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The Quaternary fluvial-lacustrine system in the Akarçay Basin (SW Anatolia): depositional environments and paleoclimatic interpretation

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Abstract: The Akarçay Closed Basin, located in southwest Anatolia, contains deformed formations and the drying Akşehir and Eber lakes. This study aimed to interpret the paleoenvironmental and paleoclimatic conditions of the Akşehir and Eber lakes, which are reported to have been connected during the Pleistocene. Based on sedimentological and mineralogical data, three different depositional subenvironments were defined, corresponding to the formation and development stages of the lake. Sedimentary facies analysis of the Pleistocene deposits in the basin revealed the following facies associations, listed from bottom to top: 1) an alluvial fan and fluvial facies association, representing the formation stage of the lake, which developed due to tectonic activity and a humid/wet climate; 2) a lakeshore facies association, corresponding to the expansion stage when the lake spread shallowly, and 3) a lake center facies association, corresponding to the closing stage when the lake began to dry, characterized by limited levels of clastic deposition under very shallow lake conditions. In the lakeshore and lake center facies association, *Valvata piscinalis*, *Dreissena iconica* and *D. polymorpha* species living in shallow waters and streams, as well as *Laevicaspia caspia* species living in mesohaline environments were identified. X-ray diffraction analysis was performed on the levels that best represented the facies associations in the basin, revealing that the dominant clay minerals in the sequence were illite and kaolinite. Combined evaluation of the sedimentological, mineralogical, and paleontological data suggests that the abundance of *Valvata piscinalis* and *Dreissena iconica*—both stream-dwelling species—at levels with increased kaolinite content indicates rainy and humid climatic periods when stream-fed conditions prevailed in the basin. Conversely, the dominance of *Laevicaspia caspia* and the intervals marked by illite deposition indicate cold and arid climatic periods.

Key words: Akarçay Basin, facies associations, paleoclimatology, paleoenvironment, SW Anatolia, Quaternary

1. Introduction

Western Anatolia is a transition region both tectonically and climatically and includes the “Isparta Angle” connecting Southwestern Anatolia to Central Anatolia. This region was affected by compressional regimes from the Early Mesozoic to the Late Miocene, followed by extensional regimes from the Late Miocene and regional uplift events (Şengör, 1987; Barka and Reilinger, 1997; Koçyiğit and Özacar, 2003; Gürbüz et al., 2021; Tuncer et al., 2023). Regional uplift continued to increase steadily throughout the Early Pleistocene, leading to the formation of numerous Neogene–Quaternary-aged lacustrine basins, characterized by high-relief, graben, and horst structures around the Isparta Angle (Nemec and Kazancı, 1999; Yağmurlu et al., 2004; Alçiçek and Jiménez-Moreno, 2013; Üner et al., 2015; Tagliasacchi and Yağmurlu, 2019; Gürbüz et al., 2021; Tuncer et al., 2023). One of these basins is the Akarçay Basin, which contains the drying Akşehir and Eber lakes, located within a graben from the

Early Miocene and bounded by the Emir Mountains to the north and Sultan Mountains to the south (Öğdüm et al., 1989). Lacustrine environments, which have historically and currently interacted with other water sources through rivers and channels, preserve climatic records—such as those related to vegetation, tectonism, geomorphology, and anthropogenic factors—more clearly than open basins (Bradley, 2015). In this context, sediments from lake basins bearing traces of climatic and ecological changes can be used for paleoenvironmental assessments, and paleoclimatic interpretations can be made through mineralogical, geochemical, and stable isotope analyses from the sediments (Singer, 1984; Chamley, 1989; Chen et al., 2008; Ocakoğlu et al., 2013; Tudryn et al., 2013; Ocakoğlu et al., 2016; Guimaraes et al., 2016; Orhan et al., 2021; Yakupoğlu and Kazak Taştan, 2022; Tagliasacchi et al., 2024). Therefore, the Akarçay Basin—containing closed lake systems—was selected as the study area, considering its potential to provide suitable data for observing climate

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changes. While several of the pioneering studies in the region have focused on geological, geomorphological and tectonic features (Atalay, 1977; Umut et al., 1987; Koçyiğit and Özacar, 2003; Tiryakioğlu et al., 2015), sedimentological characteristics (Kazancı et al., 1994; İleri, 2002), hydrogeochemistry (Özdemir Çallı et al., 2022), lake level changes (Şener et al., 2010; Dönmez, 2018), lake shoreline management (Bahadır, 2012), and recent climate change (Yıldırım et al., 2011; Çatal and Dengiz, 2015; Coşkun, 2020), this study offers a broader climatic perspective by revealing paleoclimatic data through lithofacies relationships and mineralogical compositions of the Pleistocene deposits in the Akarçay Basin, supported by paleontological and paleoecological interpretations. This study aims to investigate the accumulation processes of Pleistocene sediments in the Akarçay Basin in detail, to determine the lithofacies of the units and reveal the facies relationships, and to identify periods of climatic change in the Pleistocene based on paleoclimatic and paleoenvironmental interpretations derived from the clay mineralogy of the sediments, supported by paleontological data.

2. Geological setting

The part of south-west Anatolia called the “The region of lakes” includes many lakes, mostly tectonic and some karstic in origin, distributed within depressions of the Taurus Mountains, which form part of the Alpine–Himalayan belt (Kazancı and Roberts, 2019). Spanning an area of 7500 km², the study area is influenced by both the temperate, humid Mediterranean climate of the Aegean Region and the arid steppe climate of Central Anatolia (Çatal and Dengiz, 2015). The Akşehir and Eber lakes, part of this region, developed in a depression between the plateaus of the Sultan and Emir mountains, resulting from glaciers melting with climate change after the ice age (Atalay, 1977). The formations comprising the Paleozoic basement of the Sultan Mountains underwent metamorphism and folded, leading to the development of fault systems. Among these, the Sultandağı Fault formed during the Upper Oligocene due to the effects of the Alpine orogeny (Ketin, 1959, 1966). This NW–SE trending fault, which forms the southern boundary of the basin and significantly influences the depositional character, is a dip-slip normal fault approximately 90 km long (Tiryakioğlu et al., 2015). The Üçkuyu, Çukurcak, and Bolvadin faults, cutting the structural axis of the Sultan Mountains, are located in the region with SW–NE orientation (Kazancı et al., 1994).

The basement comprises the Paleozoic Çaltepe Formation (Özgül and Gedik, 1973), which includes dolomite and recrystallized limestone. Overlying these basement units are the Hacıalabaz Formation (Demirkol,

1982), composed of Jurassic limestone, and the Koçbeyli Formation (Atalay, 1977), consisting of Cretaceous pink and purple limestones. Mesozoic units are predominantly found in the Emir Mountains to the north and the Sultan Mountains to the south of the Akşehir and Eber lakes. The development of Neogene units began with the uplift of the Sultan Mountains. The Miocene Aşağıçiğil and Ayaslar formations (Umut et al., 1987), unconformably overlying older units, consist of reddish-brown sandstone and conglomerates. The Upper Miocene Aşağıçiğil Formation, containing sandstone, claystone, lignite, and peat, is mostly transitional to the Ayaslar Formation.

The tuffs at the base of the volcanic stack that surfaced in the Miocene-Pliocene in the basin were named as “Seydiler Tuff and Agglomerate” by Metin et al. (1987), “Köroğlu Volcanics” by Göktaş (2010) and “Seydiler Ignimbrites” by Aydar et al. (1998). Seydiler Ignimbrites consist of white-cream colored, thick-bedded tuffs and ignimbrites and come to the surface by cutting older units (Aydar et al., 1998). The Argıthanı Formation, which contains clay, marl, and limestone; the Belekler Formation, transitional with the Argıthanı Formation and composed of red-brown conglomerate and mudstone; and the Doğanhisar Formation, consisting of conglomerate sandstone and mudstone, form the Pliocene sediments of the basin (Umut et al., 1987). The Pleistocene Dursunlu Formation, consisting of yellow, white and yellowish-green claystone, sandstone, and marls, also contains rare lignite bands.

Lithologies of the Dursunlu Formation are particularly observed around Dursunlu, Çavuşlu, Gözpinarı, and Tuzlukçu localities in the basin (Figures 1 and 2). Paleobeach and ancient lake sediments consisting of sand, clay, and silt around the Akşehir and Eber lakes are Miocene–Quaternary in age and are the last products of the completion phase of the lake form. In the study conducted by Kazancı et al. (1994) in the region, the shells found in sand pits were dated to an age of 30,000 years, and the existence of a lake with a depth of approximately 50 m was reported. It was stated that the lake, called Büyük Akarçay Lake, was divided into two—Akşehir and Eber lakes—approximately 6000 years ago due to the effects of the Üçkuyu Fault in the region (Kazancı et al., 1994; İleri, 2002).

3. Materials and methods

3.1. Field studies

Fifteen measured stratigraphic sections were collected from areas where the Pleistocene lacustrine sediments and their lateral and vertical facies relationships could be most clearly observed in the study area. Samples obtained from measured sections were collected systematically. Moreover, Northeast of Taşköprü village, in Sultandağı

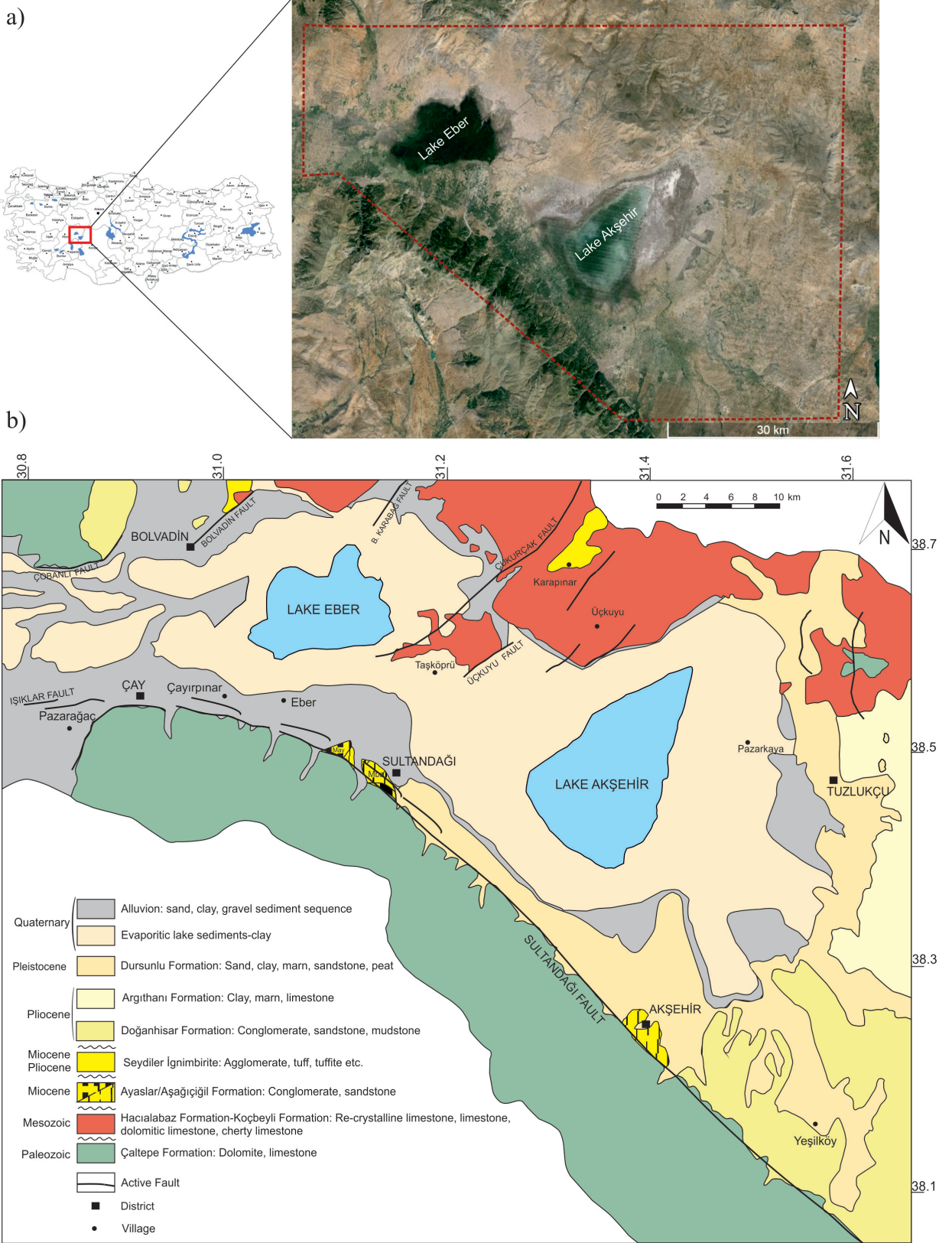


Figure 1. a) Location of the study area shown with Google Earth image, b) Geological map of the study area (lithology adapted from Umut et al., 1987; Kazancı et al., 1994; faults adapted from Emre et al., 2013; background modified from earth.google.com).

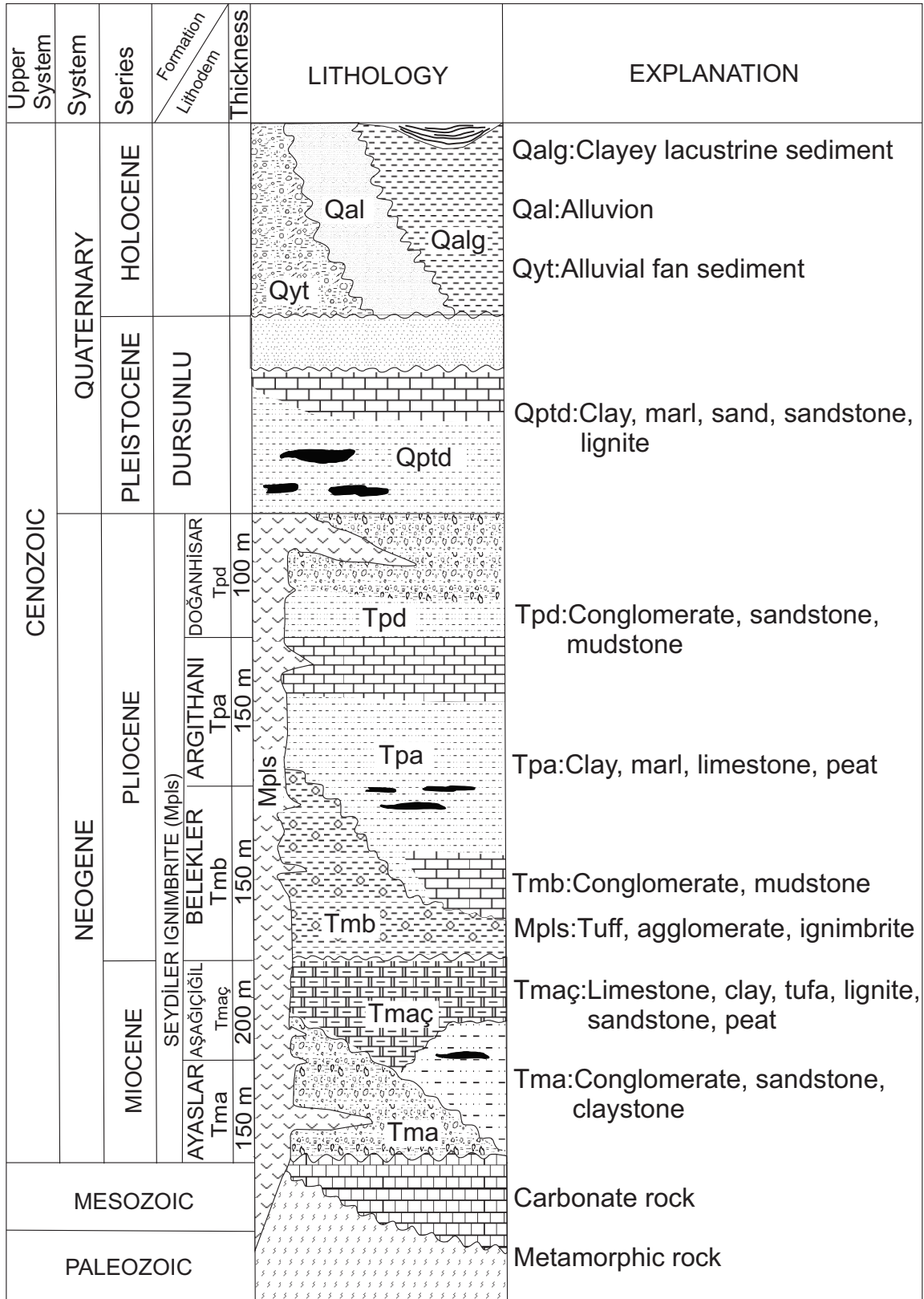


Figure 2. Generalized section of the study area, modified from Umut et al. (1987) and Kazancı et al. (1994).

county, Afyon Province, two 12 m. drillholes were drilled (SK-1 and SK-2) (Figure 3). The samples were classified by sediment type and lithology and were separated into facies and facies associations.

The studied deposits were divided into ten sedimentary facies, which were further grouped into three facies associations (Table 1). Classification of facies is based on the descriptive terminologies of Miall (1996) and Alçiçek et al. (2007). In interpreting the facies, the following references were used: Collinson (1978), Miall (1978), Rust (1978), Morison and Hein (1987), Nemeç (1990), Besly and Collinson (1991), Miall (1996), Schubel and Lowenstein (1997), Kazancı et al. (1999), Dunagan and Turner (2004), Ilgar and Nemeç (2005), Eren (2006), Alçiçek et al. (2007).

3.2. Laboratory studies

Fifty-eight samples systematically collected from 15 measured stratigraphic sections and 79 samples taken from 2 drilling cores cut into 20 cm slices were subjected to dry and wet sieve analyses at the General Geology Laboratory of Çanakkale Onsekiz Mart University, Department of Geological Engineering. Paleontological analyses were performed on a total of 12,531 fossil shells separated from their sediments by sieve analyses. Fossil shells were examined with an OLYMPUS SZ/PT-SZ60

stereomicroscope and identified to the species level with reference to the literature. Taxonomic identification of mollusks was carried out using the publications of the following researchers: Wenz (1938–1944); Kapan et al. (2018), Neubauer et al. (2018), Yıldırım et al. (2023); WoRMS¹.

For mineralogical analysis, 17 samples (2 silty-clay, 1 sandy-clay, 1 caliche, and 13 clay) were selected from critical levels where sharp lithological changes were thought to indicate environmental change. Analysis of these samples were performed using quantitative analysis with a PANalytical Empyrean X-ray diffractometer, operating at $\lambda = 1.54\text{Å}$, 45 kV, and 40 mA at the Çanakkale Onsekiz Mart University Science and Technology Applied Research Center (ÇOBİLTUM). The paleoclimatic conditions of the investigated area have been evaluated using data obtained from the analyses, including the presence of minerals such as kaolinite, illite, halite, and gypsum.

4. Results

4.1. Sedimentary facies and facies association

The Akarçay Basin was divided into three separate facies associations according to the depositional environment

¹WoRMS (2020). World Register of Marine Species [online]. Website <https://www.marinespecies.org> [accessed 05 May, 2024].

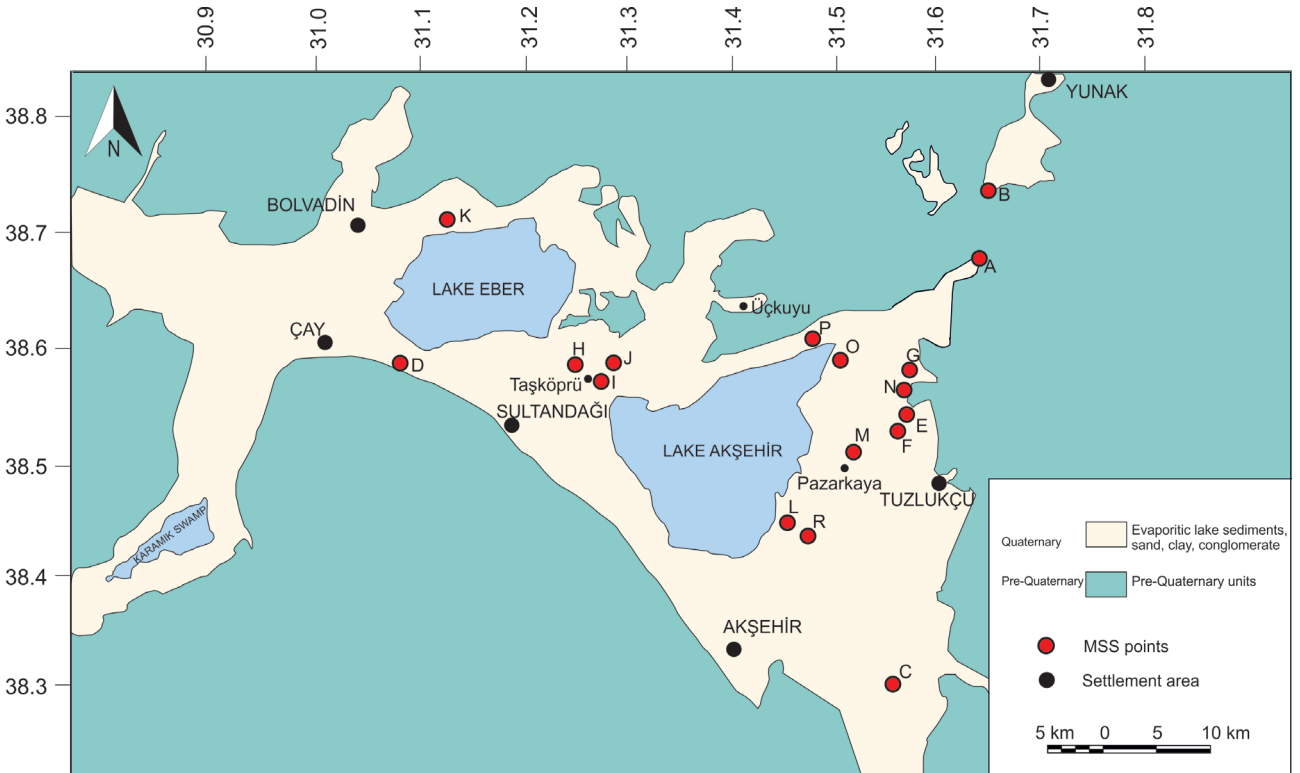


Figure 3. Map of measured stratigraphic sections around Akşehir and Eber lakes (A: Ayrıtepe, B: Kuzören, C: Yeşilköy, D: Çayırpınar, E: Tuzlukçu sand field, F: Mevlütü south, G: Mevlütü turn, H: Taşköprü sand field, I: Taşköprü SK-2, J: Taşköprü SK-1, K: Eber Lake, L: Ortaköy streamside, M: Pazarkaya, N: Lake Akşehir channel, P: Lake Akşehir level, R: Ortaköy).

Table 1. Description and interpretation of the sedimentary facies and facies associations in the investigated area (Collinson, 1978; Miall, 1978; Rust, 1978; Morison and Hein, 1987; Nemeç, 1990; Besly and Collinson, 1991; Miall, 1996; Schubel and Lowenstein, 1997; Kazancı et al., 1999; Dunagan and Turner, 2004; Eren, 2006; Alçiçek et al., 2007)

FACIES	DESCRIPTION	INTERPRETATION
Gm Matrix-supported gravel	Moderate gravel-block grains supported by a matrix, yellowish-brown matrix consisting of mud and muddy sand, reddish-brown pebble, moderately sorted to well-sorted, angular to subangular, ungraded or poorly graded, lamination thickness ranges from 0.5 to 5 m, 100 to 200 m in lateral extent, alternating with Fl and Lm	Debris flow deposits (Nemeç, 1990; Miall, 1996)
Gl Laminated gravel	Laminated reddish-brown pebbles, contains low-angle cross-bedded coarse limestone clasts, poor-sorted to moderately sorted, subangular to rounded, moderate gravel size, lamination thickness ranges from 10 to 15 cm, 800 to 900 m in lateral extent, alternating with Lm and Sh	Coarse-grained gravel or fluvial deposits during inundations with excessive grain density (Morison and Hein, 1987). Braided channels and bars in alluvial systems (Miall, 1996)
Fl Mud	Reddish-brown mud cracks, bed thickness ranges from 2 to 5 m, tens of meters in lateral extent, alternating with Gm and Lm	Over embankment flood plain sediments and sediments on mud flats (Miall, 1996)
Lm Caliche	Massive structured caliche, white, cream and red colors, layer thickness ranges from 40 to 70 cm, 50 to 100 m in lateral extent, alternating with Gm and Fl	Sediments in arid and semiarid climate conditions and secondary CaCO ₃ accumulations within soils (Eren, 2006)
Sp Planar cross-bedded sand	Contains moderate to fine sand grains, with few pebbles, yellowish-brown colored sand, moderately sorted and angular gravels within the sand, very low-angle (~5°) cross beds, tens of meters in lateral extent, alternating with Sm	Progression of the bed load in lateral direction (Rust, 1978)
Sh Horizontal-bedded sand	Yellowish-brown sand containing gravel, bed thickness ranges from 1 to 1.5 m, normal graded, several tens of meters in lateral extent, alternating with Gl	High speed flows at shallow depths (Collinson, 1978). Stream flows forming with progression of the bed load in lateral direction (Rust, 1978)
Sm Massive sand	Fine gravel with moderate to very coarse grain size and brownish-yellow sand; massive structure. Lateral extent ranges from 50 to 100 m, alternating with Sp, Fs _c and Fs _o .	Subaerial hyperconcentrated flows or subaqueous high-density turbidity currents (Miall, 1996; Alçiçek et al., 2007)
Fs _c Silty clay	Beige gray and green colored clay, contains small lens-shaped structures, containing gastropod and bivalve shells, bed thickness ranges from 8 to 10 m, 40–50 km in lateral extent, alternating with Fs _o and Ev	Low energy lacustrine environments, representing periods of reduced or stagnant rainfall (Miall, 1978; Dunagan and Turner, 2004)
Fs _o Organic-rich clay	Dark gray organic clay, many small-sized moderately rounded clasts, containing gastropod and bivalve shells, bed thickness ranges from 4.5 to 5.0 m, 10–15 km in lateral extent, alternating with Sm and Fs _c	Swamp or shoreline plains with shallow water deposits (Besly and Collinson, 1991; Kazancı et al., 1999). Low energy deep lacustrine and anoxic environments (Dunagan and Turner, 2004; Alçiçek et al., 2007)
Ev Evaporite	Contains beige-white colored bands, band thickness ranges from 10 to 20 cm, 10–20 m in lateral extent, alternating with Fs _o	Permanent saline water environment (Schubel and Lowenstein, 1997; Alçiçek et al., 2007)

(Figure 4). These are: 1) the alluvial fan and fluvial facies association (Afs); 2) the lakeshore facies association (Ls); and 3) the lake center facies association (Lc). The Sultandağı Fault began its tectonic activity in the Early Messinian (Tiryakioğlu et al., 2015). In such high-energy environments, facies containing large gravel and block lithologies are present (Miall, 1996; Alçiçek et al., 2015). A transition from high-energy environments at the basin margins to low-energy fluvial environments in the basin interior shows the presence of gravel and block lithologies (Miall, 1996; Ilgar et al., 2022). In this study, facies consisting of these lithologies with coarse grain sizes were interpreted as an alluvial fan and fluvial facies assemblage (Afs). In low-energy environments, where precipitation decreases and sedimentation is relatively reduced, accumulations dominated by fine gravel and sand lithologies can occur (Miall, 1978; Alçiçek et al., 2007). In the basin, facies containing lithologies with fine gravel locally within a fine to medium sand matrix have been referred to as lakeshore facies assemblage (Ls). It has

been stated that areas with a semiarid, dry climate and low-energy environments are represented by lithologies with clay-sand grain sizes (Miall, 1978; Beuning et al., 1997). Facies composed of silt, clay, and occasionally very fine sand lithologies are referred to as lake center facies assemblage (Lc) in this research (Figure 5) (Table 1).

4.1.1. Alluvial fan and fluvial facies associations (Afs)

The Afs association, observed in the A, B, C, and D sections, includes the matrix-supported gravel facies (Gm), laminated gravel facies (Gl), mud facies (Fl), and caliche facies (Lm). It was observed that it has a spread of approximately 65 km and a thickness of 5 m around Eber and Akşehir lakes. The alluvial fan and fluvial facies association (Afs) comprises facies formed from intercalations of angular and abundant gravel lithologies with a sand matrix and coarse-grained horizontally laminated sand lithologies (Figure 6). Alluvial fan and fluvial environments are generally high-energy and dominantly contain poorly rounded and coarse-grained material (Miall, 1996; Alçiçek et al., 2015).

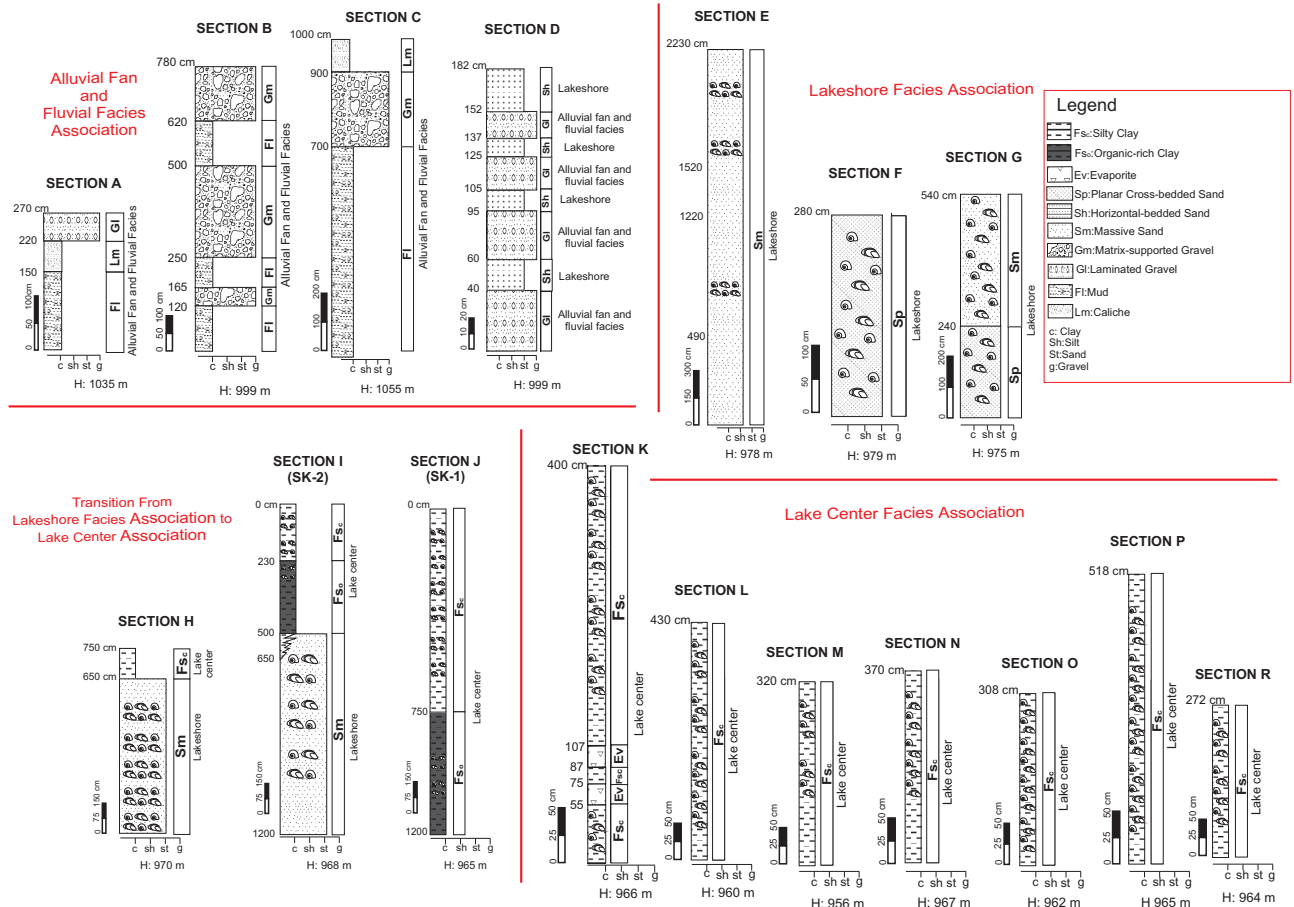


Figure 4. Sedimentological measured sections and drilling logs (SK-1 and SK-2) with facies descriptions and facies associations of the investigated area.

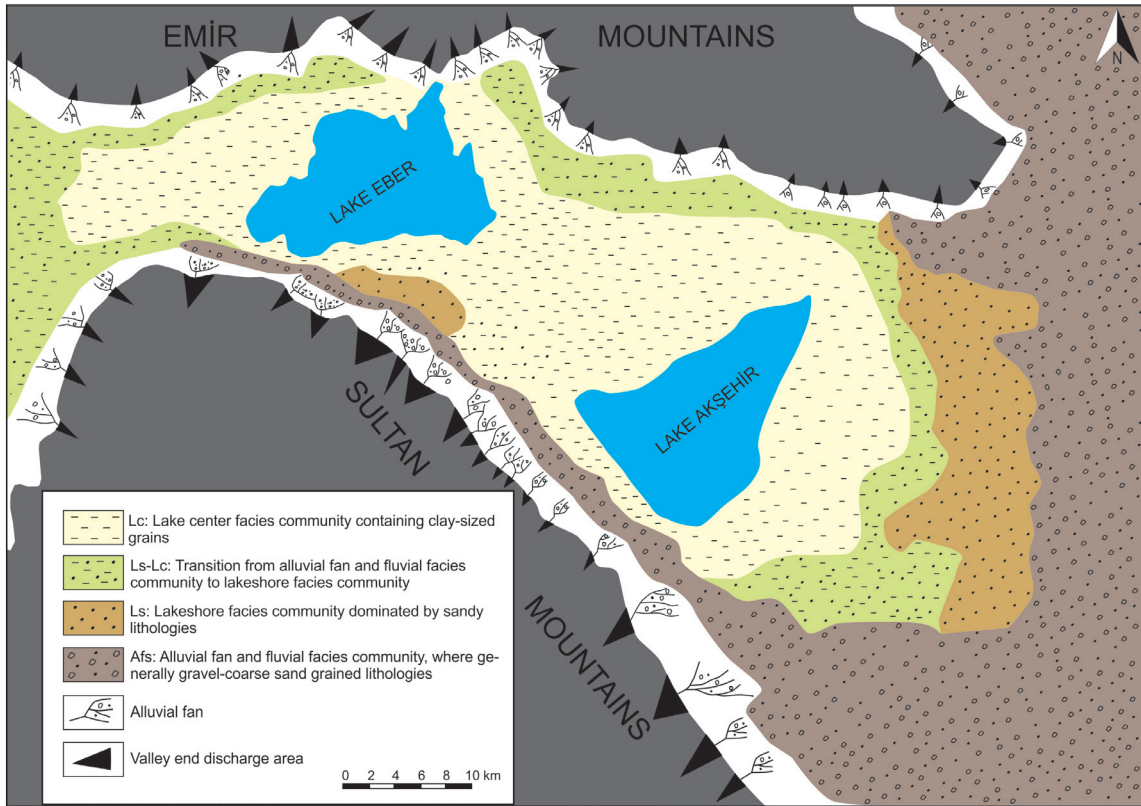


Figure 5. Schematic model showing facies associations in the study area (areal distribution of facies associations, schematic depositional environments).

4.1.2. Lakeshore facies association (Ls)

This facies association includes the planar cross-bedded sand facies (Sp), horizontally bedded sand facies (Sh), and the massive sand facies (Sm). It was observed in the field that it has a spread of approximately 10 km and a thickness of 22 m in the southeast of Lake Eber. Moving toward the lake center, there is a transition from angular gravel and coarse sandy lithologies to those with lithologies with moderate sand-fine gravel grain size (Miall, 1996; Ilgar et al., 2022). This association represents the lakeshore facies association (Figure 6). During the deposition of this facies association, the energy of sedimentary processes was lower compared to the period when alluvial fan and fluvial facies associations developed (Miall, 1996; Alçiçek et al., 2015).

4.1.3. Lake center facies association (Lc)

This association comprises silty clay (Fs₁), organic-rich clay (Fs₂), and evaporite (Ev) facies. This facies community, which can reach a thickness of 5 m and spread over approximately 65 km, is located in the close vicinity of Akşehir and Eber lakes. It dominantly contains lithologies with clay-silt grain size (Figure 6) and transitions to the lakeshore facies association, which comprise moderate sand-fine gravel grain sizes moving away from the lake (Miall, 1978; Beuning et al., 1997).

4.2. Basin evolution based on sedimentary facies

The first facies in the environment is the matrix-supported gravel facies (Gm). The increase in matrix proportions toward the top of the sequence, lateral arrangement of moderately sorted gravel, and the intercalation of load structures with clay, sand, and mud facies shows deposition during underwater debris flows (Miall, 1996; Ilgar and Nemec, 2005). Subsequently, laminated gravel facies (Gl) was deposited as longitudinal bars or gravel spreads during floods with extremely high grain density (Morison and Hein, 1987; Miall, 1996). The mud facies (Fl) formed in fluvial-swamp areas where flooding reduced and suspended sedimentation was greater (Miall, 1996). This association, ending with the caliche facies (Lm), reflects the formation stage of the lake (Miall, 1978; Atabey et al., 1998).

The Sp facies, containing angular clasts in moderate- to fine-grained sand without fossils, and the Sp facies, containing gravel in fine-grained sand with lateral bedding, likely formed from the lateral progression of the bed load (Rust, 1978). The moderate- to very coarse-grained fine gravel and fossil sand facies likely developed from excessively intensified flows. It is thought that the Sh facies is a product of braided rivers transitioning into alluvial

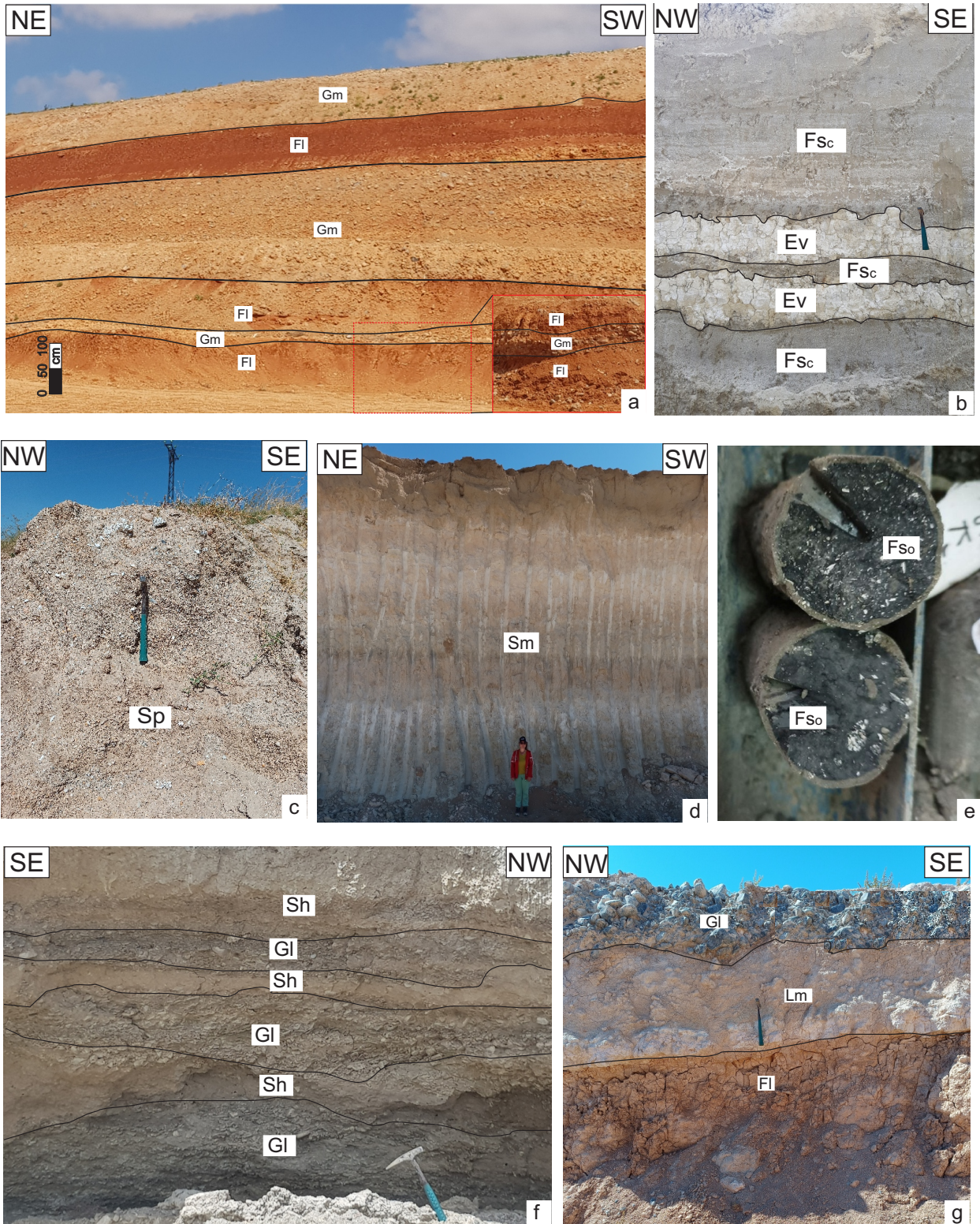


Figure 6. a. Outcrop photograph of the section B (Gm and Fl from the AFS facies association), b. Facies found at the section K (F_{sc} and Ev from the LC facies association), c. Image from the section G (Sp from the LS facies association), d. Outcrop photograph from the section E (Sm from the LS facies association), e. Fossil shells observed in the drill core from section J (SK-1 drillhole) (F_{s0} from LC facies association), f. Outcrop photograph from section D (Sh from LS facies association and Gl from AFS facies association), g. AFS facies association observed within the section A.

fans. The Sm facies, developed from excessively intensified flows and rapid deposition, represents a transitional phase between the alluvial fan and fluvial facies association and the lake center facies association. This facies association corresponds to the expansion stage when the lake spread in shallow form.

The facies Fs₃, defined by lithologies containing clay and occasionally silt, indicates a low energy lacustrine environment with little rainfall (Miall, 1978; Dunagan and Turner, 2004). This level contains *Valvata piscinalis* (Müller, 1774) and *Laevicaspia caspia* (Eichwald, 1838) from the Gastropoda class and *Dreissena iconica* (Schütt, 1991) and *D. polymorpha* (Pallas, 1771) from the Bivalvia class, indicating the lake was fed by rivers with abundant *Valvata piscinalis*. The clays containing organic material (facies Fs₀) is interpreted as shallow water deposition associated with swamp or shore plain environments (Besly and Collinson, 1991; Kazancı et al., 1999). The presence of abundant *Laevicaspia caspia*, a species living in mesohaline environments, suggests deposition during a dry climate. The Ev facies observed at this level, with fine lamination and no fossils, indicates long-term saline water conditions (Alçiçek et al., 2007). The lake center facies association reflects a stage of significantly reduced sedimentary processes, with the lake becoming shallower and starting to dry.

4.3. Clay mineralogy and paleontological data

The analysis results of 17 samples considered to be critical in terms of climate change are shown in Table 2. Three samples were chosen from the section C (no. 15), section A (no. 16), and section B (no. 17) belonging to the alluvial fan and fluvial facies association. Two samples were taken from the section P (nos. 2 and 7), one from the section M (no. 4), two from the section K (nos. 8 and 9), and eight samples from the section J (SK-1) (nos. 1, 3, 5, 6, 10, 11, 12, and 13), and the section I (SK-2) (no. 14) drill cores belonging to the lake center facies association, and one sample from the section I (SK-2) belonging to the lakeshore facies association. The minerals identified in the study area and their degrees of abundance are presented in Table 2. The whole-rock composition of samples analyzed using X-ray diffraction identified the clay minerals illite (14.80%–48.40%), mixed layered illite-smectite (4.00%–26.20%), kaolinite (0.20%–40.40%), montmorillonite (0.70%–37.30%), vermiculite (0.20%–8.00%), albite (13.40%–25.50%), and anorthite (14.90%–22.30%). The silicate group minerals include cristobalite (1.70%) and quartz (2.20%–47.70%). The carbonate group minerals identified are calcite (6.80%–55.90%) and aragonite (2.90%–33.20%) and the evaporite minerals as halite (1.20%) and gypsum (8.10%). In the clay group, illite and kaolinite were the dominant minerals. The Akarçay Basin, kaolinite amounts vary from 0.20% to 40.40%, with a mean

value of 10.56%. Illite percentages range from 14.80% to 48.40%, with a mean value of 29.20% (Figure 7).

The species *Dreissena iconica*, *D. polymorpha*, *Valvata piscinalis*, and *Laevicaspia caspia* were identified in the Sp, Sh, and Sm facies of the lakeshore sediments and in the Fs_c and Fs₀ facies of the lake center sediments (Table 3). A total of 2633 samples from *Dreissena iconica*, 2702 *D. polymorpha*, 1025 *Valvata piscinalis*, and 1035 *Laevicaspia caspia* were identified.

5. Discussion

5.1. Paleoenvironmental and paleoclimatic implications

Clay minerals are closely related to the physicochemical conditions of the sediments in which they have been found. The combination of primary minerals with secondary products, reflecting degrees of alteration, can indicate local climate and plant cover (Frouin et al., 2013).

The most commonly used clay minerals for correlating regional and global paleoclimate records are smectite, kaolinite, illite, and chlorite (Singer, 1980, 1984; Raucsik and Varga, 2008). An excess of illite minerals suggests cold and dry climate conditions, while increased smectite proportions indicate tropical–semiarid climate conditions (Singer, 1980, 1984; Chamley, 1989; Chen et al., 2014; Alexandrine et al., 2019). The sharp decrease in smectite is used to determine the origin of weathered sedimentary rocks affected by neotectonic collapse (Chen et al., 2014). An increase in smectite often results in a relative reduction in kaolinite minerals (Liu et al., 2005). Smectite, observed as mixed-layered smectite-illite and smectite-chlorite, can form through the alteration of volcanic or volcanoclastic material or degradation due to climatic effects in rocks with an authigenic source (Chamley, 1989; Roeser et al., 2012). The decrease in contribution from local volcanic rocks leads to a decrease in smectite (Chen et al., 2014). Mixed-layered laminated illite-smectite minerals are considered main indicators of temperate climate. Illite minerals help differentiate cold-dry periods associated with glaciation from hot-humid interglacial periods. Kaolinite clays are typically found in hot and wet tropical climates (Liu et al., 2020). The increase in kaolinite characterizes the traces of a transgressive system under hot and wet paleoclimatic conditions (Holanda et al., 2019). Therefore, changes in illite, smectite, and kaolinite ratios can be used to monitor paleoclimatic fluctuations coinciding with global climate change (Chen et al., 2014). Sediments subjected to intense chemical weathering, influenced by climate events, are rich in kaolinite (Singer, 1984). A kaolinite/illite ratio of 0 indicates a hot and dry climate; if the ratio is <1, it represents a transition from a hot and subtropical climate to a semiarid climate; and if the ratio is >1, it indicates rainy climate conditions (Raucsik and Varga, 2008). The presence of illite, along with mixed-layered illite-smectite,

Table 2. Percentage mineral compositions of lacustrine sediments from the Akarçay Basin.

SAMPLE NUMBER	MINERAL COMPOSITION (%)														
	Facies	Kaolinite	Montmorillonite	Vermiculite	Anorthite	Illite	Illite-Smectite	Albite	Cristobalite	Calcite	Quartz	Aragonite	Halite	Gypsum	Kaolinite/illite
1	Lc-1			1.1			26.2	23.6		12.1	36.9				0
2	Lc-1	0.2		0.4		15.7				55.9	24.4	3.4			0.01
3	Lc-1	11.5	1.4	1		40.2				8.9	26.9	10.1			0.29
4	Lc-1	40.4	37.3							20.1	2.2				-
5	Lc-1	6.1	0.8	0.7		36.7				17.7	13	25.1			0.17
6	Lc-1	8.4		1.1		25.4				14.6	17.2	33.2			0.33
7	Lc-1	4.2		0.2	14.9		4			34.3	39.4	2.9			-
8	Lc-3			0.5		15.7	12.2		1.7	21	40.8			8.1	0
9	Lc-1			0.5		23		25.5		24.5	26.5				0
10	Lc-2	8.1		0.7		29.2				19.4	31	11.6			0.28
11	Lc-2	9.3		1.1		38				21.8	29.8				0.24
12	Lc-2	8.5		0.7		48.4				23.9	18.6				0.18
13	Lc-2	6.9		0.7		29.4				26.7	29.5	6.9			0.23
14	Lc-3			0.9		17.3		13.4		6.8	47.7	12.7	1.2		0
15	Afs-1			8	22.3	42.2					27.5				0
16	Afs-4	3.1	0.7	0.7		32.8				47.5	15.1				0.09
17	Afs-3	20	20			14.8				42.3	2.9				1.36
MAXIMUM		40.40	37.30	8.00	22.30	48.40	26.20	25.50	1.70	55.90	47.70	33.20	1.20	8.10	1.36
MINIMUM		0.20	0.70	0.20	14.90	14.80	4.00	13.40	1.70	6.80	2.20	2.90	1.20	8.10	0.00
MEAN		10.56	12.04	1.22	18.60	29.20	8.10	20.83	1.70	24.84	25.26	13.24	1.20	8.10	0.23
TOTAL		126.7	60.2	18.3	37.2	408.8	42.2	62.5	1.7	397.5	429.4	105.9	1.2	8.1	3.18

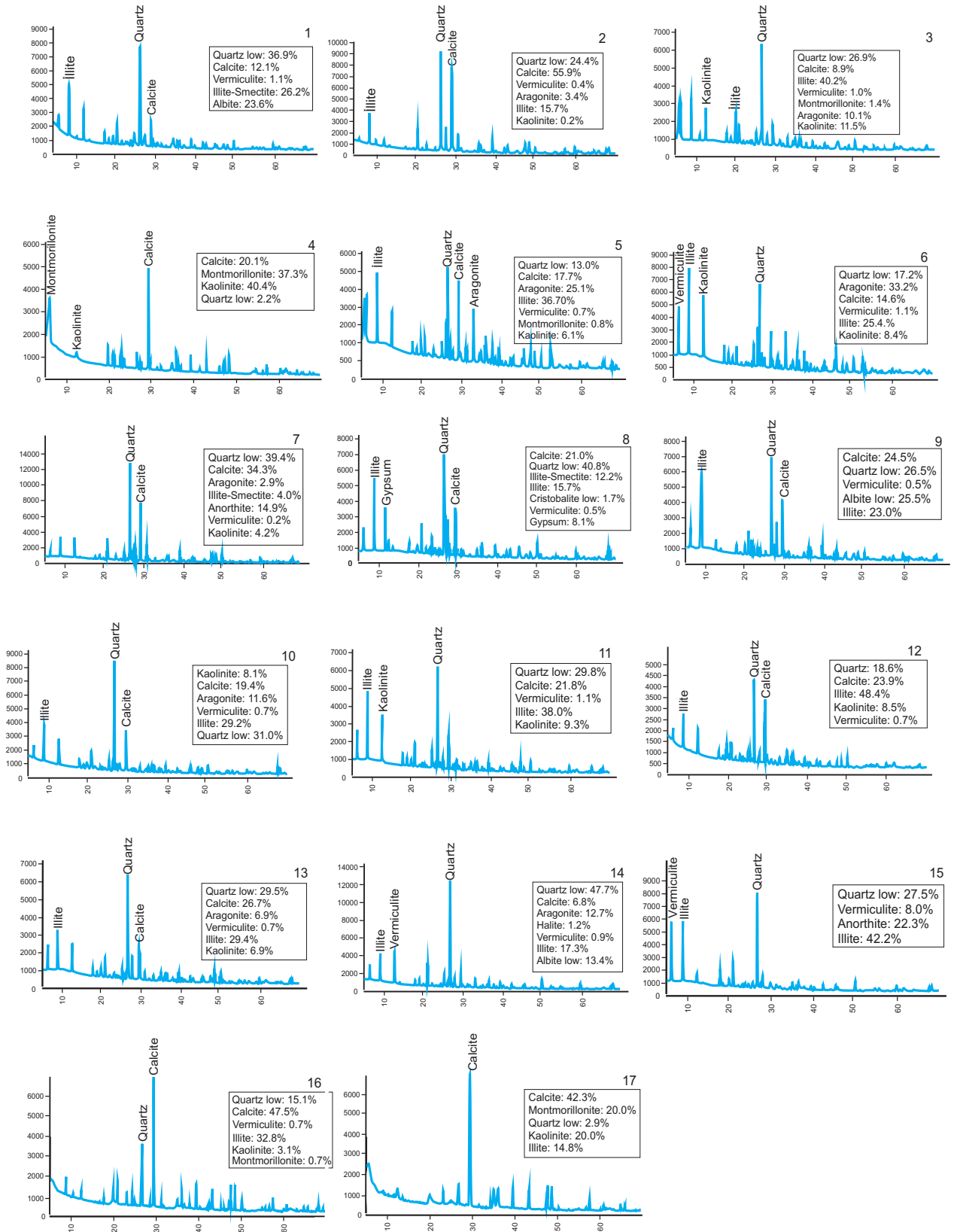


Figure 7. XRD results from the Akarçay Basin.

Table 3. Mollusk species observed in facies in the study area.

Facies association	Facies	Mollusks
Lake center (Lc)	F _s Silty clay F _s Organic-rich clay	<i>Dreissena iconica</i> Schütt, 1991 <i>Dreissena polymorpha</i> (Pallas, 1771) <i>Valvata piscinalis</i> (Müller, 1774) <i>Laevicaspia caspia</i> (Eichwald, 1838)
Lakeshore (Ls)	Sh Laminated sand Sm Massive sand	<i>Dreissena iconica</i> Schütt, 1991 <i>Dreissena polymorpha</i> (Pallas, 1771) <i>Valvata piscinalis</i> (Müller, 1774) <i>Laevicaspia caspia</i> (Eichwald, 1838)

albite, and anorthite, indicates that illite in the study area formed due to physical weathering (Yakupoğlu and Kazak Taştan, 2022).

As a result, smectite mineral is used to determine the source rock of sediments (Singer, 1980; 1984, Chamley, 1989; Deconinck et al., 2013; Chen et al., 2014), smectite, illite and kaolinite minerals are used in paleoclimatic studies (Liu et al., 2003; 2005, 2017; Yin et al., 2018; Holanda et al., 2019; Yakupoğlu and Kazak Taştan, 2022; Jamaluddin et al., 2023; Perri et al., 2024), smectite mineral is used to determine the effect of tectonism (Huyghe et al., 2011; Chen et al., 2014), illite (cold-arid climate), smectite (warm climate), and kaolinite (warm and humid climate) minerals are used to determine glacial-interglacial global climate changes (Varga et al., 2011; Albuquerque et al., 2016).

In this section of the study, the paleoclimatic conditions of the investigated area have been evaluated using data obtained from the analyses, including the presence of minerals, such as kaolinite, illite, halite, and gypsum, and paleontological analyses.

The dominant minerals throughout the basin were illite, kaolinite, calcite, and quartz, suggesting that the lake was consistently fed by the same drainage system. Illite was absent in samples no. 1 (section H), 4 (section M), and 7 (section P) in the Akarçay Basin (Table 2), while the percentage of kaolinite was high. The absence of illite and the high percentage of kaolinite indicate that these levels were deposited in relatively warm and humid climatic conditions. In samples no. 9, 10, 11, 12, and 14 (Table 2), the illite percentage increased, while in samples no. 8 and 14, gypsum and halite were detected in evaporite sediments, and the kaolinite percentage decreased.

This suggests that arid climate conditions prevailed when these levels were deposited. Singer (1984) emphasized the importance of an interdisciplinary approach to interpreting paleoclimate, stressing the need to correlate paleoclimate data obtained from clay minerals with data derived from microfossils and oxygen isotopes.

In this paper, mollusk fauna were used to obtain paleoclimatic and paleoenvironmental data. *Dreissena iconica* and *D. polymorpha* are endemic to the lake and indicate calm, clear freshwater conditions. The presence of

Valvata piscinalis, which inhabits rivers, suggests that the lake was fed by freshwater. The abundance of *Laevicaspia caspia*, a species that inhabits brackish water, suggests that the climate was hot, the lake's salinity increased, and shallow conditions prevailed.

The combined sedimentological, mineralogical, and paleontological data indicate that the paleoecological features of the basin experienced periodic variations between dry and wet climatic periods (Figure 8). The increased presence of kaolinite and the numerical rise of *Valvata piscinalis*, which inhabits rivers, suggest that humid climate conditions dominated during the deposition of the F_s facies. High illite percentages in samples containing *Laevicaspia caspia*, which lives in mesohaline waters, indicate a transition from humid to arid climate conditions, corresponding lithologically to the F_s facies.

The presence of evaporite minerals such as halite and gypsum in lithologies equivalent to the Ev facies, with a kaolinite/illite ratio of 0, shows the dominance of hot and arid climates in the basin during these times. The increase in illite percentages in samples from the Gm and Lm facies, which contain caliche, indicates a dry climate. At levels equivalent to the Fl facies, when the lake began to spread, the relative increase in kaolinite suggests a humid climate.

5.2. Comparison with other localities in SW-Anatolia

In this section of the study, paleoclimatic and paleoenvironmental data obtained from the Akarçay Basin were compared with data obtained from other sedimentary basins in Southwestern Anatolia (Figure 9).

The Akarçay Basin, which was formed under the influence of the Isparta Angle, opened in the Miocene and began to accumulate sediments (İleri, 2002). In the Karacasu Basin in SW Anatolia, alluvial fans and fluvial facies began to accumulate in the late Miocene, and arid climate conditions dominated the basin during this period (Alçiçek and Jiménez-Moreno, 2013). Paleoclimatic studies conducted in the Çal Basin, which was deposited during the same period, revealed the presence of a warm, semiarid to arid climate and a grass-dominated steppe ecosystem during the late Tortonian (late Miocene) (Alçiçek et al., 2012). In the Burdur Basin, which was deposited simultaneously with the Çal Basin, terrestrial

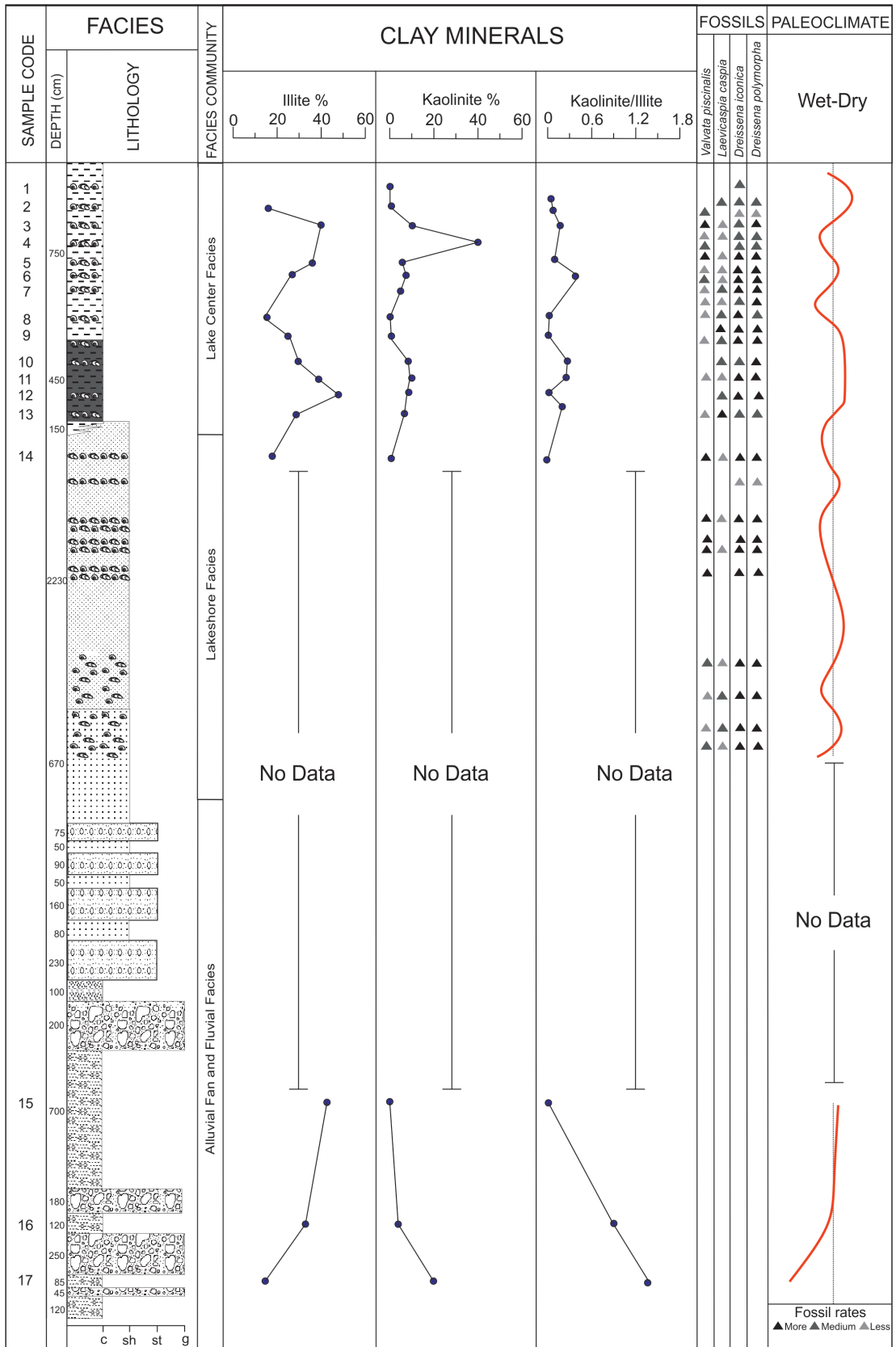


Figure 8. Climate periods linked to illite-kaolinite and mollusk fauna in the Akarçay Basin.

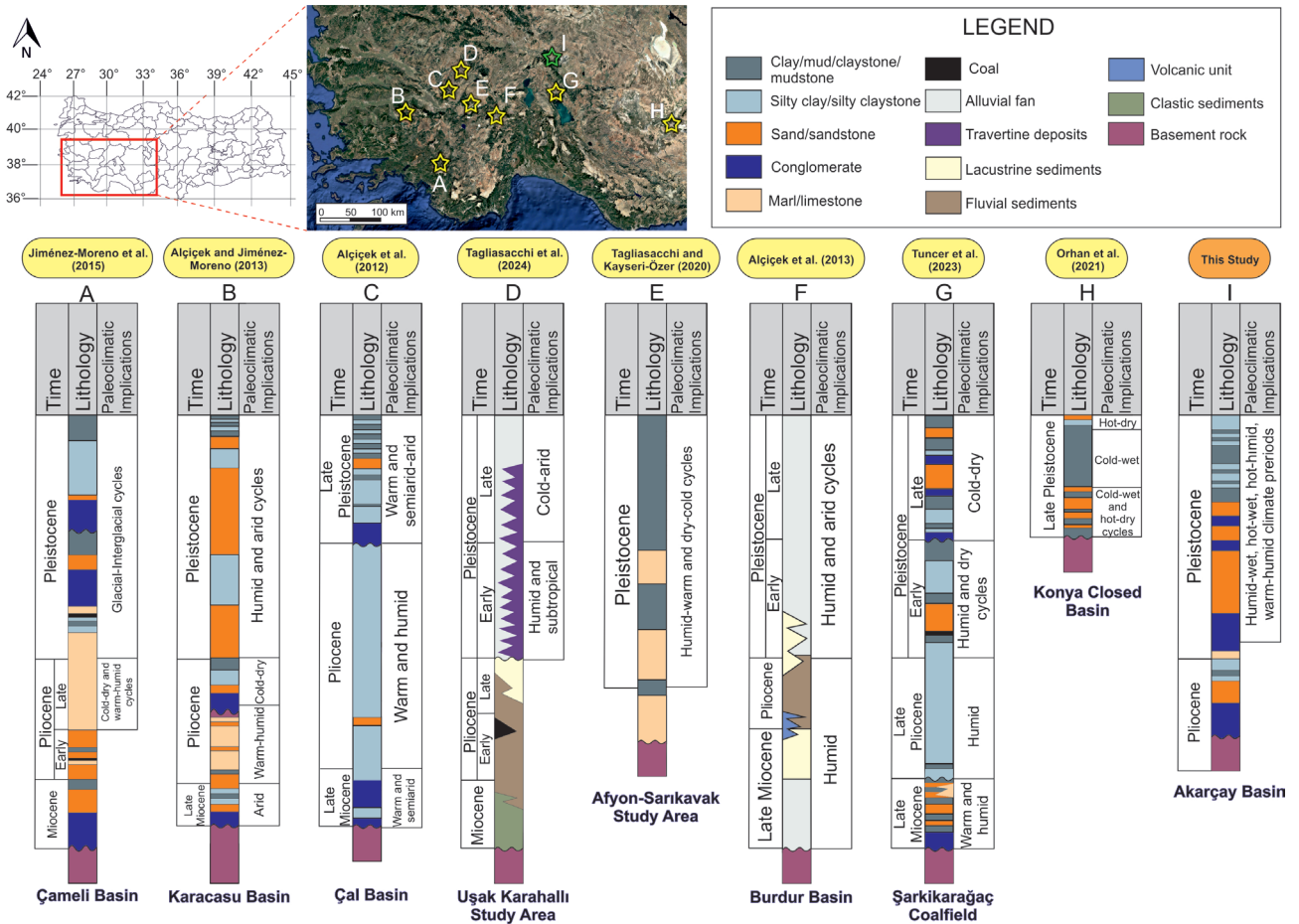


Figure 9. Generalized stratigraphic sections and paleoclimatic data from SW Anatolian basins (Alçiçek et al., 2012; Alçiçek and Jiménez-Moreno, 2013; Alçiçek et al., 2013; Jiménez-Moreno et al., 2015; Tagliasacchi and Kayseri-Özer, 2020; Orhan et al., 2021; Tuncer et al., 2023; Tagliasacchi et al., 2024)

sedimentation began in the late Miocene, characterized by alluvial fans, fluvial, and palustrine depositional environments, indicating humid climatic conditions (Alçiçek et al., 2013).

In the Early Pliocene, a new rifting occurred in Southwestern Anatolia due to the effect of the regional extension regime, and in this period, humid climate conditions were observed in the Burdur Basin (Alçiçek et al., 2013). During the Pliocene period, following the marine floods in the Mediterranean that ended the Messinian salinity crisis, a warm and humid climate with large lakes and savanna-type open habitats developed in the Çal Basin (Alçiçek et al., 2012).

In the late Pliocene, sediments in the Akarçay Basin were uplifted and eroded due to the effect of faults bordering the basin (İleri, 2002). During this period, coarse-grained sedimentary rocks were deposited in the basin due to the effect of weathering (Kazancı et al., 1994), this situation may be related to hot and dry climate conditions, as well as strong water or wind currents in the basin. During the late

Pliocene period, the warm and humid climate observed in the Çameli Basin enabled the development of large forests and lakes. The alternation between *Artemisia* steppe (cold and dry) and forest vegetation (warm and humid) in the Karacasu Basin indicates that there are transitions between cold and dry climate periods and warm and humid climate periods (Jiménez-Moreno et al., 2015).

Alçiçek and Jiménez-Moreno (2013) stated that the Karacasu Basin was generally dominated by a warm and humid climate during the Pliocene, but they associated the abundance of *Artemisia* steppe (indicating cold and dry periods) at the end of the Pliocene with glacial-interglacial cycles in the Northern Hemisphere and concluded that there were cold-dry climate conditions in the late Pliocene. During the Pliocene-Pleistocene transition, the decrease in tree pollen and the increase in pollen of steppe plants in the Çal Basin and the presence of coarse-grained sedimentary rocks were associated with arid and cold climate conditions (Alçiçek et al., 2012). In our study, it is determined that arid climate conditions

were effective during the Pliocene-Pleistocene transition in the Akarçay Basin due to the observation of caliche type facies. In the Early Pleistocene, it was determined that arid conditions dominated in Afyon (Sarıkavak) based on the dating of tufas in the region and pollen analyses, but the increase in gymnosperm pollen indicated a short humid and rainy phase (Tagliasacchi and Kayseri-Özer, 2020). In the Çal Basin, the strong positive correlation of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotope ratios revealed that fluvial systems became dominant again, along with a semiarid to arid climate (Alçiçek et al., 2012). In the Middle Pleistocene, it was observed that the climate in the Uşak-Karahallı region changed from humid and subtropical conditions to cooling and aridity, and then returned to a temperate and humid phase (Tagliasacchi et al., 2024). During the Late Pleistocene, the Çal Basin was dominated by an open steppe ecosystem and seasonal fluidity was observed due to snowmelt originating from the surrounding highlands (Alçiçek et al., 2012). In the Isparta Şarkikaraağaç coal field, it was stated that the warm and humid climate of the Early Pliocene turned into cool conditions during the Pleistocene and the lake level dropped towards the Late Pleistocene (Tuncer et al., 2023). Orhan et al. (2021) interpreted the climate changes in the Konya Closed Basin over the last 50,000 years by analyzing the geochemical properties of sediments. They revealed that there were four warm and four cold periods in the basin, and these were consistent with the warm climate of Dansgaard-Oeschger (D/O) events (D/O 2-12) and the cold climate of Heinrich events (H 2-5) during the last glacial periods. In this study, paleoclimatic and paleoenvironmental interpretations of the Akarçay Basin from the Pleistocene to the present, based on paleontological findings and X-ray diffraction (XRD) data, revealed the existence of wet-dry climate transitions. Based on the paleoecological characteristics of the lake's endemic species—*Dreissena iconica* and *D. polymorpha* representing freshwater environments, *Valvata piscinalis* representing fluvial environments, and *Laevicaspia caspia* representing brackish water environment—it can be said that the paleoclimatic conditions in the basin shifted from wet to dry periods.

6. Conclusion

The paleoenvironmental, paleoclimatic, and paleogeographic evolution of the ancient lake in the Akarçay Basin was interpreted using stratigraphic, sedimentological, paleontological analyses, and mineralogical data obtained from the Pleistocene sediments.

1) The basin was divided into three different facies associations: alluvial fan and fluvial (Afs), lakeshore (Ls), and lake center (Lc) facies associations according to depositional environments. These depositional environments correspond to different periods in the development stages of the lake: (i) In the initial stage of

lake formation, during the Pliocene, alluvial fans were deposited under the influence of tectonism and a humid climate, moving inward from the edges of the basin, transitioning from high-energy facies to low-energy facies. (ii) In the expansion stage when the lake spread shallowly in the Pleistocene, instead of alluvial fan sediments spreading into the basin, fine-grained sediments were deposited in a lakeshore environment. (iii) In the stage when the lake began to dry at the end of the Pleistocene, with the further decrease in energy in the lake center depositional environment, limited clastic deposition occurred, indicating that the lake was shallow.

2) Mineralogical analysis revealed illite and kaolinite as the dominant clay minerals. Illite was absent in samples with high kaolinite percentages from section H, level 4 in section M, and level 7 in section P (Table 2), suggesting that these layers accumulated under relatively warm and humid climatic conditions in those parts of the basin.

3) It was concluded that dry-wet period transitions were observed in the periods when rainfall was abundant in the basin, with the findings of *Dreissena iconica* and *D. polymorpha* representing freshwater environments, *Valvata piscinalis* representing fluvial environments, and *Laevicaspia caspia* representing brackish water environments.

4) Increased *Dreissena iconica*, *D. polymorpha*, and *Valvata piscinalis* in kaolinite-rich sediments suggest wet climate, while the presence of *Laevicaspia caspia* and minerals like illite, gypsum, and halite points to dry conditions.

5) When the Quaternary sediments of the Akarçay Basin are compared with the neighboring basins in Southwestern Anatolia (Çal, Çameli, Karacasu, Uşak-Karahallı, Afyon-Sarıkavak, Şarkikaraağaç coal basin) in terms of paleoclimate, it is clearly observed that they are similar to the arid climate conditions of the Pliocene-Pleistocene transition and the glacial-interglacial climate oscillations in the Late Pleistocene sediments of the Konya Closed Basin.

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