) **Laminated** (between 1 mm and 1 cm thick). Some of these laminae show a slightly crenulate, sometimes intraclastic morphology. (3) **Massive mudstones** made up of micrite. Carbonate varves and fine laminae may have been preserved as aragonite, with a microprismatic texture, although they usually show a neomorphic (secondary) calcitic fabric formed by equant, anhedral to poikilitic crystals (0.05–0.15 mm long). Many laminae are made up of (focal) pelletal textures; they may also display silification by cryptocrystalline and microcrystalline quartz,chalcedony, and locally opal-CT.

Sulfate is only a minor component in the borate-bearing sequences. Some gypsum is present as lenticular crystals in the Emet district and, locally, in the two borate units in the Bigadiç district. Celestite, which is associated with quartz, may replace colemanite.

**Ulexite** (NaCaB₄O₉·8H₂O) is characterized by a white, sometimes silky luster, and a very fine fibrous texture. Main lithofacies are the following: **Nodular and banded-nodular.** Ulexite nodules display various morphologies, from almost spherical to cauliflower-like, flattened, irregular, or interpenetrating; the sizes of these nodules range between < 1 cm (micronodules) and 40 cm (Fig. 2A). Nodules are either isolated within the host sediment or are in close associations forming layers; they are commonly composite (multinodular). Ulexite nodules display two crystalline fabrics: (1) the most common is made up of small groups of almost parallel fibers or needles; these fibrous groups exhibit micronodular or fusiform shapes in which the fibers display breakage and tangential to fassicular fabrics; and (2) less common is a large, fibrous-radiating fabric, which forms large nodules or massive lithofacies consisting of multicentral, radial fibers, which may reach up to 5 mm in length. **Vertically elongated (columnar).** Many ulexite layers are formed by narrow nodules elongated vertically (Fig. 2B). This lithofacies forms strong, resistant layers in which the length of the fibers can be up to 1 cm.

**Laminated.** Very thin layers (< 1 cm thick) of ulexite may alternate with carbonate varves and lutitic laminae. The inner structure of these ulexite laminae tends to be micronodular. In the micronodules, the fiber fabric varies from randomly oriented to normal to bedding.

**Fig. 1**—A) Location of the borate districts and Neogene basins in western Turkey. B) Neogene stratigraphic sections and borate units from the Bigadiç, Emet, and Kestelek districts. (Simplified from Kistler and Helvaci 1994.)
Massive-banded. Bands (1 cm to a few decimeters thick) and layers of ulexite are common; they are formed by fibrous, massive to poorly nodular masses (Fig. 2A).

Fibrous (satin-spar) veins. These veins (< 1 mm to 20 mm thick) are common and crosscut and cement all materials (borates and matrix). Fibers are up to several centimeters in length.

Interpretation of Ulexite Lithofacies.—Some of these lithofacies are similar to those found in modern playas of North America and salars of South America, and in many saline lakes that precipitate ulexite worldwide. In these settings, ulexite is present mainly as (1) soft, light nodules (“cotton balls”) that develop interstitially below the surface down to a depth of a few meters, and (2) massive-banded and massive-nodular beds (Muessig 1966; Smith 1985). In the Pleistocene Blanca Lila Formation (NW Argentina), Vandervoort (1997) reported the presence of a “horizontally bedded lithofacies” of ulexite, which is formed by 1–3 cm thick ulexite bands composed of vertically aligned crystals, suggesting a subaqueous (lake-bottom) origin.

The most common lithofacies of ulexite in the Turkish deposits (nodular, banded-nodular, columnar) are displacive within the sedimentary matrix. We can interpret them as having grown interstitially during periods of underground position of the water table in the sedimentary environment. The columnar lithofacies, in which narrow nodules seem to grow upward competitively, could be related to persistent capillary action, or could be favored by preexisting plant-root structures on the exposed lake floor. The laminated lithofacies could correspond to subaqueous deposition during shallow lake stages. Some ulexite bands and thin laminae associated with carbonate varves and laminated claystone could represent lake-bottom precipitates in deeper lakes. The cementing fibrous veins are diagenetic, secondary precipitates.

LITHOFACIES AND PETROLOGY OF COLEMANITE

The main lithofacies of colemanite (Ca$_2$B$_2$O$_7$	extsubscript{1.5}H$_2$O) are the following: 

Nodular and banded-nodular lithofacies. Colemanite nodules have variable sizes between < 1 cm (micronodules) and more than 50 cm (meganodules) (Fig. 2D), and display different shapes, from spherical to ovoid, hemispheroidal, flattened, discoidal, lenticular, flaser-shaped, cauliflower-like, kidney-like, elongated, and irregular. Each nodule is a single structure or may be composite, and is isolated or grouped in open- or close-packed patterns deforming and trapping the matrix. The nodules are composed of elongated, fibrous, or bladed crystals that radiate from the core outward as stellate clusters, in some cases ending in idiomorphic apices. These crystals are several centimeters in length, and are arranged in subgroups with the same optical orientation. These crystals are usually straight, but locally they are slightly curved.

Some nodules display growth bands concentrically arranged (zoned growth), which involve (1) a coarsely crystalline colemanite core with a blocky, cementing fabric, (2) an intermediate zone of radiating fabric, and/or (3) an outer zone with a dendritic fabric. In the last zone, the shape of the single nodule changes to composite. The contact between the intermediate zone and the outer zone may be gradual or sharp, the sharp contact acting as a discontinuity along which the crystals of the intermediate zone were dissolved. The crystalline core may project through the intermediate zone by means of septarian-like radiating bands. Locally, the centers of the nodules may be empty or may have a vuggy texture, and a drusy coat made up of euhedral, coarse crystals of colemanite surrounds the central hollow. The presence of borate-rich fluids filling these drusy cores has been reported (Helvaci 1995).

Fibrous-banded lithofacies. Fibrous growth of colemanite in bands and thin layers is common. These occurrences are made up of fibrous crystals arranged perpendicular to the bands on both sides of the stratification joints or central partings.

Interstitial crystals. Euhedral, centimeter-size crystals of colemanite are present within the matrix, either isolated and unoriented (Fig. 2F) or grouped in small, irregular aggregates. Such crystals may display internal banding, as well as anhedral to fibrous syntaxial overgrowths.

Massive, vuggy-brecciated lithofacies. Some colemanite layers may exhibit breccias, vugs, drusy cavities, and septarian structures, as well as coarsely crystalline masses. Vugs and cavities are commonly coated or cemented by euhedral, transparent, coarse crystals.

Fibrous (satin spar) veins (between < 2 mm and > 10 cm thick) parallel to or crosscutting the host sediment and borate layers are common.

Secondary, replacive lithofacies (on ulexite). This lithofacies will be described in detail in the Acep section in order to distinguish between primary and secondary colemanite.

Interpretation of Colemanite Lithofacies.—There are no modern occurrences of colemanite in the borate-precipitating environments to compare with the ancient formations. Nodular, banded-nodular, fibrous-banded, and interstitial crystal lithofacies all have characteristics of displacive and/or poikilitically cementing precipitates that nucleated within an unconsolidated matrix from interstitial solutions. Continuous growth and overgrowth (zoned pattern) drove back and deformed the matrix, which was injected around the nodules and crystals, or was poikilitically cemented. The presence of curved crystals and some mechanical readjustment suggest that growth was concurrent with compaction. The euhedral crystals are petrographically primary; in general, the nodules do not have pseudomorphs or relics of any precursor phase. These features are compatible with primary lithofacies grown under synsedimentary conditions and with continued growth during initial burial.

Most interlocking, displacive nodules and meganodules of colemanite resemble the “mosaic” or “chicken-wire” fabric of the anhydrite formations found in modern or ancient sabkhas (Shearman 1966; Schreiber 1988). In the Turkish deposits, large nodules could also be interpreted as having grown in shallow to ephemeral lakes and playas beneath the sediment-air interface. Other nodules, however, are associated with deeper lacustrine facies. They are smaller and flaser-shaped (Fig. 2G), and tend to partly displace and partly incorporate the laminated matrix. They have also grown interstitially, beneath the water-sediment interface.

The septarian-like radiating bands and associated vuggy texture of some nodules have frequently been regarded in the literature as evidence of mineral transformation (from inyoite, meyerhofferite, or ulexite into colemanite), with associated volume loss (Gale 1913; Foshag 1921; Rodgers 1919). Barker and Wilson (1975) also ascribed the common brecciation, and contorted and convoluted bedding of some borate deposits in the Death Valley region (California) to this volume decrease. Our observations in several sections of the Emet deposits (see below) indicate that there is often a gradual transition in the various nodular morphologies between (1) small masses or “protonodules”, very rich in lutitic matrix, in which thin, colemanite-cemented cracks radiate in a dendritic-like pattern from a crystalline center (Fig. 2E), and (2) large colemanite nodules with an empty core coated by euhedral, transparent colemanite, and with associated septarian-like radiating bands. Protonodules are found at the base of the colemanite layers, and they evolve, upward in each layer, into large colemanite nodules, which may or may not display radiating bands and empty cores.

Given these observations, and the petrographic absence of any remnants of precursor borates in these nodules, we interpret this lithofacies as nucleation zones of colemanite in very soft, fluid-rich masses of matrix. These masses underwent fracturing (by progressive dehydration?) that was coeval with colemanite precipitation and cementation. It was the matrix, and not any preexisting nodular mass, that underwent this shrinkage-crack pattern. Other authors have interpreted similar nodules as products of physicochemical processes regardless of mineralogic transformations (Helvaci and Firman 1976; Bowser and Dickson 1966). In the Kirka deposit (Fig. 1A), Palmer and Helvaci (1995) analyzed the boron isotopic composition (δ$^{11}$B) of colemanite nodules containing cracks; their results suggest that such
nODULES FORMED AS PRIMARY PRECIPITATES FROM A BRINE THAT PROGRESSIVELY CHANGED ITS ISOTOPIC COMPOSITION.

THE MASSIVE, VUGGY-BRECCIATED LITHOFACIES SEEMS TO REPRESENT MAINLY A PARTIAL DISSOLUTION/REPRECIPITATION PRODUCT OF FORMER COLEMANITE LITHOFACIES, IN PARTICULAR, IN THOSE DEPOSITS WHERE OTHER BORATE MINERALS ARE ABSENT. Nevertheless, when this lithofacies is associated with ulexite (see below, Acep deposit), a replacement origin cannot be disregarded.

FIBROUS (SATIN SPAR) VEINS ARE SECONDARY, CEMENTING LITHOFACIES FORMED BY CIRCULATION OF FLUIDS THROUGHOUT THE BORATE FORMATION WITHIN FRACTURES AND CAVITIES. DIFFERENTIAL COMPACTION, AND DEFORMATION BY TECTONISM OR UPLIFT CREATED THE NECESSARY NET OF FRATURES.

OTHER CALCIUM-BEARING BORATES—Inyoite (Ca₂B₅O₇·13H₂O), meyerhoffiterite (Ca₂B₂O₇·7H₂O), priceite (Ca₅B₅O₁₃·9H₂O), hollite (Ca₆SiB₁₀O₃₅·5H₂O), and hydroboracite (CaMgB₆O₁₁·6H₂O) ARE PRESENT AS INTERSTITIALLY GROWN, NODULAR LITHOFACIES IN LAMINAR MUDSTONES. EVIDENCE OF DIRECT PRECIPITATION FROM SOLUTIONS ON A DEPOSITIONAL FLOOR IS ALWAYS ABSENT. SOME OF THESE BORATES REPRESENT EARLY GROWTHS, SUCH AS INYOITE CRYSTALS, HOLLITE MICRONODULES, OR MEYERHOFFITE NODULES. OTHERS (PROBERTITE, HYDROBORACITE, AND PARTLY INYOITE) REPLACE ULEXITE OR COLEMANITE, THEIR ORIGIN BEING MOST PROBABLY SECONDARY (HELVACI 1995).

BORATE SEDIMENTATION IN THE VARIOUS LACUSTRINE SETTINGS

THE CA-DOMINATED BORATE PARAGENESIS IN THE BAGIDIC BASIN

In this district, the current production from the lower borate unit comes from the Yeniköy mine and Tüllü open-pit mine, the borate unit being 0.2–65 m thick. The sequence at Tüllü consists of beds of colemanite, claystone, marl, and cherty limestone; ulexite is present only in trace amounts. Colemanite layers are made up of the following facies (Fig. 3A, B): Facies 1: alternations of carbonate varves and finely laminated dark claystone. Facies 2: laminated, pelletal mudstone (and some nodules of colemanite). Facies 3: nodular colemanite (and minor intercalations of laminated mudstone). There is evidence of subaerial exposure (mudcracks) in Facies 2 and 3.

The vertical arrangement of these facies defines depositional cycles, as in colemanite Units C and D (Fig. 4A). Unit D displays a lutite–carbonate–borate succession, which can be interpreted as a shallowing-upward evaporitic cycle. Three stages are involved in this cycle (Fig. 5): (I) Deep lake stage (very few meters to tens of meters), characterized by sedimentation of dark, finely laminated claystone in rhythmic alternations with carbonate varves (Facies 1), which may reflect seasonal climatic changes. Probably, the water mass was stratified, with an anoxic or hypersaline lower mass. (II) Shallow lake stage (< 1 m to a few meters). This stage represents a drop in water level, which resulted in sedimentation of laminae of pelletal carbonate mudstone (Facies 2) in a probably unstratified water mass, with only minor episodes of subaerial exposure. Some calcium borate nodules could develop in the carbonate or in the top sediments of the former stage. (III) Shallow-ephemeral to playa-lake stage. In this stage, an underground position of the water table and associated brine evolution resulted in interstitial growth of large nodules, thin layers, and crystals of displacive colemanite (Facies 3).

THE NA-Ca BORATE PARAGENESIS IN THE BAGIDIC BASIN

The upper borate unit, 20–110 m thick, is composed of alternating beds of limestone, claystone, clayey limestone, marl, and tuff. The borate horizon, up to 30 m thick, lies in the middle of the unit. Colemanite and ulexite are present in the various deposits. The Acep deposit is an open-pit mine in the center of the basin; it produces predominant ulexite and associated colemanite. One representative borate unit in this deposit is made up of the following four facies (Fig. 4B): Facies a: alternations of laminated claystones and carbonate varves. In this unit some levels of laminated and massive-banded ulexite may intercalate in the carbonate varves and laminated mudstones (Fig. 2C). Facies b: nodular/columnar ulexite. Facies c: thinly banded, banded-nodular, and columnar ulexite, with minor colemanite. Facies d: irregular alternations of nodular ulexite, with nodular and vuggy colemanite lithofacies.

This vertical succession can also be interpreted as a shallowing-upward cycle. The basal facies, Facies a, represents a relatively deep-lake stage. Nevertheless, the facies of laminated mudstone present in the Tüllü cycles is absent here, suggesting a higher Na/Ca ratio in the Acep deposit. Facies b and c represent a shallow-water to playa setting. The uppermost facies, Facies d, in which colemanite is predominant, is interpreted as the stable playa-lake stage.

Earlier interpretation of the various borate deposits in the Bagidic district (HELVACI 1995) indicated that colemanite (calcium borate facies) precipitated toward the marginal zones of the borate lakes, and ulexite (higher Na/Ca ratio) toward the center. In fact, colemanite is predominant in the marginal zone (Tüllü) (Fig. 6A), though locally some ulexite can be deduced from the presence of pseudomorphic micrornodules of this mineral (indicated as Ps (U) in Figure 4A) now preserved in colemanite. A dominance of ulexite can be expected, with minor colemanite in the center (exemplified by Acep) (Fig. 6A).

REPLACIVE, SECONDARY COLEMANITE.—In the representative borate unit of the Acep deposit (Fig. 4B), some of the colemanite in Facies c, and a large part of the colemanite in Facies d, both replaced the former ulexite. Some petrographic details of this replacive colemanite lithofacies in Facies c are given in Figure 4B (right side). The replacement process may be simple (Fig. 4B, uppermost enlarged drawing): large, euhedral porphyroblasts of colemanite replace fibrous ulexite. But elsewhere, various lithofacies (nodules, disoidal nodules, radial aggregates, bands, irregular masses) of replacive colemanite are embedded in ulexite. These replacive lithofacies usually retain (1) micromodules of former ulexite (Fig. 3D, E), (2) relics of ulexite fibers, and (3) the original lamination of the clayey matrix (Fig. 3F).

A tentative interpretation of the diagenetic succession is as follows (Fig. 3F): (1) after initial precipitation of thin bands of ulexite and laminae of matrix, some ulexite replacement by colemanite occurred in irregular masses, which preserved the lamination; and (2) renewed growth of displacive ulexite disrupted the original lamination and totally surrounded the early-replaced masses of colemanite (C in Figure 3F). As a result, the original lamination was preserved only in some discrete masses of this secondary colemanite. Under the microscope, these laminae of colemanite preserve micromodules of ulexite, as well as micro-convolution and other depositional microstructures of the laminated matrix. This suggests that the partial replacement by colemanite was early diagenetic and intercalated during the progressive precipitation of ulexite. This replacement becomes more important in Facies d (Fig. 4B), where massive, vuggy-brecciated lithofacies of colemanite is associated with common colemanite nodules. All of this suggests a progressive change in the brine chemistry from sodic to calcic, which resulted in partial replacement of ulexite by colemanite under syn-sedimentary conditions. Nevertheless, the processes described here are complex, and the textural observations could be inconclusive. Thus, the formation of replacive colemanite in late diagenesis, i.e., during (moderate) burial, or by reaction diageneric remains a possibility.

THE CA-DOMINATED BORATE PARAGENESIS IN THE EMET BASIN

The various deposits in the Emet district (Espey, Kililik, Hisarık) are dominated by thick layers (up to 5–10 m) of nodular/megagranular colemanite interbedded cyclically with claystone and tuff (Fig. 3C). Thin-bedded carbonate, laminated dark claystone, and other facies suggestive of a deep environment are absent. Native sulfur and realgar replace colemanite.

Figure 7A shows a representative section in the Espey deposit. The nodular colemanite has irregular shapes and displaces or (locally) cements poikilitically the host sediment. Bent (not broken) crystals in the colemanite nodules are common, suggesting that growth was coeval with mechanical
Fig. 3—A) Depositional cycle in the Tulü deposit (Bigadiç). Facies: tuff layer at the base; 1, alternations of carbonate varves and laminated dark claystones; 2, laminated carbonate; 3, nodular colemanite. Hammer for scale. B) Alternations of laminated carbonates (2) and nodular colemanite (3). Tulü deposit (Bigadiç). Hammer for scale. C) Playa (inland sabkha) cycles in the Espey deposit (Emet): nodular colemanite alternates with tuffaceous-clayey bands. Hammer for scale (arrows). D) Nodule of replacive
Fig. 4—Detailed stratigraphic sections of A) Tülü (lower borate unit), and B) Acep (upper borate unit) open pits, Bigadiç district, with details of lithofacies, rock units, carbonate-borate depositional cycles, and the replacement of ulexite by secondary colemanite.

Colemanite; the inner structure shows remnants of micronodules of precursor ulexite. Acep deposit (Bigadiç). Length, 7 cm. E) Micronodules of ulexite preserved pseudomorphically in a large nodule of colemanite (only a very small part of it is visible), which displays radiating crystalline fabric (arrows) crosscutting the thin section in a northwest-southeast direction; bar, 0.32 mm. Normal light. Acep district. F) Fibrous and massive-nodular layers of ulexite alternating with laminated clay. Several zones of the ulexite were replaced by colemanite (C); in these zones the original lamination was preserved. Acep deposit (Bigadiç). Scale (lens cap), 6 cm. G) Pseudomorphs of former inyoite (?) replaced by blocky-mosaic fabrics of colemanite (see, for instance, this mosaic inside the central pseudomorph). Note the interstitial, displacive growth of pseudomorphs within the soft, laminated matrix. Bar, 0.32 mm. Normal light. Acep deposit.
Ill. 5—Scheme (without scale) of the lacustrine evolution in the Bigadiç district. I) “Deep” (perennial, stratified) stage; II) Shallow stage; III) Shallow-ephemeral to playa-lake stage. This scheme, based mainly on the Tülü open-pit mine, is also valid for the rest of the Bigadiç deposits. Facies: 1, alternations of laminated dark claystones and varve-like carbonates; 2, laminated carbonate; 3, interstitial, nodular, displaceable colemanite (or ulexite), b, borates. In each stage, the top of the water table is indicated by a (black) triangle.

compaction of the deposits. Several layers of colemanite display colemanite-poor, matrix-rich protonodules at the base (Fig. 7A, lowermost enlarged drawing). Some pseudomorphs of ulexite micronodules can be observed petrographically (Ps (U) in Figure 7A). The cyclicity, together with the impressive, stratiform growth of colemanite as interlocking meganodules, and the absence of any marker of subaqueous sedimentation, suggest a permanent underground position of the borate brine, and a playa-lake or inland sabkha environment. Subaqueous sedimentation, suggest a permanent underground position of the metamorphic basement. The open-pit mine, is also valid for the rest of the Bigadiç deposits. Facies: 1, alternations of laminated dark claystones and varve-like carbonates; 2, laminated carbonate; 3, interstitial, nodular, displacive colemanite (or ulexite), b, borates. In each stage, the top of the water table is indicated by a (black) triangle.

The interpretative distribution of this paragenesis is shown in Figure 6C. Some ulexite and probertite are present in a position equivalent to colemanite Unit D inside the old mine in this district (Fig. 7B). In this layer, secondary probertite replaces ulexite on the macroscopic scale. The presence of these minerals points to significant Na–Ca borate precipitation in the central part of the basin, probably during a severe playa-lake episode.

Fig. 6—Representation (without scale) of the interpreted borate distribution in the basins studied. A) Ulexite–colemanite, in Bigadiç. B) Colemanite (and ulexite), in Emet. C) Colemanite, ulexite and probertite, in Kestelek.

(I Kestelek district I

GENERAL DIAGENETIC EVOLUTION

The most important types of diagenesis recognized in ancient borate deposits are burial (thermal) and reaction diagenesis. In the Neogene deposits of Death Valley and Boron (California), Smith and Medrano (1996) estimated ranges of burial between 1100 and 1900 m for the most important borate transformations (1100 m for the meyerhoffertite-to-colemanite transformation; 1500 m for the ulexite-to-probertite transformation; 1900 m for the borax-to-kernite transformation), which were caused by thermal diagenesis. This estimate was based on the diagram phase relations by Hanshaw (1963) assuming a geothermal gradient of 30°C/km. Reaction diagenesis occurs when ground waters carrying a mix of cations different from those of the borate bodies interact with the borate minerals. In many Neogene deposits the presence of mineral zonation, as well as veins of ulexite,
colemanite, or borax crosscutting the borate deposits, can be attributed to reaction diagenesis that occurred while the deposits were uplifted during Neogene and Quaternary times (Smith 1985).

The mineralogic, petrographic, and sedimentologic characteristics of the Turkish deposits studied by us are summarized in Table 1. Assuming for these Neogene deposits a geothermal gradient of $30^\circ$C/km—similar to the case of the Death Valley deposits—the required burial depth for some of the above-mentioned transformations (meyerhoffenerite to colemanite, ulexite to probertite) is difficult to accept. Also, a temperature higher than $70^\circ$C, at which the ulexite-to-colemanite transformation occurs (Hanshaw 1963), would have involved an important burial depth ($>1500$ m). On the other hand, such a burial depth would have transformed into anhydrite the len-

ticular gypsum, present in some deposits as in Emet, which remains as mineralogically primary gypsum.

All available evidence indicates that these deposits were in fact never buried below about 300-500 m, and thermal diagenesis cannot reasonably be applied to them, at least as a widespread process. Thus, on the basis of the geologic-structural setting, and in the light of our sedimentologic and petrographic observations, we postulate that the most important diagenetic processes affecting the Turkish deposits occurred during early diagenesis to moderate burial (about 300 m), and during their final exhumation.

Summing up our observations on the sedimentology and the diagenesis of borates in the Bigadić, Emet, and Kestelek districts, the following points should be borne in mind:
Table 1.—Mineralogic, petrologic, and sedimentologic characteristics of the studied borate deposits

<table>
<thead>
<tr>
<th>CHARACTERISTICS</th>
<th>lower borate</th>
<th>upper borate</th>
<th>EMET</th>
<th>KESTELEK</th>
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<tr>
<td>MINERALOGY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major borates</td>
<td>C</td>
<td>U,C</td>
<td>U.C</td>
<td>C</td>
</tr>
<tr>
<td>Accessory borates</td>
<td>U</td>
<td>I</td>
<td>LM</td>
<td>Hw</td>
</tr>
<tr>
<td>Other minerals</td>
<td>Ca</td>
<td>Ca</td>
<td>Ca</td>
<td>Ca,Ca,G</td>
</tr>
<tr>
<td>ORE ZONES</td>
<td>Ca</td>
<td>Ca</td>
<td>Ca</td>
<td>Ca</td>
</tr>
<tr>
<td>ORE GEOMETRY</td>
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<td>U-C</td>
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<td>U-C</td>
</tr>
</tbody>
</table>

COLEMANITE LITHOFAECIES

<table>
<thead>
<tr>
<th>Nodular, banded-nodular</th>
<th>dom.</th>
<th>dom.</th>
<th>dom.</th>
<th>dom.</th>
<th>dom.</th>
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</thead>
<tbody>
<tr>
<td>Fibrous-banded</td>
<td>rare</td>
<td>rare</td>
<td>rare</td>
<td>rare</td>
<td>rare</td>
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<tr>
<td>Interstitial crystals</td>
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<td>rare</td>
<td>rare</td>
<td>rare</td>
<td>rare</td>
</tr>
<tr>
<td>Massive, vuggy-brecciated</td>
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<td>rare</td>
<td>rare</td>
<td>rare</td>
<td>rare</td>
</tr>
<tr>
<td>Replacement on ulexite</td>
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<td>rare</td>
<td>rare</td>
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</table>

ULEXITE LITHOFAECIES

<table>
<thead>
<tr>
<th>Nodular, banded-nodular</th>
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<th>rare</th>
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<tr>
<td>Vertically elongated</td>
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<td>rare</td>
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</tr>
<tr>
<td>Laminited</td>
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<td>rare</td>
<td>rare</td>
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</tr>
<tr>
<td>Massive-banded</td>
<td>rare</td>
<td>rare</td>
<td>rare</td>
<td>rare</td>
<td>rare</td>
</tr>
</tbody>
</table>

COLEMANITE Carbonate | Clay/varsis | Clay/varsis | Clay/varsis | Clay/varsis | Clay/varsis |
| Ulexite | Carbonate | Clay/varsis | Clay/varsis | Clay/varsis | Clay/varsis |
| COLEMANITE Carbonate | Stone | Carbonate | Stone | Carbonate | Carbonate |
| Ulexite | Ulexite | Ulexite | Ulexite | Ulexite | Ulexite |

SEDIMENTARY STRUCTURES

| Mudcracks | rare | rare | rare | rare | rare |

LAKE ENVIRONMENT

<table>
<thead>
<tr>
<th>Shallow to ephemeral</th>
<th>Shallow to ephemeral</th>
<th>Shallow to ephemeral</th>
<th>Shallow to ephemeral</th>
<th>Shallow to ephemeral</th>
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</thead>
<tbody>
<tr>
<td>U by C, macroscopic</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>U by C, micronodules</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>U by C, relics</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>I(l') by C, micro pseudomorphs</td>
<td>—</td>
<td>—</td>
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<tr>
<td>U by Per, macroscopic</td>
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<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Others</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

(1) Minerals: C, colemanite; U, ulexite; I, inyuite; M, meyerhofferite; Hw, howlite; Pr, primelite; Pb, pyrlobite; Hb, hydroboracite; Tu, tunellite; Ca, calcite; Ar, aragonite; Ce, celestite; Q, authigenic silica; R, rearing; O, opaline; S, native sulfur; G, gypsum.
(2) Only the principal lithofacies are quoted.
(3) Shallowing-upward cycles.
(4) Lake environment during the borate stage.
Abbreviations: dom., dominant; com., common

Major primary, interstitially grown precipitates are nodular colemanite and ulexite, which developed under synsedimentary conditions and continued to grow during initial burial.

The precise timing of some particular diagenetic processes, such as the scarce, microscopic replacement of micronodular ulexite, and inyuite (?) by colemanite, the aragonite-to-calcite transformation, replacement of carbonate by silica or celestite, replacement of colemanite by rearg and native sulfur, etc., is difficult to establish, although many of these processes may have acted from early diagenesis to moderate burial.

Some ulexite was (macroscopically) replaced by secondary colemanite (in the Acep deposit). Although evidence of timing for this replacement is inconclusive, textural observations suggest that this could have occurred during early diagenesis more likely than in late diagenesis, i.e., from moderate burial (thermal diagenesis) to uplift conditions (reaction diagenesis).

Some ulexite was also (macroscopically) replaced by secondary probertite (Kestelek deposit), probably during early diagenesis.

Pseudomorphs of colemanite after possible inyuite were observed petrographically in the Acep (Fig. 3G) and Tulu (?) deposits (Fig. 4, Table 1).

Some dissolution and recrystallization (massive, vuggy-brecciated lithofacies) of colemanite, as well as cementation by different borates (crosscutting satin-spar veins) seem to have occurred during initial burial to late (reaction) diagenesis.

**DISCUSSION ON THE GENESIS OF COLEMANITE**

**Mechanisms for Colemanite Precipitation**

Holocene environments in which calcium-bearing borates are precipitated worldwide are characterized by predominant ulexite and borax, with minor amounts of inyuite, meyerhofferite, and probertite (Muessig 1958, 1966) but an absence of colemanite. This fact has triggered a discussion on the origin of colemanite, which is the predominant, almost exclusive calcium borate deposits based on the following facts:

1. Rodgers (1919) found evidence that colemanite and meyerhofferite in the Neogene Furnace Creek Formation (Death Valley) can be partly attributed to the replacement of inyuite.
2. The presence of septarian structures in colemanite nodules has been ascribed to the volume loss due to the transformation of highly hydrated to less hydrated Ca borates.
3. Experimental work (Hanshaw 1963; Christ et al. 1967)
indicates that the stability of hydrated Ca borates is strongly dependent on the temperature (T) and activity of water ($a_{H_2O}$) of the brines: at low T and high values of $a_{H_2O}$, inyoite is stable, whereas colemanite requires elevated T and low $a_{H_2O}$.

**Alteration (Breakdown) of Ulexite to Colemanite.**—This hypothesis is based on the following premises: (1) the widespread presence of ulexite in Holocene borate environments; (2) the existence of colemanite cores in some ulexite nodules in the Neogene Boron deposit (California) (Bowser and Dickson 1966); (3) experimental studies (Hanshaw 1963; Christ et al. 1967) showing that ulexite transforms to colemanite above 70°C. Foshag (1921) suggested that this alteration (with borax as a by-product) is favored in the presence of percolating NaCl solutions.

**Precipitation of Colemanite by Ulexite Reaction with Ca Carbonate.**—Gale (1913) first proposed a colemanite origin by metasomatic replacement of limestone. Crowley (1996) also discussed the possibility of forming diagnostic colemanite from primary ulexite in the presence of calcium carbonate. One of the mechanisms proposed was the reaction of water (almost saturated in ulexite) with preexisting Ca carbonate. In this case, colemanite could be precipitated by the replacement of Ca carbonate.

**Theoretical or Deduced Primary Precipitation of Colemanite.**—Crowley (1996) discussed the possibility that primary colemanite could precipitate from fractionation of brines in which the initial content of Ca + Mg > HCO$_3$ + BO$_3$, with Na–Ca–Cl ending brines. This author pointed out that the conditions for this precipitation are difficult to meet, since massive quantities of NaCl (halite) would be included in the end-stage evaporative products formed from a Na–Ca–Cl brine. However, there are no colemanite deposits containing substantial amounts of halite.

Barker and Barker (1985) reviewed the data on thermodynamic properties and chemical equilibria of hydrated borates and discussed the conditions for a hypothetical primary precipitation of colemanite that overcomes the kinetic and physicochemical barriers for its nucleation and sedimentary stability. Thus, colemanite could precipitate on the Earth’s surface, if conditions of low $a_{H_2O}$, relatively high temperature, and low Na/Ca ratio existed. The range of $a_{H_2O}$ at which colemanite precipitates partly overlaps that of colemanite, and the common occurrence of borate in the modern Death Valley playa suggests that colemanite could also form at the extreme temperatures encountered on this playa. These authors deduced that the colemanite of the Neogene Furnace Creek Formation was partly a sedimentary product in a perennial, heliothermal lake, capable of maintaining floor temperatures of 35–70°C.

**Applicability of the Mechanisms for Colemanite Formation to the Turkish Deposits.**

The first three aforementioned mechanisms for colemanite formation cannot be considered as generalized processes for the Neogene Turkish deposits, for the following reasons:

**Field and Petrographic Evidence.**—It should be pointed out that in the Turkish deposits: (a) we did not find either colemanite cores inside the ulexite nodules or colemanite rims surrounding cores of ulexite; (b) we did not find evidence or vestige of any by-product involved in the ulexite transformation (residual NaCl-rich solutions, precipitates of borax or halite); (c) in some colemanite deposits, such as the Emet deposit, the carbonate sedimentary matrix of borates is practically absent; thus, extensive colemanite precipitation from ulexite (or from water nearly saturated in ulexite) with preexisting Ca carbonate does not seem reasonable; (d) the formation of colemanite nodules with septarian-like cracks suggests a tectural, not a mineral change. Finally, two types of genetically differentiated colemanite were distinguished: (i) a dominant one, which appears to be a primary precipitate formed under synsedimentary conditions in all deposits studied, and which displays various lithofacies, and (ii) a secondary one, which is produced by macroscopic ulexite replacement in the Acep deposit.

**The Required Physicochemical Conditions.**—The relatively high temperature necessary for colemanite formation is a condition probably achieved in the modern, arid and very hot Death Valley ephemeral lake (Barker and Barker 1985), but probably these high temperatures were never attained in other large areas of borate precipitation during the Quaternary. Most South American salars of the Andean region, as well as numerous shallow lakes and playas in central Asia (Qaidam Basin, Tibet Plateau) are located at altitudes between 2000 and 5000 m, and are characterized by moderate to very low temperatures during most of the year. In a general paper on the modern borate lakes in China, Sun and Li (1993) showed that precipitation of borates is mainly controlled by low temperatures. In these lakes, as is in the South American salars, colemanite is absent. In contrast, the Miocene Turkish deposits were formed at low altitudes and in arid to semiarid environments. Thus, it is possible that the required temperature for colemanite formation was reached, at least episodically.

The absence of colemanite precipitates in the modern borate-forming lakes and playas of North America is significant. Nevertheless, finds of other pure calcium borates, such as inyoite, meyerhofferite, priceite, or tertschite, in these environments are also very rare. For instance, in a detailed mineralogic study carried out by Crowley (1996) on the efflorescent crusts at Eagle Borax Spring (Death Valley), none of the above-cited borates were found associated with ulexite and proterite (the sodium-bearing borates). The absence of colemanite in the Death Valley deposits could perhaps be attributed to the hydrochemical requirement, i.e., insufficiently low Na/Ca ratio of the predominant type of brines (Barker and Barker 1985).

Palmer and Helvaci (1995) analyzed the boron isotopic composition of borax, ulexite, and colemanite in the Kirka deposit. The results were consistent with all three minerals being primary precipitates from the evaporite brine, with colemanite precipitating from a brine at lower pH than ulexite, and borax precipitating from a brine at higher pH than ulexite. In the Bigadiç district, where significant amounts of ulexite and colemanite coexist in several deposits, new isotopic data (Palmer and Helvaci 1997) suggest that, in general, the two borates are primary minerals, colemanite having precipitated at a lower pH than ulexite.

**Implications of Quaternary Occurrences of Inyoite and Meyerhofferite.**—Well-documented findings of Holocene inyoite are scant, and are mainly limited to those reported by Muessig (1958) in a saline pan in Peru, and by Helvaci and Alonso (1994) in Lagunita Playa (northwestern Argentina). Vandervoort (1997) documented an inyoite occurrence in the Pleistocene Blanca Lila Formation (northwestern Argentina). In this case, the displaceable lithofacies of inyoite is considered to be mineralogically primary, though early diagenetic: this inyoite possibly precipitated from boron-rich brines percolating downward through the sedimentary section during or following the deposition of the overlying ulexite beds. This author noticed that the inyoite described by Muessig (1958) in Peru is also located beneath an ulexite-bearing unit. Given the few inyoite occurrences found in Quaternary playas and salars, there is no firm sedimentologic basis for considering inyoite as the current precursor of colemanite in the Neogene formations. Moreover, in these modern occurrences, inyoite always displays idiomorphic, coarse crystalline textures. We found no firm evidence of this presumably primary mineral in the Turkish deposits, but only some colemanite micropseudomorphs of possible inyoite (?) in the Bigadiç deposits. In the Kirka district (Fig. 1A), Inan et al. (1973) assumed that inyoite instead of colemanite was the depositional phase, but this interpretation was not accompanied by petrographic evidence. Our observations in this district suggest that inyoite is mainly a secondary precipitate, which usually replaces colemanite or ulexite; nevertheless, some primary precipitation of inyoite in this deposit cannot be ruled out.

Meyerhofferite occurrences in Quaternary deposits are also extremely scarce. Small amounts of this borate have been found (together with proterite) in the ephemeral lake of Death Valley (California). As in the case of inyoite, there is no sedimentologic reason for assuming that this mineral
could have been a significant precursor of nodular colemanite in the ancient borate deposits. In the Simav deposit (the Bigadiç district), the presence of several cycles with ulexite at the base and meyerhoffiterite at the top suggests that the latter could be a primary precipitate attributed to progressive impoverishment of sodium in the brines. Moreover, no relation between meyerhoffiterite and colemanite was observed. The boron isotopic composition of meyerhoffiterite in this deposit also suggests that this mineral formed directly from the evaporite brine (Palmer and Helvacı 1997).

Occurrences of Other Primary Calcium Borates in the Turkish Deposits.—The presence of mineable priceite, Ca₅B₅O₁₅·7H₂O, and howlite, Ca₂B₅Si₂O₁₀(4OH)₂, in the Sultançayır borate district of western Anatolia (Fig. 1A) has been interpreted as original precipitates grown in a gypsum sediment (Helvacı 1994). New observations indicate that (a) these borates precipitated interstitially in a deep-lake environment, and (b) synsedimentary reworking favored incorporation of clastic nodules of both minerals in the depositional cycles (Ortī et al. 1998). This finding suggests that our information on the sedimentologic possibilities for precipitating some calcium borates, which are rare in modern environments, is incomplete.

**Possible Setting for Primary Colemanite Precipitation in the Turkish Deposits**

The interpretation of the perennial saline, heliothermal lake model as the most likely analog for the Neogene Furnace Creek Formation (California) accounts for the raised temperatures for precipitation of primary colemanite (Barker and Barker 1985). This interpretation could also be applied to the Turkish deposits, at least in part. In fact, heliothermal conditions could exist in the relatively deep lacustrine environments (Kestelek), and also in some shallower ones (Bigadiç). Precipitation of aragonite in these lakes as a precursor of calcite also suggests warm waters at the onset of the borate stage. The existence of a density-stratified system with associated heliothermal conditions would have ensured a bottom temperature high enough for colemanite to precipitate on the lake floor or beneath it.

It should be pointed out that none of the colemanite lithofacies found in these deposits are typical of a lake-bottom precipitate. This suggests that primary, large, interlocking nodules of colemanite developed interstitially beneath the depositional floor of a shallow lake, at a depth of some meters or tens of meters. It seems possible that such growth could be attributed to the kinetic barrier (very slow growth velocity) affecting this mineral.

We cannot apply the heliothermal model directly to those Turkish deposits which we interpret as having formed in a permanent playa or saline mud flat settings, as in the Emet district. Nevertheless, it is possible that once the necessary low Na/Ca ratio was attained in the initial brines, the temperature was high enough to favor either direct nucleation of colemanite or a very rapid transformation of early-formed ulexite micronodules into colemanite. In the Sultançayır deposit (Fig. 1A), a complete diagenetic transformation of gypsum into anhydrite during moderate burial (up to 300 m only) is observed (Ortī et al. 1998), which suggests the possible existence of a high geothermal gradient in this Turkish region during Miocene times. This might have influenced, to some extent, the early precipitation of colemanite. Thus, we conclude that the heliothermal lake model can in part account for the Turkish deposits, although a playa setting also seems appropriate. Presumably, an important sodium impoverishment in the initial brines exerted a major control over precipitation of colemanite.

**CONCLUDING REMARKS**

1. In the borate-producing Neogene basins of Anatolia, several lacustrine environments were identified, i.e., permanent playas (Emet deposits) and perennial, deep lakes which could evolve to shallow lakes (Kestelek deposit) or even to playa settings (Bigadiç deposit).
2. These borate deposits display depositional, shallowing-upward cyclicity, consisting of a vertical succession of claystone–carbonate–borate, with the borate layer at the top of the cycle.

3. The observed facies distribution (mineral zonation) is depositional, with calcium borates occupying the marginal zones of the basins and sodium borates the centers.
4. Nodular colemanite is mainly a primary precipitate that formed interstitially (displacing and cementing the matrix) under synsedimentary conditions, in both subaerial (playa) and subaqueous (beneath a lake floor) settings.
5. Nodular ulexite is also a primary precipitate, interstitial and mainly displacive, which formed in the same synsedimentary setting as colemanite. Some thin laminae of ulexite may have been a primary, lake-bottom precipitate in deep-water to shallow-water stages.
6. Macroscopic replacement of ulexite by secondary colemanite is present only locally. There is no conclusive evidence for the timing of this replacement, either during early diagenesis (most probably) or during late diagenesis. There is some evidence of a possible inyoite (?) precursor for colemanite, but this is only local and of little significance.
7. Minor borate redistribution—mainly crosscutting veins of colemanite and ulexite—occurred during late diagenesis, probably linked to uplift and exposure of the borate deposits.

**ACKNOWLEDGMENTS**

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**REFERENCES**


MIOCENE COLEMANITE-ULEXITE DEPOSITS


ROCHBERG, A.P., 1919, Colemanite pseudomorphs after inyoite from Death Valley, California: American Mineralogist, v. 4, p. 135-139.


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