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Geology, mineralogy and depositional setting of the Beypazarı Trona (Natural Soda) Deposit (Ankara, Türkiye)

Beypazarı Trona (Doğal Soda) Sahasının Jeolojisi, Mineralojisi ve Depolanma Ortamı, Ankara, Türkiye

Cahit Helvacı*

Dokuz Eylül University, Faculty of Engineering, Department of Geological Engineering TR-35370 Buca-İzmir/Türkiye

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Abstract: The Beypazarı district is a large area of volcano-sedimentary rocks in the interior of central Anatolia, situated ~100 km northwest of Ankara. Trona, lignite, and bituminous shale occur in the lower part, and Na-sulfate and gypsum occur in the upper part of the sedimentary sequence of the Miocene Beypazarı basin**.** The Neogene Beypazarı Basin extends in an east-west direction from Beypazarı to Nallıhan and consists of a sedimentary sequence of up to 1200 m total thickness. The pre-Neogene basement rock assemblages of the Pontides limits the basin to the north. The Central Sakarya Region consisting of ultrabasic, granitic and metamorphic rocks bounds the basin to the south.

The trona deposit, located 250–300 m below the surface, was discovered incidentally in the summer of 1982 by the General Directorate of Mineral Research and Exploration (MTA) while carrying out a drilling project on lignite deposits. An extensive exploratory drilling program was undertaken by MTA during the period 1983–1985 on behalf of Etibank. Proven trona reserves are 210 million metric tons, and total reserves are estimated to be 240 million metric tons. The Beypazarı trona deposit is the world's second largest trona deposit after the Green River deposit, Wyoming, USA. In addition, there are ~400 million metric tons of lignite, 340 million metric tons of bituminous shale, and 1 million metric tons of Na-sulfate in the Beypazarı Basin.

The trona deposit located north of Zaviye village is associated with shale in the lower part of the Hırka Formation and alternates with bituminous shale and claystones. Based on borehole data, it is estimated that the areal extent of the trona deposit is ~8 km^2. The trona beds were deposited as two lens-like bodies within a 70–100 m thick zone in the lower part of the shale unit. A total of 33 trona beds are known: 16 in the lower trona lens and 17 in the upper lens. The total thickness of the lower trona horizon ranges from 40 to 60 m, and the total thickness of the upper trona horizon is ~40 m. The interval between the lower and the upper trona horizons varies from 30 m to 35 m. The central part of the trona deposit is generally thicker than the marginal parts, and the trona beds grade laterally into dolomitic mudstones and claystones toward the edges of the basin. The total thickness of the trona beds in both lenses varies between 21 and 34 m in the central parts, and 2.5 and 12 m in the marginal parts of the ore bodies. The common thickness of the individual trona beds in both trona horizons ranges from 0.4 m to 2 m. The isopach contours of both trona horizons are restricted by the Zaviye fault.

The principal sodium-carbonate minerals are trona and minor nahcolite occurring in the marginal parts of the trona deposits, and trace amounts of pirssonite and thermonatrite occur locally. Trona and dolomite are associated throughout the trona zone. Calcite, zeolites, feldspars, and clays are the most common minerals within the rocks associated with the trona deposit. Trona crystals, generally white and occasionally grayish due to the presence of impurities, formed as massive crystals and as disseminated crystals in the claystone and shales. The products of zeolitization, dolomitization, and chloritization are rather widespread within the rock units associated with trona.

Correspondence / *Yazışma*: helvacicahit@gmail.com

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The Beypazarı Basin was affected by an extensional tectonic regime during the Middle-Late Miocene period. This extensional regime converted to a unidirectional compressional regime during the Late Miocene–Early Pliocene period. The sediments associated with the trona, lignite, and bituminous-shale deposits formed in fluvial, lacustrine, and playa-lake (perennial and ephemeral) environments. The Beypazarı Basin is mainly filled by clastic materials and the penecontemporaneous products of adjacent volcanic activity, centered northeast of the basin. The most likely sources of Na for the formation of trona and other sodium-carbonate salts were thermal springs, tuffs interbedded with the sediments, and extensive Neogene volcanic rocks interfingering with sedimentary rocks in the northeastern part of the basin.

Keywords: Associated rock units, Beypazarı deposit, Tectonics, Trona, Turkey.

Öz: *Beypazarı Neojen Havzası, Beypazarı'ndan Nallıhan'a kadar doğu-batı doğrultusunda uzanan ve toplam kalınlığı 1200 m'ye varan bir tortul istiften oluşmaktadır. Pontidlerin Neojen öncesi temel kaya toplulukları havzayı kuzeye doğru sınırlamaktadır. Ultrabazik, granitik ve metamorfiklerden oluşan orta Sakarya Masifi havzayı güneyde sınırlar. Beypazarı ilçesi, Orta Anadolu'nun iç kesimlerinde, Ankara'nın ~100 km kuzeybatısında yer alan geniş bir volkano-sedimanter kaya topluluğunu kapsar. Beypazarı Miyosen havzasının sedimanter istifinin alt kısmında trona, linyit ve bitümlü şeyl; üst kısmında ise Na-sülfat ve jips bulunur.*

Beypazarı-Çayırhan bölgesinde, yaşları Orta ve Geç Miyosen arasında değişen, ~1200 m kalınlığında bir sedimanter istif yüzeylemektedir. Miyosen istifi, açısal bir uyumsuzluk boyunca temel kayalar üzerine oturur; temel kayalar Paleozoyik ile Eosen arasında değişen metamorfik, ofiyolitik, karbonat ve kırıntılı kayalardan oluşur. Beypazarı Neojen havzası esas olarak flüvyal, gölsel ve volkano-sedimanter kayalar ile kaplıdır. Miyosen istifi, Teke volkanikleri haricinde yedi sedimanter formasyona ayrılmıştır. Bu tortul kaya birimleri sırasıyla Çoraklar, Hırka, Akpınar, Çayırhan, Bozbelen ve Kirmir formasyonları ile Sarıyar Kireçtaşı'dır. Tersiyer volkanik kayaları havzanın kuzeydoğu kesiminde Beypazarı ve Kızılcahamam bölgeleri arasında dağılım göstermektedir. Neojen öncesi tortul kayalar Neojen havzasını batıdan sınırlar ve yaşları Paleosen'den Eosen'e kadar değişir.

Zaviye köyünün kuzeyinde yer alan trona yatağı, Hırka Formasyonu'nun alt kısmındaki şeyllerle ilişkilidir ve bitümlü şeyl ile kiltaşlarıyla ardalanmalıdır. Sondaj verilerine dayanarak, trona yatağının alansal genişliğinin ~8 km^2 olduğu tahmin edilmektedir. Trona yatakları, şeyl biriminin alt kısmında 70-100 m kalınlığında bir zon içinde, iki merceksel gövde olarak çökelmiştir. Alt trona merceğinde 16 ve üst mercekte 17 olmak üzere toplam 33 trona yatağı bilinmektedir. Alt trona horizonunun toplam kalınlığı 40 ila 60 m arasında değişmektedir ve üst trona horizonunun toplam kalınlığı ~40 m›dir. Alt ve üst trona horizonları arasındaki zon 30 m ile 35 m arasında değişmektedir. Trona yatağının orta kısmı genellikle kenar kesimlerine göre daha kalındır ve trona yatakları havzanın kenarlarına doğru yanal olarak dolomitik çamurtaşları ve kiltaşlarına merceksel olarak kamalanır. Her iki mercekte de trona yataklarının toplam kalınlığı orta kısımlarda 21 ila 34 m, cevher kütlelerinin kenar kesimlerinde ise 2,5 ila 12 m arasında değişmektedir. Her iki trona horizonundaki tekil trona yataklarının kalınlığı yaygın olarak 0,4 m ile 2 m arasında değişmektedir. Her iki trona horizonunun izopak konturları Zaviye fayı tarafından sınırlandırılmıştır.

Ana sodyum-karbonat mineralleri tronadır, daha az oranda trona yataklarının kenar kesimlerinde oluşan nahkolit ve yersel olarak oluşan eser miktardaki pirsonit ve termonatrittir. Trona ve dolomit, trona zonu boyunca birbiriyle ilişkilidir. Kalsit, zeolitler, feldispatlar ve killer; trona yatağının ilişkili kayaları içinde en yaygın minerallerdir. Genellikle beyaz ve bazen de safsızlıkların varlığından dolayı grimsi olan trona kristalleri, kiltaşı ve şeyllerde masif ve dissemine kristaller olarak oluşmuştur. Zeolitleşme, dolomitleşme ve kloritleşme ürünleri trona ile ilişkili kaya birimlerinde oldukça yaygındır.

Beypazarı havzası, Orta-Geç Miyosen döneminde genişlemeli bir tektonik rejimin etkisi altında kalmıştır. Bu genişleme rejimi, Geç Miyosen-Erken Pliyosen döneminde tek yönlü bir sıkışma rejimine dönüşmüştür. Trona, linyit ve bitümlü-şeyl çökelleri ile ilişkili tortullar flüvyal, gölsel ve playa-gölü (kalıcı ve geçici) ortamlarda oluşmuştur. Beypazarı havzası esas olarak kırıntılı malzemeler ve havzanın kuzeydoğusunda yoğunlaşan, bitişik volkanik faaliyetin yarı eşzamanlı ürünleri tarafından doldurulmuştur. Trona ve diğer sodyum-karbonat tuzlarının oluşumu için en olası Na kaynakları termal su kaynakları, tortullarla arakatmanlı tüfler ve havzanın kuzeydoğu kesimindeki tortul kaya arakatkılı geniş yayılımlı Neojen volkanik kayalardır.

Anahtar Kelimeler: *Beypazarı yatağı, İlişkili kaya birimleri, Tektonik, Trona, Türkiye.*

INTRODUCTION

The Neogene Beypazari Basin is limited to the north by the Western Pontide mountain belt. This part of the Pontides consists of metamorphic, volcanic, and sedimentary rocks, which are Paleozoic to Tertiary in age (Ketin, 1966; Saner, 1979). The Middle Sakarya Massif consists mainly of metamorphic, acid-plutonic, and ultrabasic rocks, and occurs at the southern margin of the Beypazari Basin (Saner, 1979). Tertiary volcanic rocks are distributed in both the northeastern part of the basin and between the Beypazari and Kızılcahamam areas (Figure 1). Pre-Neogene sedimentary rocks ranging from Paleocene to Eocene in age limit the Neogene basin to the west.

The Neogene Beypazari Basin is one of the most economically important basins in Turkey, containing lignite, bituminous shale, and trona deposits. The Beypazarı trona deposit, located 250–300 m below the surface, was discovered incidentally in the summer of 1982 by the General Directorate of Mineral Research and Exploration (MTA) during a drilling project on lignite deposits. Proven trona reserves are 210 million tons, and total reserves are estimated to be 240 million tons (Helvacı et al., 1989; Helvacı, 1998; Orti et al., 2002; Helvacı et al., 2014).

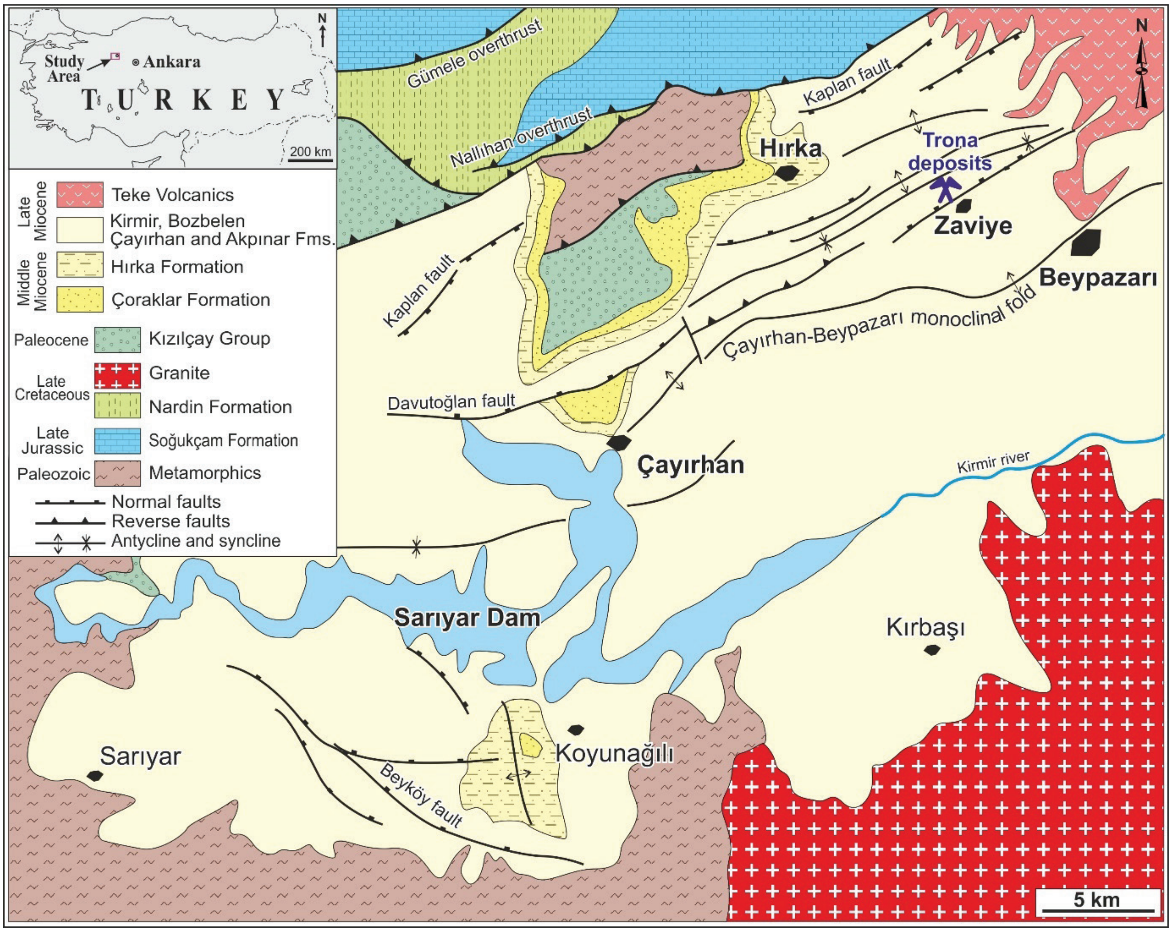

Figure 1. Geological and structural map of the Beypazarı Basin (after Helvacı, 2010).

Şekil 1. *Beypazarı havzasının jeolojik ve yapısal haritası (Helvacı, 2010'dan).*

The Beypazarı trona deposit is the second largest trona deposit in the world after the Green River deposit in Wyoming, USA. In addition, the Beypazari Basin contains ~400 million metric tons of lignite, 340 million metric tons of bituminous shale, and 1 million metric tons of sodium sulfate.

The aim is to describe the geology, stratigraphy, tectonic setting, mineralogy and basin formation conditions of the Beypazarı trona deposit.

MATERIAL and METHOD

All samples used in this study were collected from drill cores and a series of sample traverses for mineralogical and petrological studies. Core samples were collected from eight exploratory boreholes drilled by Eti Mine Works General Management of Turkey with support of the Scientific and Technological Research Council of Turkey (TÜBİTAK) and MTA in Beypazarı village. Additional hand samples from the upper trona unit were collected in mining galleries. Core samples were cut in half with a diamond wire saw and then polished for mineral identification under an environmental scanning electron microscope (ESEM) coupled with backscattered electron (BSED) and X-ray energy dispersive (EDS) detectors in order to confirm the mineralogy of minerals with the same chemical components. Selected samples were powdered or microdrilled and then analyzed by X-ray diffraction. Thin sections were prepared for optical observation with a polarizing microscope.

GEOLOGICAL SETTING

The rock units of the study area are divided into two main groups: pre-Neogene basement rocks and Neogene rock units (Figures 2 and 3). The Neogene sedimentary units generally consist of clastic, clayey, calcareous, bituminous, evaporitic, and silicified sediments.

The Neogene Beypazarı Basin is mainly filled by fluvial, lacustrine, and volcano-sedimentary rocks. Tertiary volcanic rocks are distributed in the northeastern part of the basin between the Beypazarı and Kızılcahamam areas (Öngür, 1977) (Figure 1). The Teke Volcanics are widespread in the area northeast of Beypazari and Kızılcahamam. The Miocene Beypazari sequence exposed in the volcanics consists of alternating pyroclastic breccia in the eastern part of the basin and interfingers with tuff, andesitic and basaltic lavas, and agglomerate.

The pre-Neogene sedimentary rocks limit the Neogene basin from the west and vary from Paleocene to Eocene in age. The pre-Neogene basement rocks are Paleozoic to Eocene in age and comprise metamorphic, plutonic, volcanic and sedimentary rocks. The Neogene sedimentary units generally consist of clastic, clayey, calcareous, bituminous, evaporitic, and siliceous sediments. The Neogene sedimentary sequence is divided into seven formations (Figures 1 and 2); in ascending order, they are: Çoraklar, Hırka, Akpınar, Çayırhan, Bozbelen, and Kirmir Formations, plus the Sarıyar limestone and the Teke volcanics (İnci et al., 1988; Helvacı and İnci, 1989).

STRUCTURE of BEYPAZARI BASIN

The Miocene Beypazarı Basin has approximately E-W trend and is bounded by growth faults to the north and south. The growth faults in the northern part of the basin have high displacements as a result of stepwise structural features that occur mainly at the contact between Miocene sediments and the basement rocks. The growth faults at the south-eastern margin of the basin have small displacements and only developed as an asymmetric depression in the first phase, based on analysis of tectonic features. The fluvial and lacustrine sediments were deposited in an asymmetric depression during Miocene time and were controlled by growth faults at the northern margin (Figures 1 and 3).

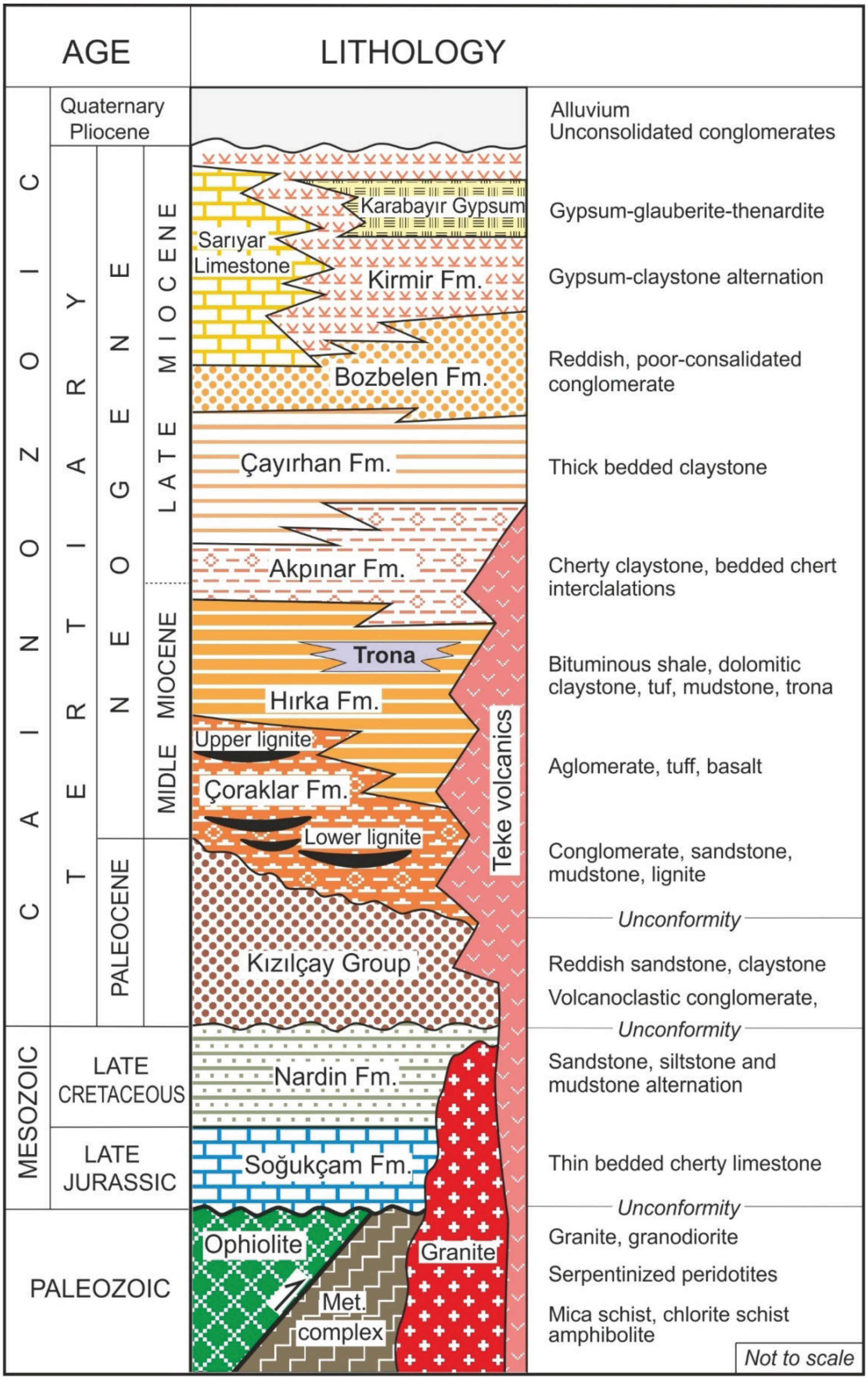

Figure 2. Generalized stratigraphic column for the Beypazarı Basin (after Helvacı, 2010).

Şekil 2. *Beypazarı trona havzasının genelleştirilmiş stratigrafik kolon kesiti (Helvacı, 2010'dan).*

The synclinal and anticlinal structures in the trona deposit (Figures 3 and 4) developed as a result of compression associated with the movement of the North Anatolian Fault during the late Miocene and early Pliocene. On the structural contour map of the upper trona zone, a NW-SE trending monoclinal fold with high-angle flank dipping to the south can be observed near Çakıloba (Figures 3 and 4). The lower and upper trona zones were affected by the asymmetric fold. The high-angle flanks of these folds generally dip to the south. In addition, this type of fold system suggests that compressional forces operated from north to south during and/or after trona deposition.

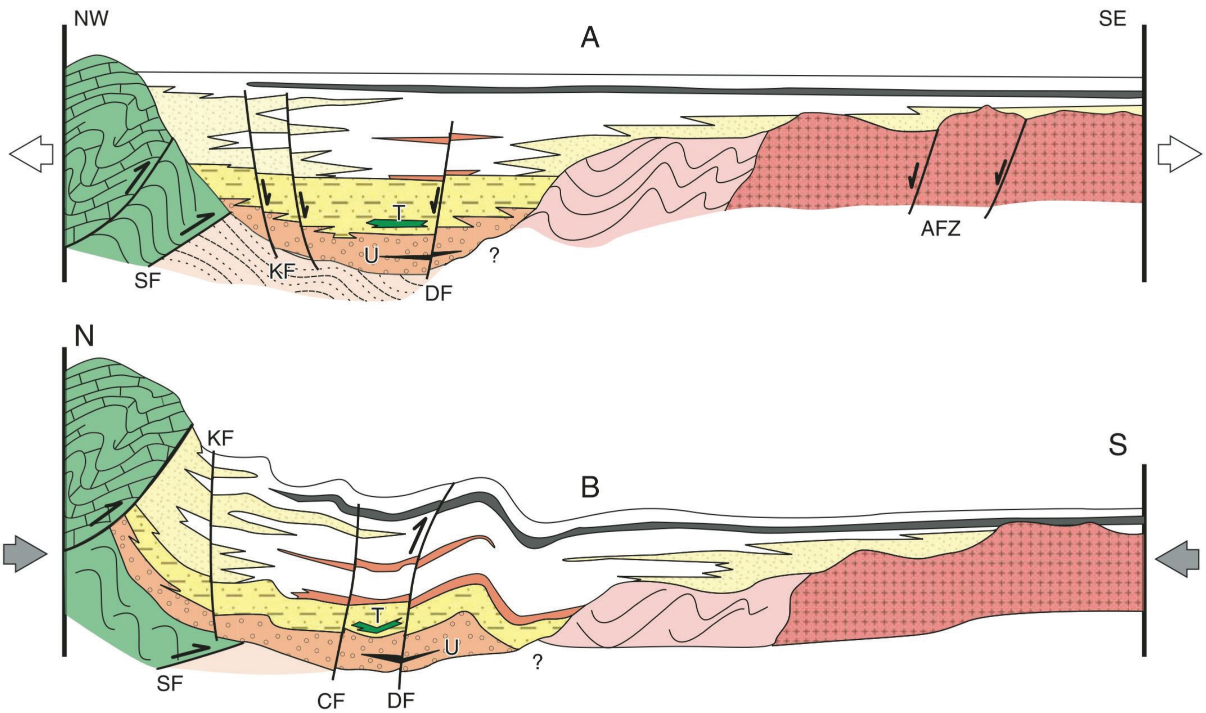

Figure 3. Tectonosedimentary evolution of the Miocene Beypazarı Basin: **(a)** Miocene extension phase. **(b)** Post-Miocene compressive phase. Big dots: lower alluvial facies, small dots: upper alluvial facies, dashed lines: lithofacies of the Hırka Formation, U: upper lignite, T: trona, diagonal stripes: carbonate rock, white color: green claystone lithofacies, dark line: evaporite lithofacies (sulfates). AFZ: Ayaş fault zone, CF: Çömlektepe fault, DF: Davutoğlan fault, KF: Kaplan fault, SF: Sekli fault, (after Helvacı, 2010).

Şekil 3. *Beypazarı Miyosen havzasının tektono-sedimanter evrimi: (a) Miyosen genişleme evresi. (b) Miyosen sonrası sıkışma fazı. Büyük noktalar: alt alüvyon fasiyesi, küçük noktalar: üst alüvyon fasiyesi, kesikli çizgiler: Hırka Formasyonu litofasiyesi, U: üst linyit, T: trona, diyagonal şeritler: karbonat kayası, beyaz ton: yeşil kiltaşı litofasiyesi, koyu çizgi: evaporit litofasiyesi (sülfatlar), AFZ: Ayaş fay zonu, CF: Çömlektepe fayı DF: Davutoğlan fayı, KF: Kaplan fayı, SF: Sekli fayı. (Helvacı, 2010'dan).*

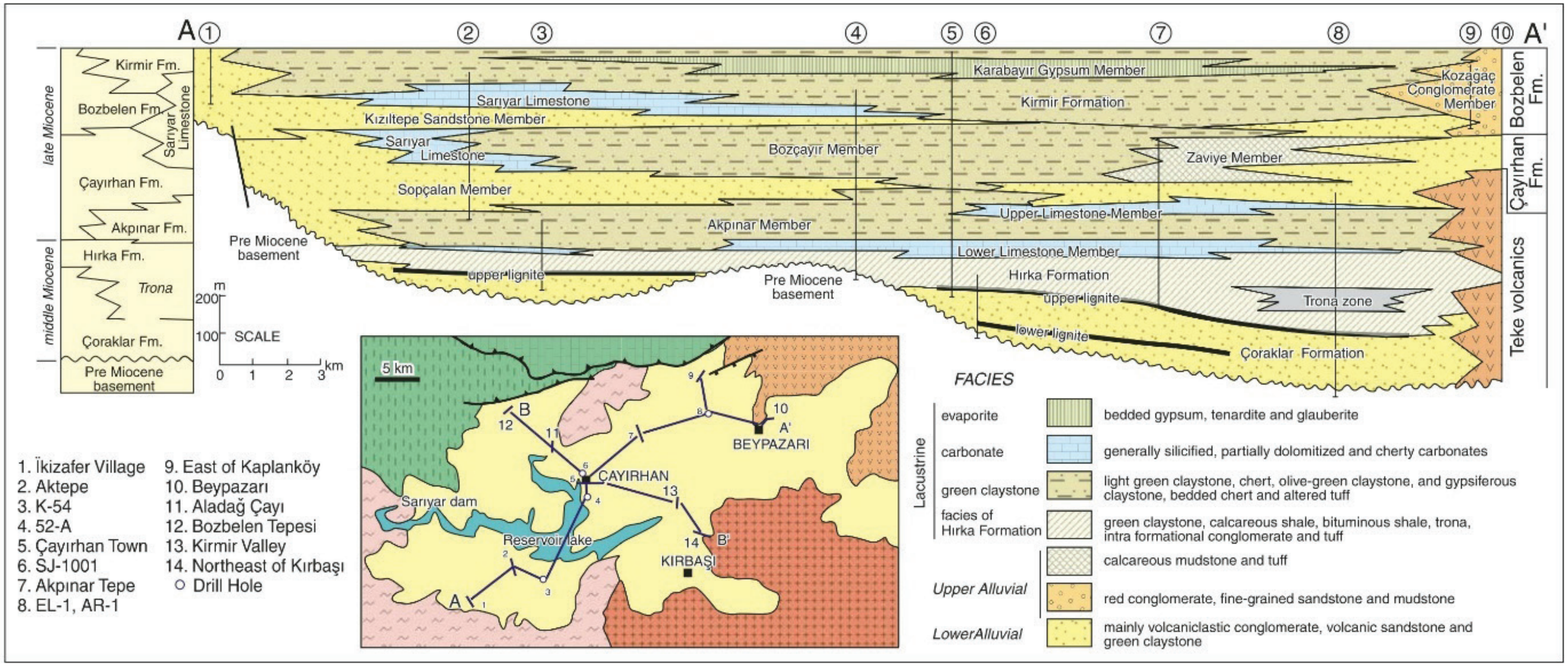

Figure 4. Stratigraphic section showing the distribution of major facies and associated rock unit assemblages in the Beypazarı Basin (after Helvacı 2010).

Şekil 4. *Beypazarı trona havzasındaki ana fasiyeslerin ve ilişkili kaya birimi topluluklarının dağılımını gösteren stratigrafik kesi (Helvacı, 2010'dan).*

The Beypazarı Basin was affected by an extensional tectonic regime during the Middle-Late Miocene. In connection with this tectonic regime, NE-SW–trending normal faults developed, and sedimentation in the basin was controlled by faults throughout the Miocene Epoch. The stratigraphic and sedimentological characteristics of the sequence and the placement of the faults indicate a half graben type of depressional basin. This extensional regime became a unidirectional compressional regime during the Late Miocene–Early Pliocene. Under the influence of this new tectonic regime, the Miocene rock units were folded, and rocks on the northern margin of the basin were thrust over basement rocks (Figure 3).

In the region, gravity tectonics characterized by growth faults began in the Early Miocene. This was replaced by a compressional regime, probably during the Early Pliocene. During this new tectonic phase, reverse faults, imbricate structures, thrust faults with different throws and overturned folds formed in the pre-Neogene rock units of the Pontides due to NW-SE directed compressional forces. E-W trending reverse faults, asymmetric folds (dipping to the south), monoclinal folds and conjugate faults striking mainly NW and NE were generated within Neogene units by NW-SE directed compressional tectonic forces.

The NW-SE compressional regime occurring in the region is probably the result of movement on the North Anatolian Fault. During the neotectonic phase, a single directional compressional regime occurred due to the forces acting from NW to SE against the passive Middle Sakarya block. The Eskişehir Fault probably limits the Middle Sakarya Massif to the south (Figure 5). Thus, growth faults that bounded the Neogene basin to the north were reactivated during the neotectonic phase and transformed into north-dipping reverse faults throughout the region. In contrast, growth faults bounding the basin to the south were not strongly affected by the neotectonic phase (after Yağmurlu et al., 1988) (Figure 5).

The rock units in the study area were a-ected by tensional and compressional tectonic forces. All facies in the northern part of the basin were folded and faulted by compressional tectonic forces in the Late Miocene during movement along the North Anatolian Fault (Figures 1, 3 and 5). In summary, the Beypazarı Basin is the result of unidirectional compressive stress acting from northwest to southeast (Yağmurlu et al., 1988).

FACIES ANALYSIS of the BEYPAZARI MIOCENE SEQUENCE

The depositional characteristics of the sedimentary rock units are shown in Figures 2 and 3. Three main facies, including di-erent lithofacies, were defined in the Beypazarı Basin. These facies are: (1) lower alluvial facies, (2) upper alluvial facies, and (3) lacustrine facies. Outlines of the facies relationships and distributions of the lithofacies components of the three major facies assemblages are shown in Figure 4 (Helvacı and İnci, 1989).

TRONA DEPOSIT

Structure of the Deposit

The trona deposit is associated with the Hırka Formation and alternates with bituminous shale, dolomitic claystone, and intraformational conglomerate. Logs and a correlation scheme for the studied boreholes are shown in Figures 6 and 7. The Hırka Formation is vertically and laterally gradational with the underlying Çoraklar Formation. The total thickness of the Hırka Formation increases towards the east and exceeds 300 m where the trona deposit occurs. The formation interfingers with the Teke Volcanics along the İnözü river. Dolomitic limestones are usually thin (1 to 3 m) and grey to the west of Beypazari (Figures 7, 8, and 9).

According to drill hole data, 33 trona horizons ranging in thickness from 40 cm to 5 m were deposited within a 70-100 m thick zone of the Hırka Formation (Figures 6 and 7). Based on borehole data, it is estimated that the areal extent of the upper trona horizon is ~8 km², while the areal extent of the lower trona horizon to the north of Zaviye village is ~5.5 km² (Figure 7).

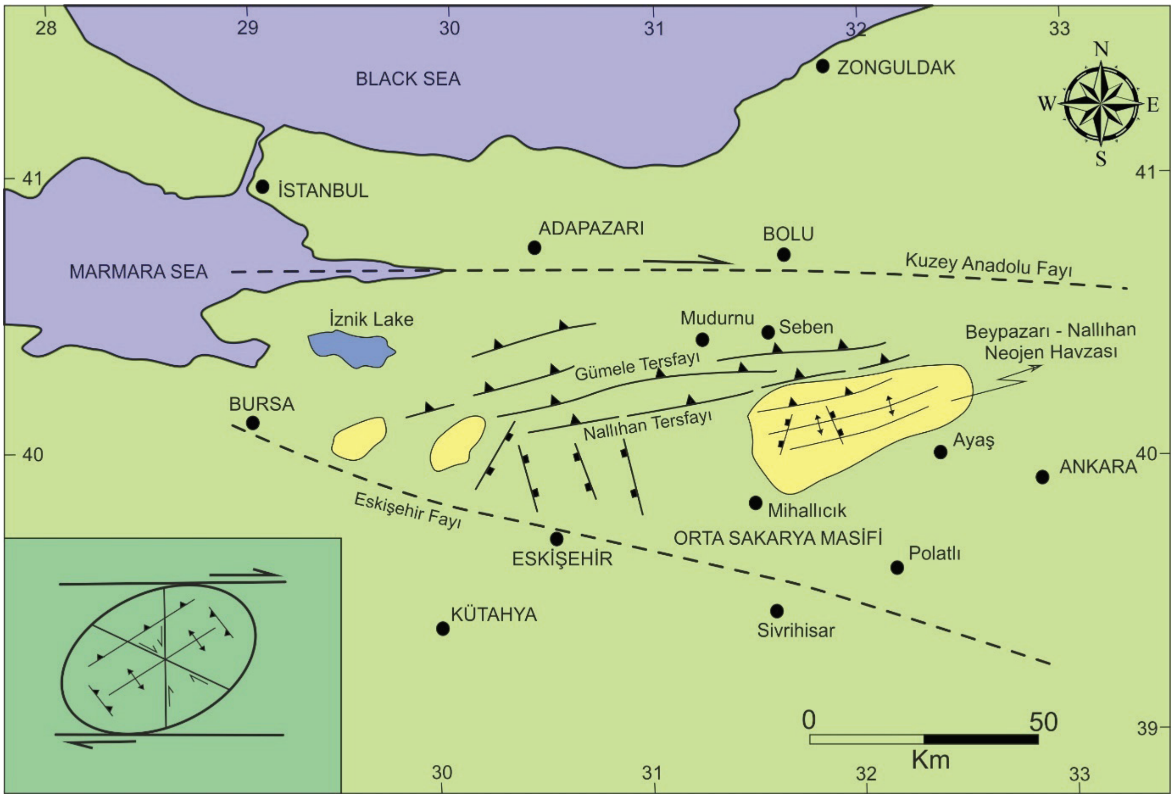

Figure 5. Geometric relations between the tectonic features in the study and the North Anatolian Fault. The structural trends expected in an east-west system are shown in the lower left corner. F: conjugate and normal faults (after Yağmurlu et al., 1988).

Şekil 5. *Çalışmanın tektonik özellikleri ile Kuzey Anadolu Fayı arasındaki geometrik ilişkiler. Doğu-batı anahtar sisteminde beklenen yapısal eğilimler sol alt köşede gösterilmiştir. F: eşlenik ve normal faylar (Yağmurlu vd. 1988'den).*

The trona deposit is located in the lower part of the Hırka Formation and alternates with bituminous shale and claystones (Figures 6 and 7). The trona deposit covers approximately 8 km^2 according to MTA drill data. The trona beds were deposited within a 70- to 100-meter-thick zone as lenticular bodies and grade laterally into, and interfinger with, mudstones, claystones, and bituminous shales at the margins of the trona deposit.

The trona was deposited as two lens-like bodies within a 70–100-m-thick zone in the lower part of the Hırka Formation (Figures 1 and 2). The central part of the trona deposit is generally thicker than the peripheral parts.

The lower trona horizon occurs between the villages of Zaviye and Çakıloba and has an elongated lens shape with NE-SW orientation. It is bounded to the south by the Zaviye Fault (Figure 1). In many places, the thickness of the lower trona horizon varies over short distances, as noted in the drill holes. Eight of the 16 trona beds are significant for their thickness and areal extent (Figure 7). Changes in the lateral thickness of the lower trona horizon are likely related to the paleolake topography and geochemical conditions of the depositional environment. In many places, this lower trona zone contains brownish claystones overlying the trona and bituminous shale.

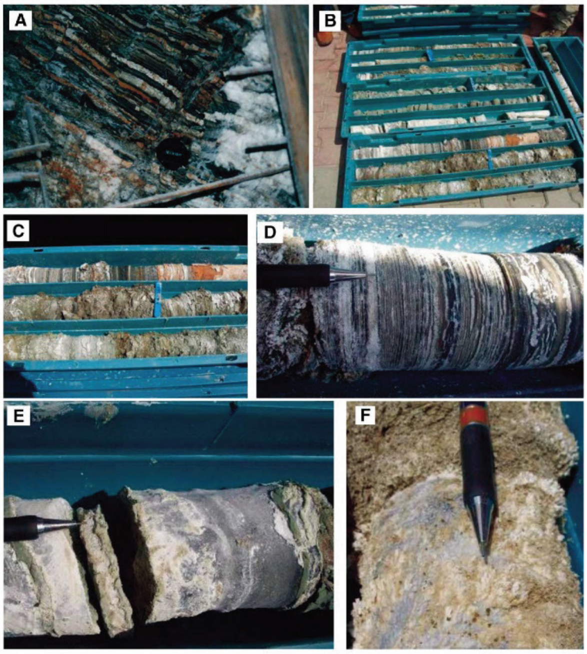

Figure 6. a) Interbedding of trona and bituminous shale beds in the main shaft of the trona mines. **b)**, **c)** and **d)** Interbedding of trona and bituminous shale beds in drill core **e)** and **f)** Massive trona samples in drill core (after Helvacı 2010).

Şekil 6. a) *Trona madenlerinin ana şaftında trona ve bitümlü şeyl tabakalarının arakatmanlanması.* ***b)***, ***c)*** *ve* ***d)*** *Sondajlardan alınan trona ve bitümlü şeyl tabakalarının arakatmanlanması,* ***e)*** *ve* ***f)*** *Sondajlardan alınan masif trona örnekleri (Helvacı, 2010'dan).*

The upper trona zone has nine significant trona horizons, and three of these horizons formed when the basin was at its largest areal extent; they are also the thickest and most uniform of the horizons. The average thickness of the upper trona horizon is 12 m (Figure 7). The upper trona horizon was deposited under more stable environmental conditions than the lower trona horizon. Approximately NE-SW–trending synclines and anticlines are present north of the Zaviye Fault (Figure 1).

The Zaviye Fault, which appears to have acted as a growth fault during the deposition of the trona and associated rocks, formed as a result of the extensional tectonic regime that affected this area during the Early and Middle Miocene (Figure 1). The synclinal and anticlinal structures occurring in the trona deposit developed under the influence of compression resulting from movement along the North Anatolian Fault during the Late Miocene-Early Pliocene. The lower and upper trona horizons were affected by asymmetrical folding. In addition, these types of folds suggest that the compressional forces operated from north to south during and/or after trona deposition (Figures 1 and 5).

Mineralogy

The main mineral in the saline beds is trona. Minor amounts of nahcolite are found at the margins of the deposit and trace amounts of pirssonite and thermonatrite occur randomly within the deposit (Table 1). Neither shortite nor halite appear to be present. The trona crystals are generally white, massive, and have clear crystalline columnar texture, but sometimes they appear greyish due to the presence of impurities. Trona occurs both as massive forms and as separate crystals in claystones and shales (Figure 8). Scattered euhedral trona crystals and crystal aggregates are present in the associated rocks (Figure 8). Dolomite is estimated to be the second major mineral in the trona core samples. In the transition zone between the Çoraklar Formation and the Hırka Formation, epsomite, hexahydrite, and starkeyite are common. Sulfates are abundant in the uppermost rock unit of the Miocene sequence; predominantly gypsum and less frequently bloedite and rarely thenardite and glauberite form thick sulfate deposits (Table 1).

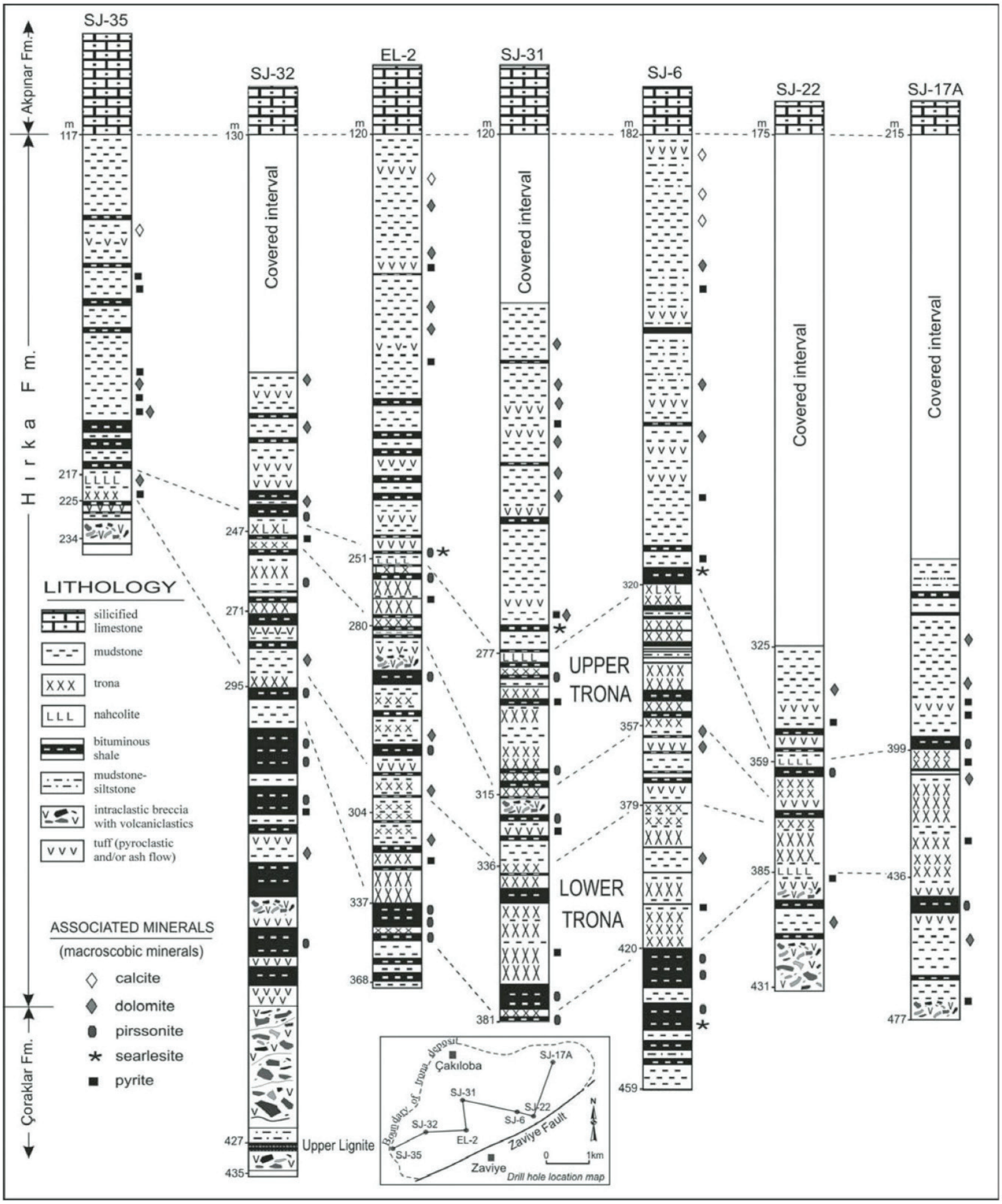

Figure 7. Lithological log correlation of boreholes based on distribution of Na-carbonate minerals in the center of the Beypazarı Basin (after Helvacı 2010).

Şekil 7. *Beypazarı havzasının orta kesimindeki sondajların Na-karbonat dağılımına dayalı litolojik kuyu logu korelasyonları (Helvacı, 2010'dan).*

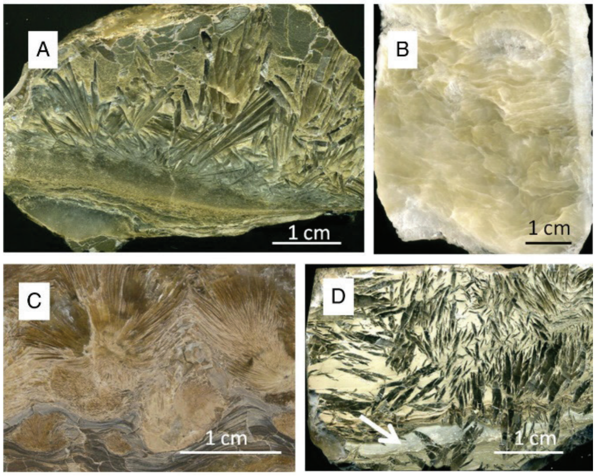

Figure 8. Trona lithofacies. **a)** grass-like trona lithofacies (Upper Trona Unit, hand sample U3A, Beypazarı trona mine), **b)** massive trona lithofacies (Upper Trona Unit, core sample EL-2-24 at 256.9 m in depth), **c)** radiating-prismatic texture of the interstitial trona lithofacies (Upper Trona Unit, hand sample U6, Beypazarı trona mine), **d)** unoriented texture of the interstitial trona lithofacies. White arrow indicates a layer of authigenic K-feldspar (Upper Trona Unit, hand sample D11B, Beypazarı trona mine). (García-Veigas et al., 2013).

Şekil 8. *Trona litofasiyesleri.* ***a)*** *ot benzeri trona litofasiyesi (Üst Trona Birimi, el örneği U3A, Beypazarı trona madeni),* ***b)*** *masif trona litofasiyesi (Üst Trona Birimi, karot örneği EL-2-24, 256. 9 m derinlikte),* ***c)*** *ara katman trona litofasiyeslerinin ışınsal-prizmatik dokusu (Üst Trona Birimi, el örneği U6, Beypazarı trona madeni),* ***d)*** *ara katman trona litofasiyeslerinin yönlenmemiş dokusu. Beyaz ok, otojenik K-feldspat tabakasını göstermektedir (Üst Trona Birimi, el örneği D11B, Beypazarı trona madeni) (García-Veigas vd., 2013).*

Minerals from the Beypazarı trona deposit were identified by direct recording of X-ray diffraction analysis using standard-powder and oriented sample techniques.

The predominant saline mineral in the saline beds is trona, with minor amounts of nahcolite occurring in the marginal and upper parts of the trona deposit (Figure 6). Traces of pirssonite and thermonatrite occur locally within the deposit (Table 1). Carbonates and other minerals in the Beypazarı trona deposit within the Hırka Formation are shown in Table 1.

The major sodium carbonate minerals are trona and minor nahcolite occurring in the peripheral parts of the trona deposits, and trace amounts of pirssonite and thermonatrite occur locally. Calcite, zeolites, feldspars, and clays are the most common minerals within the rocks associated with the trona deposits. Trona crystals, generally white and occasionally greyish due to the presence of impurities, occur as massive and disseminated crystals in clays and shales. The products of zeolitization, dolomitization, and chloritization are quite widespread within the rock units associated with the trona deposit, and the processes that formed them probably occurred shortly after deposition or during diagenesis.

Trona and dolomite are associated throughout the trona zone. Grass-like trona consists of vertically oriented crystals arranged in fan aggregates (Figure 8A). Upward- and downward -fans are rare, although upward fans are more common and longer. Massive trona consists of submillimetric, unoriented crystals with scarce matrix (Figure 8B). Radiating-prismatic trona consists of millimeter to centimeter-sized aggregates of bladed crystals organized in nodules grown in unconsolidated mud (Figure 8C). Unoriented crystalline trona consists of millimeter- to centimeter-sized crystals scattered in mud and arranged in clusters (Figure 8D).

Chemistry

The Beypazarı trona deposit contains abundant trona and dolomite, minor amounts of nahcolite, and trace amounts of S, Cl, Sr, As, and B. Variations in the chemistry of trona and nahcolite from Beypazarı are interpreted to reflect different phases of concentration that occurred in perennial saline lakes. The Beypazarı deposit contains high-grade trona and nahcolite ores; their chemical compositions are given in Tables 2 and 3. The Na_2O content of trona ranges from 37.2 to 41.78%, while nahcolite varies from 29.73 to 35.76% (Tables 2 and 3).

Table 1. Carbonates and other minerals occurring in the Beypazarı trona deposit in the Hırka Formation (after Helvacı 2010). (Note: The predominant minerals are in boldface).

Çizelge 1. *Beypazarı Trona Yatağı'nın Hırka Formasyonunda bulunan karbonatlar ve diğer mineraller (Helvacı, 2010'dan). (Not: Baskın mineraller kalın harflerle yazılmıştır).*

SULFIDES	
Pyrite	FeS_2
OXIDES	
Quartz	SiO_2
α - **Quartz**	SiO_2
Opal-C.T.	
Hematite	Fe_2O_3
CARBONATES	
Nahcolite	$NaHCO_3$
Trona	$Na_2CO_3.NaHCO_3$
Termonatrite	$Na_2CO_3.2H_2O$
Pirssonite	$Na_2CO_3.CaCO_3.2H_2O$
Brugnatelite	$Mg_6FeCO_3(OH)_{13}.4H_2O$
Calcite	$CaCO_3$
Dolomite	$CaCO_3.MgCO_3$
Magnesite	$MgCO_3$
Natron	$Na_2CO_3.10H_2O$
Gaylusite	$Na_2CO_3.CaCO_3.5H_2O$
SULFATES	
Gypsum	$CaSO_4.2H_2O$
Hexahidrite	$MgSO_4.6H_2O$
Epsomite	$MgSO_4.7H_2O$
Bloedite	$MgSO_4. Na_2SO_4.4H_2O$
PHOSPHATES	
Apatite	$Ca_5(PO_4)_3$ (OH,F,Cl)
Collaphone	$Ca_5(PO_4)_3CO_3. H_2O$

SILICATES	
Clay minerals	
- Smectite (Saponite)	
- Illite	
- Chlorite	
- Montmorillonite	
Loughlinite	$Na_2Mg_3Si_6O_{16}.8H_2O$
Searlesite	$NaBSi_2O_6.H_2O$
Hornblende	NaKCaMgFeAl, SiAlO(OH)
Tourmaline	$NaMg_3Al_6B_3Si_6O_{27}(OH)_4$
Epidote	$Ca_2(Al,Fe)_3Si_3O_{12}(OH)$
Biotite	$K(Fe,Mg)_3AlSi_3O_{10}(OH)_2$
Muscovite	$KAl_2Si_3AlO_{10}(OH)_2$
Lepidolite	$K(Li,Al)_3(Al,Si)_4O_{10}(OH,F)_2$
Phlogopite	$KMg_3(Si_3AlO_{10})F_2$
Orthoclase	$KAlSi_3O_8$
Microcline	$KAlSi_3O8$
High-sanidine	$KAlSi3O_8$
Albite	$NaAlSi_3O_8$
Analcime	$NaAl(SiO_3)2H_2O$
Natrolite	$Na_2Al_2Si_3O_{10}.2H_2O$
Heaulandite	$CaAl_2Si_7O_{18}. 6H_2O$
Clinoptiolite	$NaCaKMgAlOSi.7H_2O$
Sanidine	$KAlSi_3O_8$
Chabazite	$CaAl_2Si_4O_{12}$
Mordenite	$(Ca, Na_2, K_2) Al_2Si_{10}O_{24}. 5H_2O$
Ferrierite	$(Na, K)_2Mg (Si, Al)_{18}O_{24}. 7H_2O$
Heulandite	$CaAl_2Si_7O_{18}.6H_2O$

Table 2. Chemical analyses (in wt%) of 16 trona samples collected from drill holes in the Beypazarı trona deposit (after Helvacı 2010).

Çizelge 2. *Beypazarı Trona Yatağı sondajlarından elde edilen 16 Trona numunesinin kimyasal analizleri (ağırlık yüzdesi olarak) (Helvacı, 2010'dan).*

TRONA SAMPLES

OXIDE (%)	SJ6-13	SJ6-16	SJ6-18	SJ6-23	SJ6-26	SJ6-28	SJ6-35	SJ6-40	SJ17A-6	SJ17A-8	SJ17A-9	SJ31-5	SJ31-16	SJ32-8	SJ9-14	SJ9-17
SiO_2	0.11	0.43	0.66	0.26	0.53	1.65	1.92	1.04	2.43	1.64	0.7	1.25	1.49	0.39	0.79	1.3
Al_2O_3	0.09	0	0.06	0	0.02	0.4	1.13	0.06	0.28	0.09	0.09	0.06	0.73	0.04	0.13	0.17
$^*Fe_2O_3^t$	0.01	0	0.02	0.04	0.2	0.23	0.07	0.23	0.28	0.09	0.04	0.01	0.12	0.02	0.02	0.08
MgO	0.35	0.46	0.54	0.57	0.41	2.08	1.15	1.08	1.7	1	0.73	0.37	1.29	0.32	0.76	0.9
CaO	0	0.15	0.04	0.11	0.08	1.21	0.29	0.6	0.7	0.36	0.36	0.01	0.17	0	0.24	0.38
Na^2O	40.51	41.78	40.08	40.24	39.74	37.21	39.51	39.54	38.37	39.32	39.03	39.83	39.15	40.03	39.57	39.64
K_2O	0.01	0.01	0.02	0.03	0.04	0.12	0.06	0.06	0.17	0.06	0.02	0.03	0.43	0.01	0.04	0.06
SO_3	0.42	0.15	0.61	0.3	0.24	0.57	0.57	0.32	0.08	0.13	0.35	0.52	0.52	0.79	0.12	0.21
CO_2	28.39	29.67	28.46	29.28	28.22	29.63	28.05	28.07	27.25	27.92	29.01	28.28	29.26	28.25	28.98	29.01
H_2O	29.62	27.5	29.11	29.04	29.37	26.87	28.34	28.54	28.04	28.78	28.8	29.06	27.51	29.3	28.88	28.48
Total	99.51	100.51	99.6	99.87	98.85	100.07	99.54	99.54	99.3	99.39	99.13	99.42	100.67	99.15	99.53	100.23

Table 3. Chemical analyses (in wt%) of three nahcolite samples collected from drill holes in the Beypazarı trona deposit (after Helvacı, 2010).

Çizelge 3. *Beypazarı Trona Yatağı sondajlarından elde edilen 16 Nahkolit numunesinin kimyasal analizleri (ağırlık yüzdesi olarak), (Helvacı, 2010'dan).*

NAHCOLITE SAMPLES

OXIDE (%)	S22-14	S35-13	S35-15
SiO_2	3.91	5.53	2.08
Al_2O_3	0.77	0.61	0.03
*$Fe_2O_3^t$	0.32	0.32	0.12
MgO	2.85	2.48	1.18
CaO	1.55	3.96	0.2
Na_2O	33.18	29.73	35.76
K_2O	0.16	0.33	0.08
SO_3	0.3	0.08	0.19
CO_2	24.01	27	25.53
H_2O	32.23	29.83	35.07
Total	99.28	99.87	100.24

Sodium-carbonate minerals chemically precipitated from brines, which may have been derived partly from thermal springs and partly from surface streams and groundwater, and from the major element compositions of the nearby volcanics and granites. All the rocks are enriched in sodium relative to average values for these rock types. Surface streams and groundwater may have carried dissolved Na, Mg, HCO_3, and CO_2, into the basin from weathering of rocks exposed in the catchment area, but the main source of dissolved ions in the perennial saline lake is thought to be from leaching of the Neogene volcanics by thermal springs associated with volcanic activity in the area, and by surface streams and groundwaters.

DEPOSITIONAL ENVIRONMENT of THE HIRKA FORMATION and the TRONA DEPOSIT

The Miocene Beypazarı sequence consists of coarse- to fine-grained sedimentary rocks with trona, lignite and bituminous shale deposits, carbonates and volcanic rocks. Based on the lithological characteristics of these rock units, it is concluded that the rocks were deposited within fluvial, lacustrine, and playa lake environments. Laterally, the lacustrine and playa-lake environment sediments intertongue with fluvial sediments, and the Beypazarı Basin represents a restricted, evaporite-rich depositional cycle (Figure 9).

The lithofacies of the Hırka Formation are interpreted to have been deposited in a playa-lake type environment similar to that described by Eugster and Surdam (1973). The dolomitic claystone was deposited on the lake-margin playa and/or mud flat. The absence of gypsum and abundance of framboidal pyrite in the Beypazarı area may be explained by bacterial sulfate reduction. Thick layers of trona were deposited in a small, periodically drying, closed lake in the eastern part of this playa plain. This lake was supplied by alkaline-rich surface streams and groundwater originating from the adjacent rocks and playa flat. The bituminous shale lithofacies was deposited in a shallow, brackish-water lake environment which expanded by seasonal flooding. Characteristics of the intraformational conglomerate lithofacies indicate intrabasinal erosion, re-deposition, and sediment selection toward the depositional center of the trona deposit (Figure 9).

CONCLUSIONS

The Miocene sequence in the Beypazarı Basin is composed of coarse- to fine-grained sedimentary rocks with trona, lignite and bituminous shale, carbonates, and volcanic rocks. The rocks were deposited within fluvial, lacustrine, and playa-lake environments. Laterally, the lacustrine and playa-lake deposits interfinger with fluvial deposits. The Beypazarı Basin represents a restricted, evaporite-rich depositional cycle (Figure 9). The main sodium carbonate mineral is trona with minor amounts of nahcolite and trace amounts of pirssonite and thermonatrite. Trona and dolomite are associated throughout the deposit.

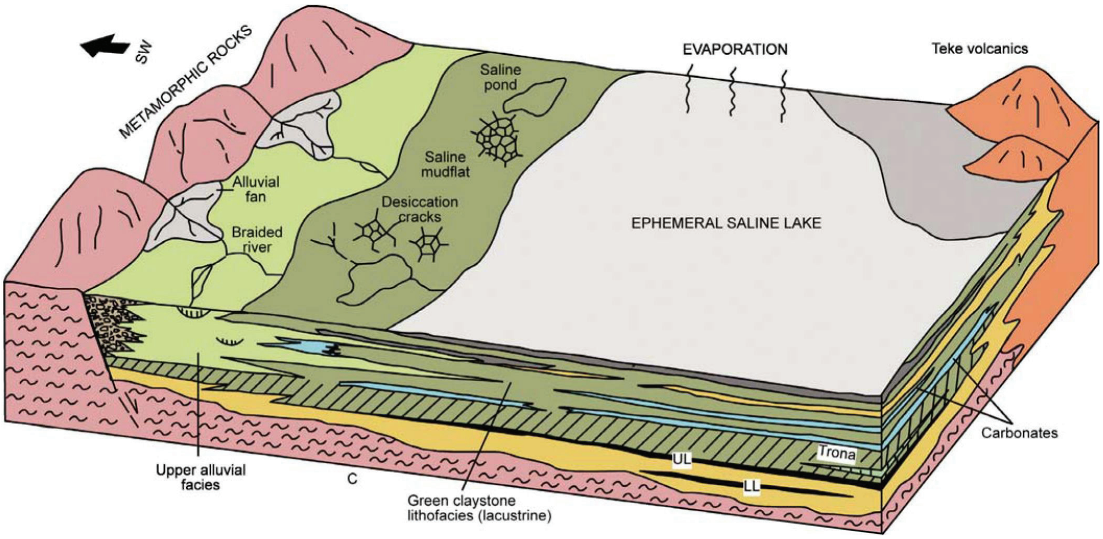

Figure 9. Block diagram of the depositional environment in the Beypazarı Basin (after Helvacı, 2010).
Şekil 9. *Beypazarı trona havzasının çökelim ortamına ait blok diyagram (Helvacı, 2010'dan).*

The dolomitic claystone, bituminous shale, trona, and intraformational conglomerate lithofacies of the Hırka Formation were deposited in a playa lake controlled by an extensional tectonic regime. The dolomitic claystone lithofacies were deposited in a lake-margin playa flat. The trona accumulated in an evaporitic lake depocenter east of the playa flat and the lake was supplied by alkaline-rich surface and groundwater originating from the adjacent playa flat and volcanic and granitic terranes. When the lake water was freshened by seasonal floods, the lake expanded and bituminous shale was deposited in a wider area. The intraformational conglomerate and associated rocks are the result of syn-sedimentary tectonism, intrabasinal erosion, re-deposition, and sediment selection towards the basin center.

The most probable source of sodium for the formation of the trona deposit is the weathering of rocks in the source area (granites and Paleocene and Cretaceous volcanics); leaching of tuffs interbedded with the sediments; and the extensive Teke Volcanics (from coeval volcanic activity) interfingered with the sediments in the northeastern part of the Beypazarı Basin (Figure 1). The Teke Volcanics were probably the major source of sodium for trona and other sodium carbonate salts. The sodium entered the playa-lake system via surface water, groundwater and thermal springs.

GENİŞLETİLMİŞ ÖZET

Beypazarı havzasındaki Miyosen istifi; trona, linyit ve bitümlü şeyl, karbonatlar ve volkanik kayalar içeren kaba ve ince taneli tortul kayalardan oluşur. Bu kayalar flüvyal, gölsel ve playa-göl ortamlarında çökelmiştir. Yanal olarak, gölsel ve playa-göl çökelleri flüvyal çökellerle arakatmanlıdır. Beypazarı havzası sınırlı, evaporit bakımından zengin bir çökelim döngüsünü temsil etmektedir (Şekil 9). Başlıca sodyum karbonat minerali trona olup, az miktarda nahkolit ve eser miktarda pirsonit ve termonatrit bulunur. Trona ve dolomit, yataklanma boyunca birbirleriyle ilişkili olarak bulunur.

Hırka Formasyonu'nun dolomitik kiltaşı, bitümlü şeyl, trona ve formasyon içi konglomera litofasiyesleri, genişlemeli bir tektonik rejim tarafından kontrol edilen bir playa gölünde *çökelmiştir. Dolomitik kiltaşı litofasiyesleri göl kenarı playa düzlüğünde çökelmiştir. Trona, playa düzlüğünün doğusundaki evaporitik bir göl çökelim merkezinde birikmiştir ve göl, kökensel olarak bitişiğindeki playa düzlüğüne ve volkanik - granitik arazilere dayanan alkali bakımından zengin yüzey ve yeraltı suları ile beslenmiştir. Göl suyu mevsimsel taşkınlarla tazelendiğinde, göl genişlemiş ve bitümlü şeyl daha geniş bir alanda çökelmiştir. Formasyon içi konglomera ve ilişkili kayalar; sin-sedimanter tektonizma, havza içi erozyon, yeniden çökelim ve havza merkezine doğru sediman seçiliminin sonucudur.*

Trona yatağı oluşumu için en olası sodyum kaynağı; kaynak alandaki kayaların (granitler, Paleosen ve Kretase volkanikleri) ayrışması, tortul arakatmanlı tüflerin yıkanması ve Beypazarı havzasının kuzeydoğu kesiminde tortul arakatkılı geniş yayılımlı Teke Volkanikleri'dir (eşzamanlı volkanik faaliyetlerden), (Şekil 1). Teke Volkanikleri olasılıkla trona ve diğer sodyum karbonat tuzları için ana sodyum kaynağıdır. Sodyum, playa-göl sistemine yüzey ve yeraltı suları ve termal kaynaklar yoluyla girmiştir.

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ORCID

Cahit Helvacı https://orcid.org/0000-0002-8659-1141

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