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Tectonosedimentary development and palaeoenvironmental changes in the Acıgöl shallow-perennial playa-lake basin, SW Anatolia, Turkey

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Abstract: The late Cenozoic extensional deformation formed several NE-trending fluvio-lacustrine basins in SW Anatolia, filled by alluvial, fluvial and lacustrine deposits. Among them, the Acıgöl basin , is notable for its tectono-sedimentary development of a prominent shallow-perennial playa-lake setting. The basin initially subsided to receive coarse-clastic alluvial deposits, merging into fluvial systems and central shallow lakes. Subsequent basin deepening with significant sediment supply from surrounding basement horsts caused gradual shrinkage of the relatively small shallow lakes, due to renewed progradation of alluvial fans and they eventually dried out completely. The sedimentation pattern and palaeoenvironmental changes record a constant tectonic, sedimentation, climatic and lake chemistry interaction from the late Miocene onward, with close relation to the coeval adjacent basins. The modern Acıgöl Lake was formed by progressively inward narrowing and deepening caused by the activity of the basin bounding faults and eventually by newly generated synthetic and antithetic fault systems. The modern depression is a typical shallow-perennial playa-lake basin with active evaporation and dominant precipitation of sodium sulphates, Mg-Ca carbonates and clay minerals. In this study three deep bore-hole logs of the recent drilling completed in the modern Acıgöl lake plain were examined to document the mode of deposition and development of the basin. The bore-hole logs show that the Acıgöl basin was gradually transformed from a perennial deep lake into shallow perennial/ephemeral playa settings.

Key Words: Neotectonic extension, Acıgöl, playa-lake, evaporite, Na sulphate, SW Anatolia

1. Introduction

Neotethyan oceanic closure gave rise to the Tauride orogeny during late Cretaceous-Eocene time in the Eastern Mediterranean, which is represented by the Lycian orogeny in SW Anatolia (Bernoulli *et al.* 1974; Şengör & Yılmaz 1981; Woodcock & Robertson 1981; Robertson & Dixon 1984; Şengör *et al.* 1985; Zanchi *et al.* 1993; Sözbilir 2005; Alçiçek & Ten Veen 2008; Gündoğan *et al.* 2008). The last stage of the orogeny records post-orogenic extension (i.e. orogenic collapse) and formed a broad array of NE-trending basins hosting terrestial alluvial, fluvial and lacustrine deposits (Figure 1). The crustal extension in SW Anatolia created several fluvio-lacustrine basins, having alluvial, fluvial and lacustrine depositional environments (e.g., Alçiçek *et al.* 2005; Koçyiğit 2005; Purvis & Robertson 2005a; 2005b; Alçiçek 2007; Ten Veen *et al.* 2009; Alçiçek 2010; Çiftçi & Bozkurt 2010).

The SW Anatolian region is described as the 'Lake District', with prominent modern deep to shallow lakes receiving active sedimentation in several intermontane basins. It has large drainage basins, generally high sedimentation rates, and the sediments in these basins reveal long but exceedingly complex developmental histories that are affected by tectonics, evolving landscapes, variable fluvial inputs and regional climate fluctuations.

The modern lake Acıgöl is the second largest alkaline lake in the world, with active precipitation of sodium, calcium and magnesium salts and its surface varies greatly due to seasonal drought (Helvacı *et al.* 2004). Over 30 species of endogenetic precipitates and authigenetic minerals have been identified in the Acıgöl lacustrine sediments (Helvacı *et al.* 2010). The most common non-detrital components of the modern sediments include: calcium and calcium-magnesium carbonates (magnesian calcite, aragonite, dolomite), and sodium, magnesium, sodium-magnesium sulphates (mirabilite, bloedite, gypsum), and halite. The basin brines have high Mg/Ca ratios and result in hydromagnesite, magnesite, and huntite deposits. The detrital fraction of the lacustrine sediments is normally dominated by clay minerals, carbonate minerals, quartz, olivine, pyroxene and feldspars (Helvacı *et al.* 2010).

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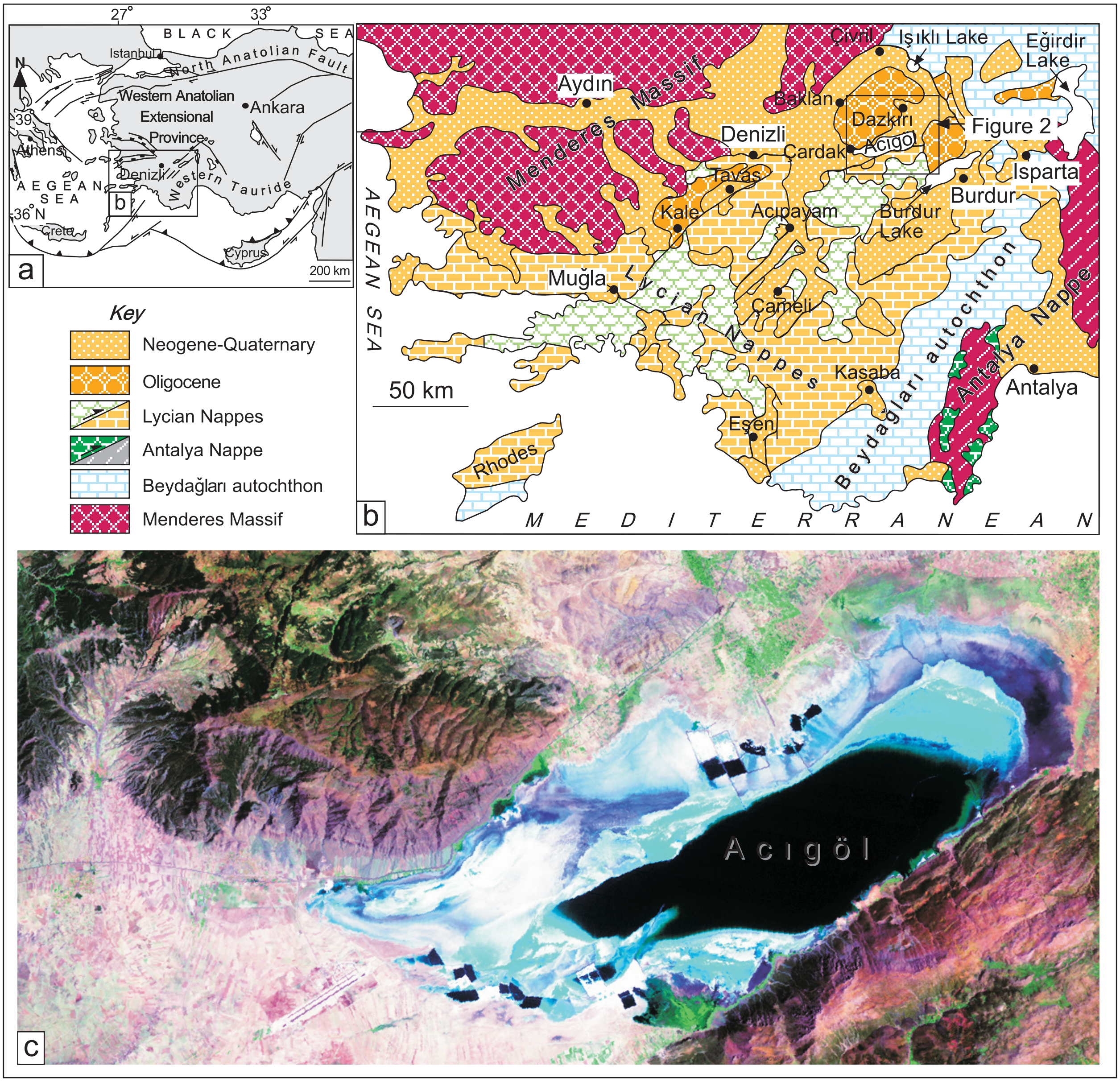

Figure 1. (a) Tectonic map of the eastern Mediterranean showing major tectonic structures (after *Alçiçek et al.* 2006). (b) Simplified geological map of SW Anatolia showing the main tectonic and sedimentary units (based on *Şenel* 1997). (c) Landsat image of the Acıgöl basin and its surroundings. The study area (see Figure 2) is indicated by the rectangle.

Around Acıgöl Lake, the mean daily temperature during January is about 3.3 °C and during July it is 24.4 °C; the mean annual temperature shows a narrow range. However, the most important characteristic of the region in terms of temperature is its extreme variability between seasons, and diurnal range. The effect of temperature on the mineral suite in the Acıgöl Lake is most obvious in the playa where the annual cycle of sediment accumulation (precipitation) and dissolution is readily apparent. In addition to temperature, another important climatic factor influencing the geolimnology of the region is the high evaporation to precipitation ratio. The region receives about 40 cm of precipitation per year, whereas as much as 75.4 cm of water can be lost annually through evaporation from open water bodies. This annual moisture deficit is one of the major variables that help to control the characteristically high salinity of water in Acıgöl Lake.

In addition to evaporation of water from the lake, wind is also an important agent of transport of clastic sediment and salts into or out of the lake. The average wind speed is moderate to high and mainly blows from the north-east. Groundwaters play a pivotal role in the geolimnology of this region. Most of the springs and groundwater in unconsolidated "surficial" aquifers is of moderate salinity and dominated by Ca, Mg, and HCO_3 ions. Springs and groundwater in the south of the Acıgöl basin are usually dominated by the SO_4 ion rather than HCO_3, and have Na-Ca-SO_4-HCO_3 solutes, whereas the springs and groundwater in the north of the Acıgöl basin dominantly have Ca-Mg HCO_3 solutes. The brine composition in the Acıgöl Lake dominantly contains Na-Cl-SO_4 (Table 1). The variable input of groundwater from these sources is one of the most significant factors in dictating the brine composition of the lakes at the surface (Helvacı *et al.* 2010).

In the modern Acıgöl Lake seasonal climate, catchment bedrock and topography are considered to be the main controlling factors for deposition of Mg-rich carbonate environments (Mutlu *et al.* 1999; Helvacı *et al.* 2004; Alçiçek 2009; Alçiçek 2010). Sediment accumulation in the lake is controlled and modified by a wide variety of physical, chemical, and biological processes. Although the details of these modern sedimentary processes can be exceedingly complex and are difficult to discuss in isolation, in broad terms, the processes operating in the lakes of the Lake District are ultimately controlled by three basic factors or conditions of the basin: (a) basin morphology; (b) basin hydrology; and (c) water salinity and composition. Combinations of these parameters interact to control almost all aspects of modern sedimentation in Acıgöl Lake. The palaeoenvironmental changes recorded in the basin-fill succession allows reconstruction of the evolution of the basin.

This study of Acıgöl Lake aims to describe changes in the palaeoenvironments by using tectonic, sedimentological and geochemical data of the alluvial-fan to lacustrine system; to deduce the overall palaeoclimatic condition of the region during and since the late Neogene; to improve understanding of the relationship of sedimentation pattern with provenance, climate, mode of deposition and tectonism in the basin; and to investigate the similarity of the region's climate and depositional style to the other coeval palaeo-Mediterranean basins.

2. Geological setting

The modern Acıgöl lake depression, at up to 836 meter a.s.l. and occupying 156 km^2, hosts shallow-brackish seasonal lakes (Erinç 1967; Sungur 1974). The Acıgöl basin is a WNW-ESE trending depression 30 km long and 10 km wide and resides, floored by Mesozoic-Paleogene carbonate and ultramafic bedrocks affected by the Lycian orogeny in SW Anatolia (Göktaş *et al.* 1989; Şenel 1997; Konak & Şenel 2002) (Figures 1 & 2). The post-orogenic stages in SW Anatolia were previously postulated as orogen-top rifts induced by multiple-rifting pulses and well documented by tectonic development, sedimentation pattern and biostratigrapy that served to constrain tectonic models for the palaeogeographic evolution (Angelier *et al.* 1981; Altunel *et al.* 1999; Ten Veen 2004; Altunel & Karabacak 2005; Alçiçek *et al.* 2005, 2006; Alçiçek 2007; Alçiçek & Ten Veen 2008; Ten Veen *et al.* 2009).

Previous geological studies around the Acıgöl basin primarily concentrated on the regional mapping and local basin stratigraphy (Göktaş *et al.* 1989; Şenel 1997; Konak & Şenel 2002; Alçiçek, 2009) (Figures 1 & 2). The Neogene basin-fill succession unconformably overlies the bedrock units of the Lycian Nappes to the south and para-allochthonous units to the north, and was tentatively named the Çameli Formation and assigned to the late Miocene-Pliocene on the basis of mammalian fossil in stratigraphically equivalent units in the Çameli basin to the south (Göktaş *et al.* 1989; Şenel 1997; Alçiçek 2009). This unit is composed of three distinctive successions, consisting of: coarse clastic alluvial-fan deposits; fine-grained and channelised fluvial deposits; palustrine and lacustrine deposits with minor evaporitic intercalations. All of them are unconformably overlain by Quaternary deposits.

The basin stratigraphy was first described by Göktaş *et al.* (1989) as the Hasandede group. Recently Alçiçek (2009) did a sedimentological study in the west part of the Acıgöl basin. The alluvial-fan deposits constitute the lowermost parts of the basin-fill and comprise coarse-grained conglomerate and reddish mudstone intercalated with stratified pebbly sandstone beds, and become thicker towards the basin-bounded fault to the south, and their basinward lateral extent is relatively short. Fluvial deposits overlie and interfinger with alluvial fan successions. The Neogene sedimentary fill of the Acıgöl basin that were basically distinguished according to their vertical and lateral relationships have been used to establish facies associations that mainly correspond to alluvial fan, fluvial and lacustrine deposits (Figure 3). The exposed lacustrine facies occurs in the uppermost part of the basin-fill succession and conformably overlies the fluvial deposits. The present lake dries up seasonally, or is confined to the eastern margin.

3. Basin stratigraphy

Three basic genetic types of sediment have long been recognised in most lacustrine basins; (a) allogenetic or detrital: material derived from weathering and erosion of the soils and bedrock of the watershed and transported to the lake by fluvial, sheetwash, gravity, or aeolian processes; (b) endogenetic: sediment originating from biological or inorganic processes occurring entirely within the water column of the lake; and (c) authigenetic or diagenetic: material resulting from mainly chemical and biological processes occurring within the sediment after deposition.

Figure 2. Simplified geological map of SW Anatolia (based on Şenel 1997).

The suite of processes operating in shallow intermittent basins or playas includes: cyclic flooding and desiccation of the playa surface, efflorescent crusts, hardgrounds, spring deposits, and intrasedimentary salts, and periodic detrital sedimentation by sheet flow and wind. A basic facies pattern is common and shares many of the same features recognised in saline lakes, and the outer shoreline/nearshore complex comprises alluvial-fan, fluvial, mudflat/sand flat, and grades basinward into a salt pan complex. The depositional pattern of the Acıgöl basin shows clearly that infilling underwent various phases represented by three distinct genetic stratigraphic units or depositional episodes. Each of these is characterised by a typical facies association, as discussed below (Table 1; Figures 3 & 4).

Alluvial fan deposits: Initial accumulation in the early evolutionary stage of the basin development mainly resulted in distal alluvial fan deposits (Alçiçek 2009). Development of distal alluvial fan deposits has probably resulted from the equilibrium between tectonic subsidence and continuous vertical aggradations in distal alluvial environments (Table 2; Figures 3 & 4). The alluvial-fan deposits consist of stratified pebbly sandstone, mudstone

Table 1. Water chemistry of Lake Acıgöl.

		November 2008	February 2009	May 2009	August 2009
EC	(microS/cm)	101,200	61,000	57,400	79,300
pH		8.2	8.4	8.8	8.8
T	(°C)	7.2	4.8	30	21
Ca	ppm	524.9	482.3	605.7	1108.7
Mg	ppm	3305.8	1579.4	1720.7	2997.6
Na	ppm	25,719.8	12,760.0	13,486.8	21,791
K	ppm	1123.3	496.9	449.1	932.2
Cl	ppm	40,000	18,055	17,214	32,523
SO_4	ppm	18,000	9030	7716	19,671
HCO_3	ppm	0	715	6800	0
Br	ppm	136.5	47.5	52.6	136.5
Li	ppm	1.3	0.7	0.6	1.3
Sr	ppm	13.5	6.9	6.9	16.5

and intercalations with a clayey dolomite assemblage increase towards the basin-bounded fault to the south, and their basinward lateral extents are the relatively short distance of several tens of metres (Figure 3).

The mudstone facies are grey-brown, massive to laminated. The mudstone layers are laterally extensive and contain plant and root detritus. The sandstone facies is composed of ungraded and horizontally stratified, moderately-sorted and fine- to medium-grained sandstones. The vertical transition from mudstone to carbonate is always gradational. The clayey dolomite beds show a tabular to discontinuous geometry and contain pedogenenesis, i.e. vertical root traces, carbonate nodules and platy structures, typical of incipient to relatively mature carbonate-rich palaeosols. The carbonates are relatively homogeneous dolomicrites that show horizontal bedding with granular desiccation cracks.

Massive siliciclastic mudstone is interpreted to have formed subaerially in distal alluvial fans. The sandstone facies shows mainly episodic sheet flood sedimentation related to floodwaters and discharged to the distal alluvial areas. In the pond areas, primary precipitation of dolomite is interpreted to be of bacterial origin (Abdul Aziz *et al.* 2003; Melchor 2007). The presence of clay minerals in the mudstone and dolomite possibly reflects the result of pedogenetic replacement processes (cf. Pimentel 2002). The clayey dolomites formed in small shallow ponds that developed on the distal low-gradient areas of fans (Sanz *et al.* 1995). These dolomites show homogeneous fine-grained fabrics and indicate early diagenesis.

Fluvial deposits: This association occurs in the marginal part of the basin-fill succession and interfingers with the palustrine and lacustrine deposits (Alçiçek 2009; Table 2). As described by Alçiçek (2009), the unit reaches up to 50 m thick and extends laterally for several tens of metres and is composed of conglomerates, horizontal sandstone, and ripple cross-laminated sandstone intercalated with mudstones layers. Sandstone beds are interpreted as the deposits of a meandering river and are ascribed to high-sinuosity, relatively narrow channels typical of a sand-rich meandering system. The lateral persistence of the channelised sandstones suggests high rates of lateral channel migration, and the lateral accretion surfaces document the lateral growth of point bars. The interbedded mudstones and thin sandstones represent floodplain sedimentation (e.g., Miall 1996; Capuzzo & Wetzel 2004).

Conglomerate beds are moderately sorted, composed of subangular to subrounded gravels and are dominated by a clast-supported, sand-filled texture. The facies is moderately to poorly sorted, subangular to subrounded and comprising granule to boulder conglomerates. They consist of a muddy sand matrix and sandstones are fine- to coarse-grained and constitute massive, stratified and planar cross-bedded sandstones. The mudstones are massive, silty or sandy, dark yellow to red and contain plant detritus.

The stratigraphic position and reworking in most of the thick conglomerate beds indicates subaerial deposition with an environment transitional from alluvial

Figure 3. (a) General overview of the Acıgöl lake plain, showing the boundary of modern lake margins with sodium-sulphate production pools. Looking from south to north. (b) Inundated lake margin of Acıgöl, showing normal fault and Upper Triassic dolomitic limestone bounding the lake in the south. (c) Oligocene conglomerate and sandstone bounding Lake Acıgöl in the north part of the basin. (d) Triassic dolomitic limestone bounding Lake Acigöl and fan deposits at the margin of the lake. (e) Close view of the alluvial fan deposits limiting the lake basin in the south part of Acıgöl. (f) Lacustrine deposits showing carbonate bearing mud flats exposed along the north-western part of the Acıgöl. (g) Laminated lacustrine deposits excavated from the modern lake bottom. (h) Modern lake sediments showing thin lamination and discoidal gypsum growing within the sediments.

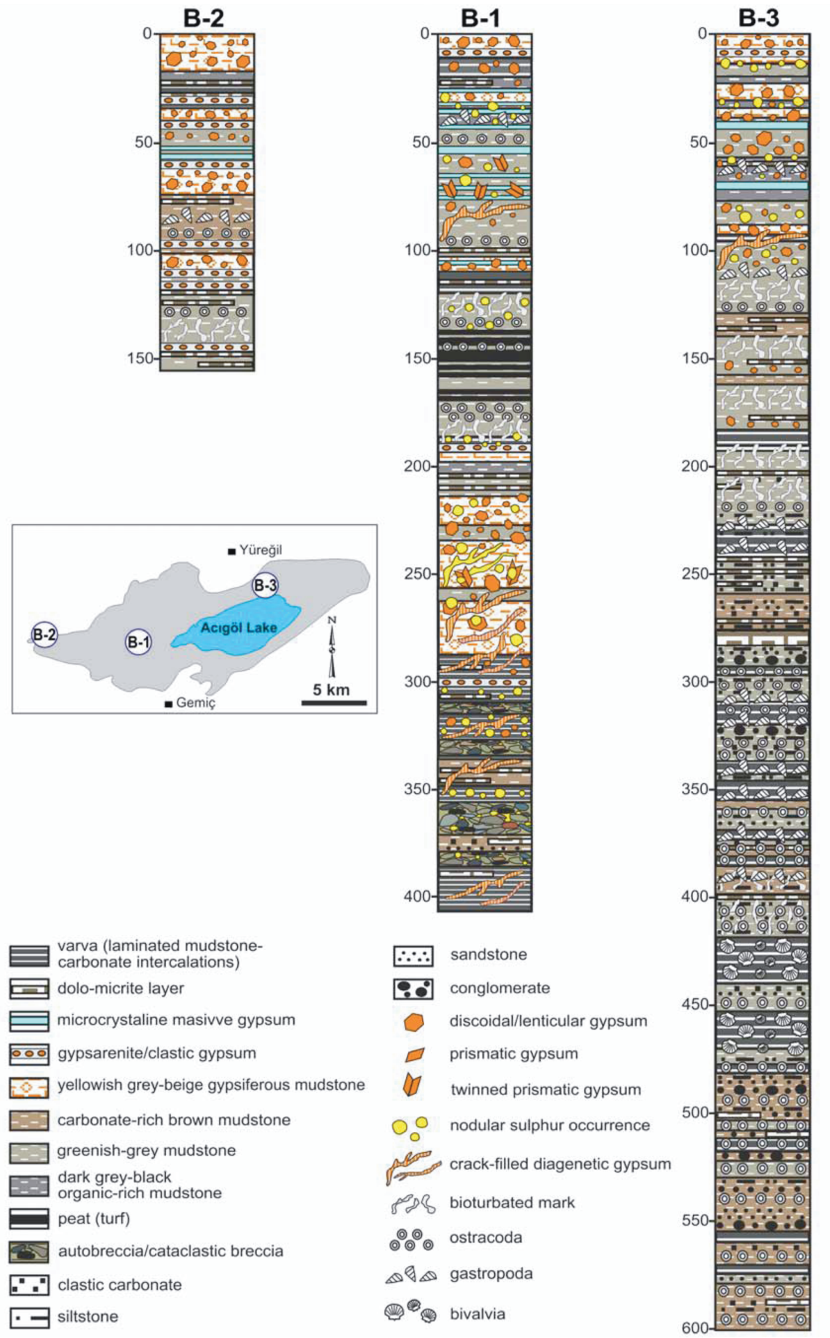

Figure 4. Bore-hole logs from the modern lake Acıgöl showing the facies relationships; Borehole-1 (B-1) = 402 m at the middle of the basin, Borehole-2 (B-2) = 151 m in the westernmost part of the basin, Borehole-3 (B-3) = 602 m in the east of the basin.

fan to palustrine lake. Conglomerate beds represent major subaerial fluvial progradation and distributary channel fills. Sandstone beds probably were formed by rapid sedimentation of debris flows (cf. Anadón *et al.* 1998).

Palustrine facies: This unit is represented by fine sand, bioturbated, fossiliferous plant-root, and peat (turf) bearing laminated marl lithofacies of a well-developed palustrine-dominated, low-energy and ramp type marginal environment (Platt & Wright 1991). In it fine-grained, palustrine magnesites were mainly deposited, as a result of more semi-arid climatic conditions, accompanied by continuing tectonic subsidence (cf. Bohacs *et al.* 2000; Djamali *et al.* 2005) (Table 2, Figures 4 & 5). Periodic fluctuations in the water table level flooded or exposed large areas, due to the low gradients of the palustrine system. In water films, progressive evaporation and variations of

Table 2. Facies of Lake Acıgöl.

Lithology	Explanations	Facies
Matrix-clast supported conglomerate	Debris flow deposits: Unsorted matrix-clast supported. Angular-subangular, mean=20 cm, max: 0.5 m. Erosive base, inverse to no grading. Silt, sand, fine pebble matrix, chaotic-massive. Muddy red-brown colour, lensoidal, tens of metres of extension. Unsorted, well rounded clast-supported. Mean=3 cm, max: 25 cm. Sand-fine pebble matrix, normal grading, cemented. Erosive base, lensoidal, tens of metres extension	***Alluvial fan deposits***
Bedded conglomerate	Hyperconcentrated flow, plastic debris flow: Unsorted, mid-well rounded clast-supported Mean=5 cm, max: 20 cm. No grading, cemented. Sand, fine pebble matrix. Erosive base, lensoidal, tens of metres extension	
Planar bedded conglomerate	Lateral and longitudinal fluvial-deltaic bars: Mid-well sorted, well rounded, clast supported, planar cross bedded. Graded, finer grading in flow direction. Mean is fine pebble, max: 5 cm. Cemented pebbles, lensoidal	***Fluvial deposi***ts
Massive pebble sandstone	Hyperconcentated-sheet flows, channel fill: Mid-coarse clast, distributed fine pebbles. No bedding, weak inverse grading. Tens of metres lateral extension, lensoidal, plant root cast, bioturbation	
Bedded sandstone	Channel fill, flooding sheet flats (Braided-meandering river): Mid-coarse clast, normal grading, parallel bedded sandstone. Distributed well rounded fine pebbles at the base. Flat base and top, cemented. Ripple top, plant root, normal grading.	
Rippled-planar-bedded sandstone	Flow/wave ripples: Very fine grained, lensoidal, ripple laminated sandstone. Asymmetric ripples in channels, symmetric ripples in deltas Lateral grading deposits: Mid-coarse clastic, erosive base, distributed fine pebbles at base, normal grade, low angle bedding, tens of metres extension Lateral transport of channel fill, bar migration: Mid-coarse clastic, rare distributed pebbles, rare distributed, weak cemented. 5-15 cm thick normal bedding, tens of meter extension	
Laminated siltstone-mudstone	Bar-set top suspension deposits: Massive-parallel laminated, distributed sand-fine pebble mudstone. Well rounded, fine pebble, cross bedded sandy lens, cemented. Grey-brown colour, hundreds of metres extension	***Palustrine facies***
Laminated marl-mudstone	Open lake, swamp: Distributed fine sand laminated marl, bioturbated, fossiliferous plant root, and peat (turf). Fractured and massive. Flat top and base, hundred of metres extension. Grey yellow colour, shell fragments	
Clayey limestone	Limnic carbonates: Massive bedding, laminated, grey green colour, conchoidal fracturing, bioturbated, shell pieces. Flat top and base, hundreds of metres of lateral extension	***Lacustrine facies***
Massive mudstone	Alluvial fan, flood plain, paleosol: Massive, fractured, carbonate nodules. Red-brown, plant roots, silty-sand lens. Alternating matrix supported conglomerate and fine pebble distribution	
Bedded limestone	Shallow limnic: White yellow coloured, porous, massive. Plant, roots, shell fragments. Clay and sand content, micrite and calcite fills	
Evaporites	Shallow limnic and mud flats: lacustrine magnesites and alternation of clayey dolomite; dolomitic clayey-marls-laminated mudstones-discoidal gypsum and gypsarenite alternation.	

Ca and Mg ratios resulted in sequential precipitation of dolomite and magnesite. Magnesites display cavities and cracks, suggesting a phase of early diagenesis. Lack of significant precipitation of evaporites during subaerial exposure and the presence of smectite, sepiolite, and palygorskite confirm open hydrology and alkaline waters with moderate salinity. The mudflats can be colonised by extensive areas of algae and cyanobacterial mats. The sediments in these areas are distinctively laminated, organic-rich, and are usually sites of biogenetic carbonate mineral genesis and diagenesis. Many of the more exotic carbonate mineral species found in the Acıgöl basin (e.g., hydromagnesite, nahkolite, kutnahorite, siderite, ankerite, huntite) have been identified in these modern biolaminated algal flat sediments.

Lacustrine facies: This association occurs in the central part of the basin fill and conformably overlies the fluvial deposits (Table 2). This unit also laterally interfingers with the fluvial deposits towards the marginal part of the basin (Figures 3 and 7). Unit thickness ranges from approximately 4 to 15 m and extends laterally 1.5-2 km. The facies association is represented by two subfacies as follows: (1) lacustrine magnesites and alternation of clayey dolomite, (2) an alternation of dolomitic clayey-marls, laminated mudstones, discoidal gypsum and gypsarenite (sand-size clastic gypsum). The most common phyllosilicates are smectite, and nontronite. The only detrital carbonate minerals identified in the lakes of the Acıgöl basin are dolomite and calcite. In bulk samples, $CaMg(CO_3)_2$ (dolomite) is usually considerably more abundant than $CaCO_3$ (calcite). This is most likely a reflection of the relative abundance of these two minerals in the bedrock of the region and the lower weathering stability of calcite relative to dolomite. The occurrence of very early diagenetic (i.e. penecontemporaneous) dolomite in the surficial sediments of Acıgöl Lake was one of the documented examples of lacustrine dolomite formation (Mutlu *et al.* 1999). This occurrence of dolomite also emphasised that dolomitisation could take place in solutions of moderate salinities and in water with high sulphate contents (Table 1). The stratigraphic record preserved in the Acıgöl basin contains sequences of very finely laminated carbonates. The dolomite crystals and crystal aggregates making up these laminae are euhedral and contain no petrographic evidence of reworking, abrasion, corrosion, or diagenetic alteration, thus suggesting the laminae were generated by inorganic precipitation from within the water column. The lack of detrital grains in these laminae and the absence of rhythmicity indicate relatively rapid and non-annual precipitation events. As shown in Figures 4, 5, 6 and 7 it is clear from the detailed mineralogical composition of the sequence that the brine underwent striking compositional changes.

The most important controls of water composition and concentration on a regional basis are: (a) composition of inflowing groundwater, (b) evaporation/precipitation, and (c) elevation or position of the basin within the drainage basin. Considering the range of water compositions in lakes of the Acıgöl basin (Table 1), it is not surprising there is an equally significant breadth of endogenetic and authigenetic minerals found in the lake. In the playas of the Acıgöl basin, there are two main types of endogenetic precipitates in the modern sediments: (a) soluble salts, comprising mainly sodium and magnesium sulphates and carbonates, and (b) precipitates, including mainly carbonates, sulphates, and silicates. There have now been almost 30 non-detrital minerals identified from Acıgöl Lake. These endogenetic and authigenetic minerals can also be subdivided according to their genesis and occurrence within the lake: (a) surficial efflorescent crusts and hardgrounds, usually occupying nearshore and seasonally flooded areas; (b) massive and bedded precipitates, most often found blanketing the floor of the basins from shallow marginal zones down to deep central areas; and (c) accumulations of salts associated with either subaqueous or subaerial water columns.

The specific carbonate mineral to be precipitated from the supersaturated solution is controlled mainly by the cations in solution, in particular the ratio of Mg to Ca in the water (Table 1). The elevated Mg/Ca ratios that characterise the Acıgöl lake waters give rise to a carbonate mineral assemblage dominated by aragonite and Mg-bearing carbonates, such as dolomite, magnesite, huntite and calcite.

The lacustrine magnesite facies comprise tabular beds 0.5-1.0 m thick of massive, compact, and well-cemented white magnesites. The magnesite is capped by an alternation of clayey dolomite, dolomitic and clayey marls. These magnesites have a mudstone to wackestone texture, with ostracods dispersed in a homogeneous micritic matrix; within this there are diffuse patches of a clotted micritic texture as well as dark mottles. The facies has a vesicular to tubular porosity: larger cavities are wholly or partially filled with fine sparry cement including smectite, sepiolite, and palygorskite. The dolomite beds alternate with dolomitic and clayey marl deposits. The dolomitic marl facies is composed of tabular beds of beige to light green marls that are tens of metres long and a few cm to about 60 cm thick. These dolomites are peloidal wackestones, comprising more or less fossil-bearing micrites, together with a significant presence of clay minerals (smectite, serpentine, sepiolite, palygorskite, illite), and dispersed ultramafic rock fragments. These deposits contain ostracods and small molluscs.

4. Bore-hole log data

Sedimentary features of the lacustrine deposits have been determined and observed in bore-hole logs of the recent

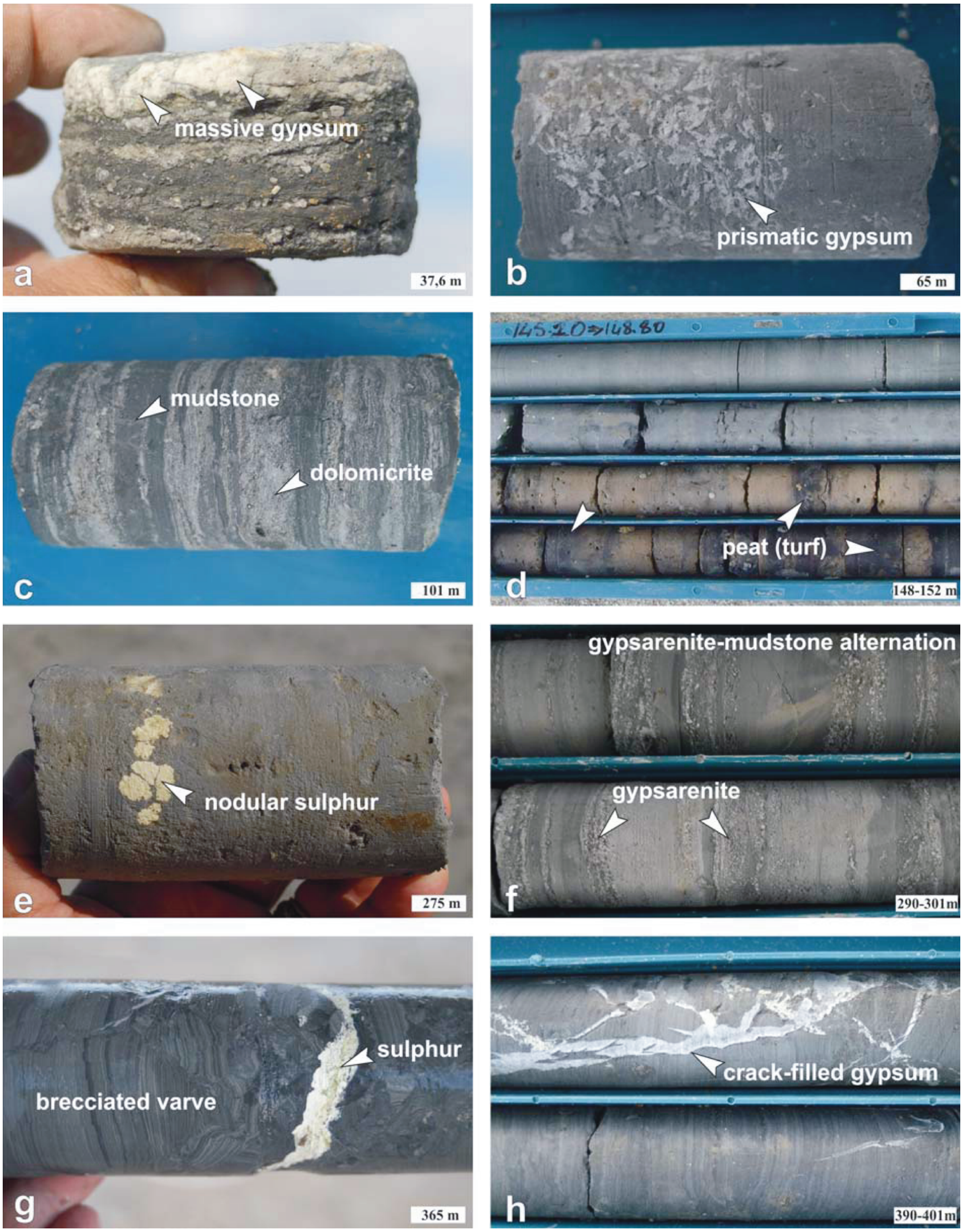

Figure 5. Representative lithofacies photographs of borehole-1 (B-1) drilled in the modern lake Acıgöl basin. (a) Microcrystalline massive gypsum layer within gypsarenite bearing dolomitic mudstone. (b) Interstitial-displacive prismatic gypsum grown within carbonate-rich mudstone. (c) Varve-like laminated mudstone and dolomicrite alternation. (d) Occurrence of peat (turf) within dolomitic mudstone. (e) Nodular sulphur masses within dolomitic mudstone. (f) Gypsarenite and mudstone alternation within organic-rich dolomitic mudstone. (g) Brecciated carbonate-mudstone alternation (varve) lithofacies due to synsedimentary tectonic faulting. Sulphur filling within brecciated cracks. (h) Diagenetic secondary gypsum fill within brecciated cracks.

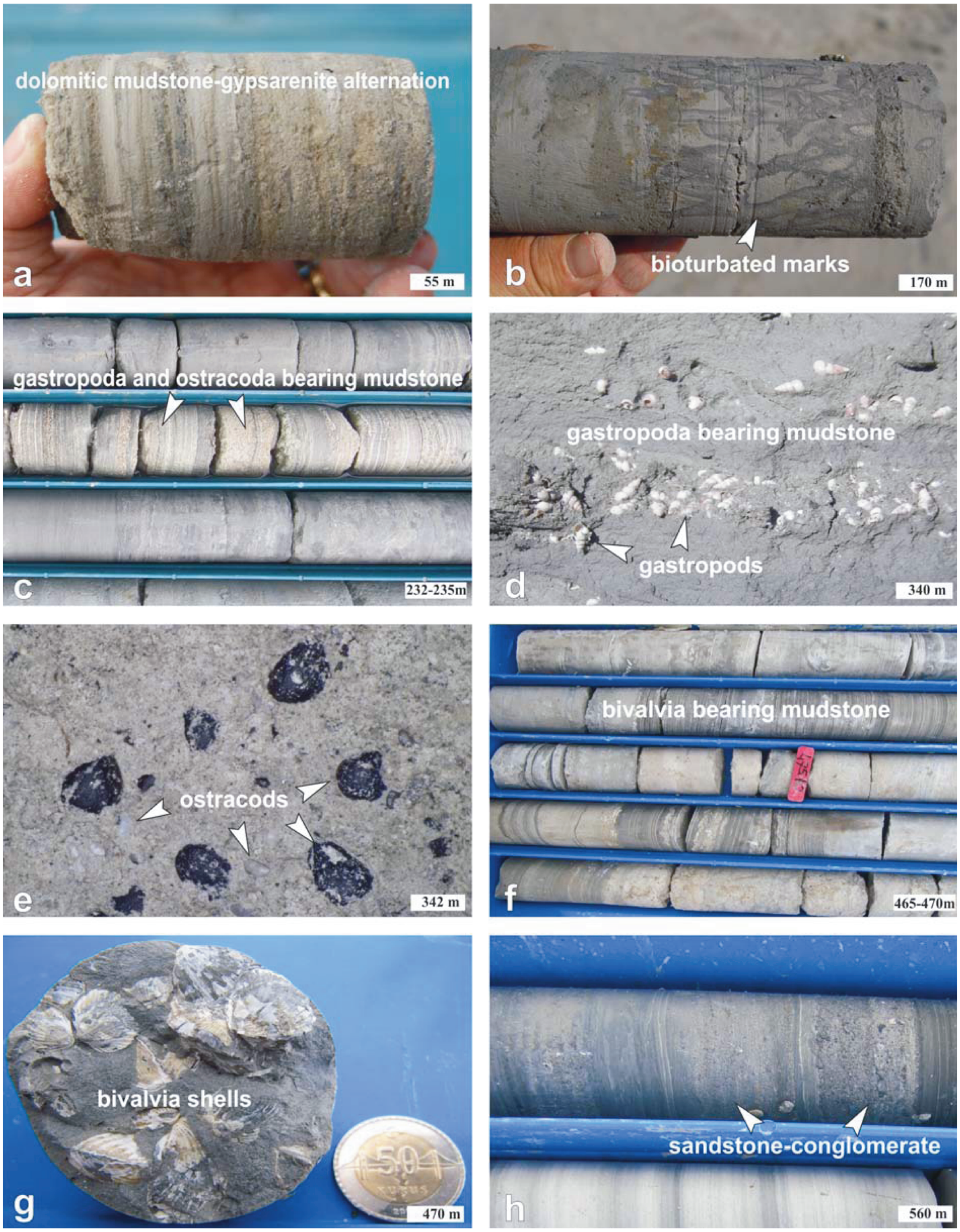

Figure 6. Representative lithofacies photographs of borehole-3 (B-3) drilled in the modern lake Acıgöl basin. (a) Ostracoda bearing dolomitic mudstone and gypsarenite alternation. (b) Bioturbated marks within carbonate-rich mudstone. (c) Gastropoda and ostracoda bearing mudstone alternating with carbonate-rich mudstone. (d) Gastrapoda within dolomitic mudstone. (e) Different types (black and white) of ostracoda within dolomitic mudstone. (f) Bivalvia bearing carbonate-rich mudstone within varve alternation. (g) Bivalvia shells within carbonate-rich mudstone. (h) Sandstone and conglomerate intercalations within varved mudstone.

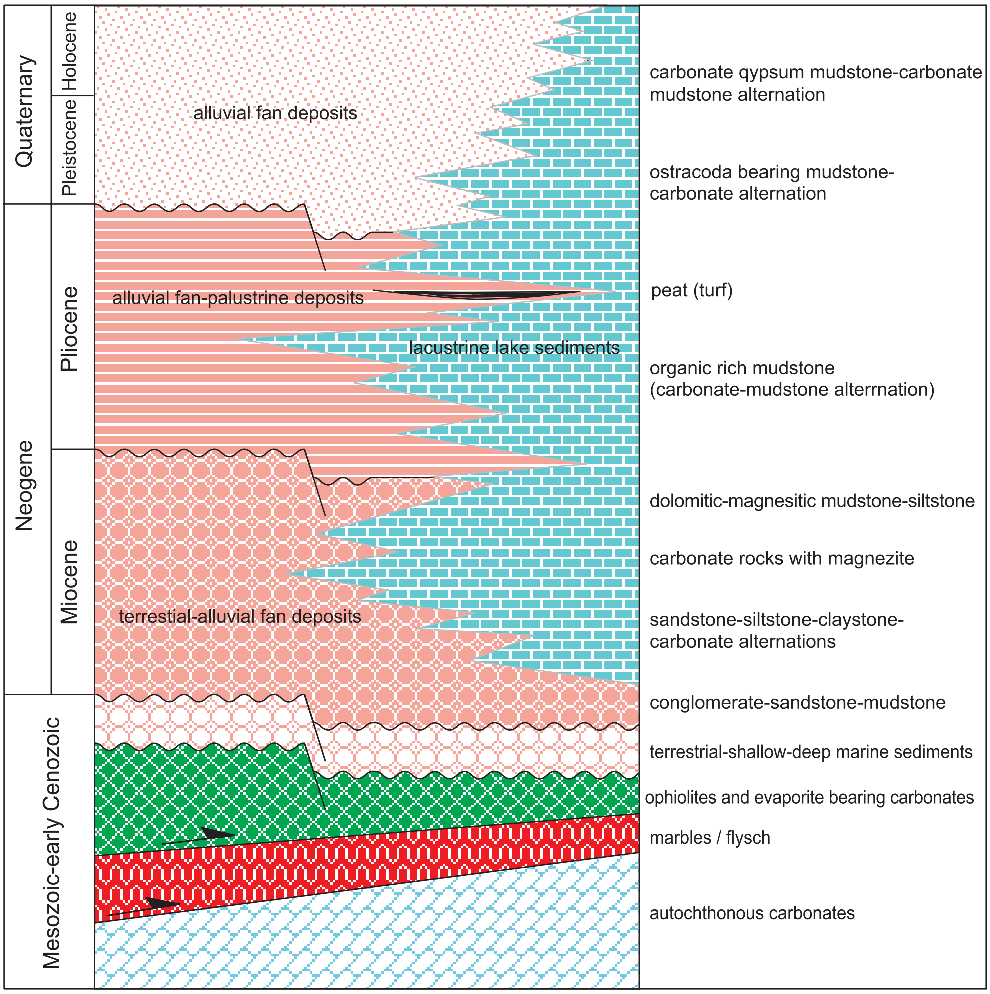

Figure 7. Palaeoenvironmental changes in the Acıgöl basin-fill succession (based on Göktaş *et al.* 1989; Şenel 1997; Alçiçek 2009; Helvacı *et al.* 2010). Note the lacustrine waxing and waning cycles and shrinking of the modern lake Acıgöl.

drilling penetrating 402, 151 and 602 m into the dried up lake plain (Helvacı *et al.* 2010) (Figures 4, 5 & 6). The sedimentary properties of those drill logs are explained below, and the sedimentation pattern along the logs shows clearly a gradual change of the depositional mode during the basin evolution. In the Acıgöl lake plain, three boreholes were drilled to document the lacustrine development and sediment composition (UTM coordinates for Borehole-1: 35S0746009/4187552; Borehole-2: 35S0736250/4187000 and Borehole-3: 35S0757250/4195000 with depths of 402, 150 and 602 metres respectively).

The logs from bore-hole drilled in the dried up lake bottom give some valuable insights into the depositional conditions of the lake (Figure 4). The data obtained from the trenches and deep drillings completed in the Acıgöl basin indicate that lake sediments show facies changing from brackish to saline water environments and the mineral formation and assemblages in these facies depends on the alkalinity of the water composition which increases upwards in the stratigraphic section in the Acıgöl lake basin (Figures 4, 5 & 7). The main evaporitic sequence containing Na-sulphate is up to 15 m deep and is completely dissolved in the evaporite-bearing muds and there is no more Na-sulphate beyond that depth. In Borehole-1, west of the modern lake, a gypsum-dominated evaporitic unit was drilled up to 285 m depth. However, up to 150 m of an evaporitic unit alternating with clastic sediments was drilled in Borehole-3. According to the sedimentary facies architecture in the borehole logs, the lake probably became enriched in Na-sulphate with time and as the lake depocentre shifted eastwards, with the western progradation of clastic materials in to the lake (Figures 7 & 8). The eastward shift of the depocentre was even provoked by movement of the eastern basin margin fault that caused lake-bottom subsidence and uplift of the western lakemargin (Figure 8). The evaporitic sequences

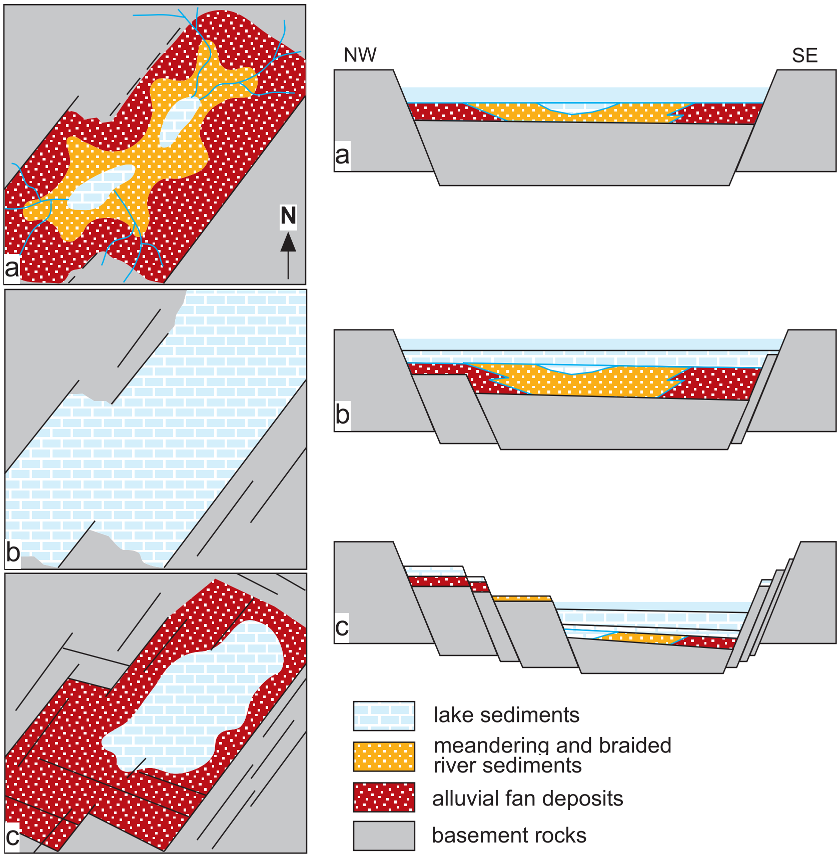

Figure 8. Interpreted palaeogeographic evolution of the Acigöl basin (based on palaeogeographic interpretation by Göktaş *et al.* 1989; Alçiçek 2009). (a) During the basin foundering stage coarse-clastic alluvial and fluvial deposits extended into shallow swampy lakes. (b) The lake expansion stage corresponded to the regional early Pliocene humid climatic conditions accompanied by successive foundering of the basin floor. (c) The renewed basin subsidence stage caused inward narrowing of the basin and an eastward shift of the depocentre to occupy the modern Acıgöl Lake.

are dominate over 285 metres in Borehole-1 to the west of the lake, whereas the evaporitic sequences alternating with detrital sediments were penetrated for 150 metres in Borehole-3 the NE of the lake (Figure 4).

In the borehole logs dolomite mineralisation dominates. The principal source of dolomite in the lake environments is clay grade detritus from the Triassic-Jurassic basement unit. The uppermost parts of the logs are predominantly dolomitic mudstone-discoidal gypsum and gypsarenite alternations, whereas deeper parts are dominated by fossiliferous, heavily bioturbated carbonate mudstone (Figure 6 b). Between 140 and 165 metres in Borehole-1 by the western part of the lake, a distinctive bituminous mudstone-peat (turf) was intersected (Figure 5 d), although no such horizon is present in the other borehole logs. Sedimentary facies and faunal composition show a transition from fresh-brackish (represented dominantly by bivalvia) to brackish and brackish-saline water (represented dominantly by ostracods) conditions. Between 150 and 600 metres in Borehole-3 some fossil shells were observed as indicative of fresh-brackish water conditions. In that interval, ostracods, gastrapods and shells are common, notably between 430 and 460 metres, where the shells predominate (Figure 6).

There is common nodular or crack filling native sulphur formed by microbial conversion of gypsum to sulphur. The activity of sulphate reducing bacteria is dominant above the peat (turf) horizons in Borehole-1 between 145 and 165 metres. The sulphur formations in the Borehole-3 are between 0 and 105 metres. This kind of sulphur formation in the gypsum bearing mudstones is common as nodular structures and rarely replaces gypsum crystals pseudomorphously. Some fractures within the varve-like laminated mudstones formed as a result of syntectonic deformation (Figure 4). Fracturing intensifies in deeper parts and the fractures in Borehole-1, in the brecciated laminated mudstones between 375 and 390 metres are cemented by sulphur occurrences (Figures 5 e

& g). In the deeper parts of the stratigraphic section, there are fissure-filled diagenetic gypsums (Figure 5 h). In the deeper parts sandstones and conglomerates are dominant in Borehole-3, implying that it is closer to the basin margin.

XRD results of the borehole samples show gypsum, calcite, dolomite, kutnohorite (Mg and Mn bearing dolomite), sulphur, saponite (Ca-Mg-Al silicate clay), quartz and pyroxene (Ca-Mg-silicate). The upper evaporitic series is dominated by gypsum, whereas in the lower parts it alternates with dolomitic mudstones. Dolomitic muds become enriched by quartz and pyroxene derived from the basement rocks in times of flooding. Petrographic studies showed that dolomitic mudstones are intercalated with gypsum and gypsarenite. In the deeper parts carbonate, fossil shell fragments and extraformational limestone clasts, quartz, olivine and pyroxene become enriched in the carbonate mudstones. There is commonly sulphur with carbon and graphite occurrences in these mudstones.

Sedimentary features of the lacustrine deposits have also been determined and observed in bore-hole logs (UTM coordinates for ACI-P01: 35**S**0755206/4192460; ACI-P02: 35**S**0754876/4192171; ACI-P03: 35**S**0754609/4191727) using the Multi Sensor Core Logger (MSCL) method at 1.60, 0.24 and 1.84 m depth below the lake surface where the water depths were 1.93, 2.20 and 2.40 m (Namık Çağatay, personal communications). Lithology, geochemistry and physical properties of these boreholes were determined by the Multi Sensor Core Logger (MSCL) method, and the results are summarised as follows:- Two different evaporitic gypsum beds are separated by a carbonate bed and the thickness of the gypsum beds increases towards the central (deeper) part of the basin, reaching 49 and 21.5 cm respectively. These data indicate that the deposition rate increases towards the centre of the basin. Carbonate-rich levels intercalated with the large crystal-bearing evaporitic (gypsum) horizons show high Sr contents indicating that aragonite also formed before the gypsum deposition. Due to formation of these minerals (Ca-carbonate and sulphate deposition) the water chemistry gradually changes to a Na-Cl (SO_4) type. XRF core scanner analyses also indicate that there are important variations in element profiles, showing carbonate and evaporate mineral formations as well as clastic materials and water input to the basin. These variations in the element profiles also indicate climatic changes, reflecting dry and wet periods in the Acıgöl basin. Four recent sediment samples collected from the Acıgöl basin were carbon dated at Arizona University, and the results give ages between 2530±65 and 4490±100 years BP (Figure 3 f, g & h). Samples taken from loose tephra layers observed within coarse-grained alluvial fan deposits near Çardak on the northern edge of the Acıgöl lake basin give ages between 4750 and 3385 years BP (Kazancı *et al.* 2012) (Figure 3 b & e).

5. Concluding remarks

The Acıgöl basin is a hydrological closed graben-type depression bounded by NE-SW trending faults. In the Acıgöl basin, distal alluvial fan, fluvial and palustrine-lacustrine sedimentation has been controlled by a combination of climatic, tectonic and source rock interactions. Seasonal climate, catchment bedrock and topography are considered to be the main controlling factors for deposition in Mg-rich carbonate and Na-sulphate environments in the modern Acıgöl Lake. The depositional pattern in the Acıgöl basin shows clearly that infilling experienced various phases, represented by distinct genetic stratigraphic units or depositional episodes. The spatial facies configurations and distributions in each of those genetic units are characteristically asymmetrical, owing to the half-graben basin structure.

Sedimentary architecture implies that the sedimentation was mainly controlled by the NE-trending Acıgöl fault to the east. Clastic materials derive from the most prominent fault scarps along the eastern margin. The modern lake Acıgöl occupies a still narrowed depression limited to the eastern basin margin. The earlier deposits of the basin have been uplifted by activated older faults or newly generated younger faults and are exposed around the modern lake depression. The Acıgöl basin of SW Turkey comprises a record of environmental changes dating the late Miocene (Göktaş *et al.* 1989, Alçiçek 2009). Detailed facies analysis in this half graben enables us to report successive depositional regimes and palaeogeographic settings. Four main facies groups characteristic of different sedimentary environments are recognised: these facies groups are arranged vertically in transgressive/regressive cycles, corresponding to the model of alkaline carbonate lakes of low gradient and fluctuating margins with palustrine fringes. This cyclicity might have developed as a result of the alternation of wetter and drier climatic conditions. The alluvial and carbonate sediments of the basin were formed in conditions ranging from warm, semi-arid to sub-humid.

The lacustrine facies deposited in the basin comprises mainly alkaline palustrine and shallow lake carbonate deposits (Figure 7). In the proximal areas distal fluvial fan, fluvial and shoal water settings developed, whereas in distal areas alkaline palustrine and lacustrine lake system were established. Later the lacustrine settings were replaced by fluvial settings.

Mineralogical and geochemical data from the Acıgöl playa can be used to derive palaeoclimatic and lake level information and Figure 8 summarises climatic reconstruction using all the data. The detrital clastic fraction of the playa sediments is derived from weathering of catchment rocks which in turn was governed by climatic conditions. During the late Miocene warm and relatively arid and semi-arid climatic conditions have been recorded in some lacustrine basins of western Turkey (Becker-Platen 1970). Dry conditions during the late Miocene were common throughout the Mediterranean area, both in marine (Messinnian evaporites) and continental environments (Hsü *et al.* 1973; Anadon *et al.* 1998; Bassetti *et al.* 2004). The late Miocene-Quaternary palaeoclimatic regime, ranging from warm, semi-arid to sub-humid conditions, was favourable for the development of distal alluvial fans, and swampy and lacustrine settings (Lutting & Steffens 1976). Well-developed cycles which occurred in the late Miocene Acıgöl basin suggest that a detailed study of these alluvial and lacustrine sequences may contribute to the knowledge of the late Miocene palaeoclimatic conditions (i.e. seasonality, short-term palaeoclimatic trends) in western Turkey.

As proposed by Alçiçek (2009), Mg-rich deposits of the late Miocene Acıgöl basin represent a unique Neogene analogue for the modern Acıgöl and Akgöl lakes. The sedimentary facies and depositional systems have been analysed to help recognise the sedimentation induced by extensional collapse accompanied climatic changes. Subsequently, in the Quaternary, the basin was transformed into a graben by activation of newly generated northerly trending normal faults, and alluvial fans were activated at the margins (Eyidoğan & Barka 1996; Temiz *et al.* 1997; Altunel *et al.* 1999; Koral 2000) (Figures 7 & 8).

The sedimentological and mineralogical data show that the basin-fill succession was deposited in an exclusively continental depositional environment that was subjected to large variations in hydrological settings. Lacustrine sedimentation was controlled predominantly by climatically driven hydrological changes that induced repeated expansion and contraction of the lakes, resulting in fluctuations in the width of lacustrine facies belts. The lithology of catchment bedrocks (ultramafic rocks) was the cause for the carbonate deposition at the onset of basin formation. The ultramafic and carbonate bedrocks in the catchment supported the transport of not only significant clastic, but also dissolved Mg-rich carbonate loads to the Acıgöl basin; hence the formation of thick alluvial deposits and fine-grained lake carbonates is common. This case history indicates that the interactions between provenance, climate, and tectonics fundamentally controlled the carbonate deposition in the relatively small Acıgöl basin. The Triassic evaporite-bearing sediments were largely deposited in Neotethyan Seas between the Eurasian and African plates in the eastern Mediterranean area. These Triassic evaporate-bearing sediments have been separated and moved several kilometres by thrust faults related to the Alpine orogonesis. A gypsiferous carbonate sequence underlies the Lycian ophiolites, and crops out in an area between Kızılyer and Menteşe villages, 20 km east of Denizli (Gündoğan *et al.* 2008). These evaporite-bearing dolomitic carbonates are thought to be the source rocks for the evaporitic sedimentation in the Acıgöl basin.

The bore-holes drilled into the Acıgöl lake basin show that first 30 metres are dominated by Ca-Na sulphate minerals deposited in a shallow basin (ephemeral or playa). Deeper parts of the stratigraphic section in the lake characterise deep conditions (permanent or perennial). The chemical composition of solutes in the lake is represented by Ca-carbonate, Ca-Mg-carbonate and Na-sulphate. In summary, present-day sedimentation in the playa basin of the Acıgöl region is controlled by the interplay of: (a) flooding of the playa which causes solution of soluble minerals of the salt pan facies and efflorescent crusts of the mudflat and sand flat facies; (b) evaporative concentration of the brine, which results in supersaturated conditions and precipitation of various soluble salts; (c) detrital influx by stream flow, wind, and spring discharge; and (d) organic productivity. In addition, evaporative pumping of shallow groundwater in the mudflats and sand flats causes growth of intrasedimentary displacive and poikilitic salt crystals in the near-surface clastic sediment.

Some artificial ponds and lakes within the Acıgöl basin are currently used to produce sulphate salts by evaporation of the lake water during the summer, and Glober's salt (mirabilite: $Na_2SO_4.10H_2O$) is obtained by natural crystallisation of oversaturated salty water during the winter. The occurrence of sodium sulphate naturally or artificially dehydrates during the summer and produces thenardite (Na_2SO_4) for commercial purposes. The hypersaline lake waters are pumped from the basin into pans (artificial pond-lakes). Upon further concentration by evaporation during the summer and then cooling during the winter, mirabilite is precipitated from the solution. The overlying brine is then drained back into the lake basin, and the salt is removed to stockpiles. In the Acıgöl basin companies simply raise the temperature of the salt to above its fusion point (about 32 °C), and then either continue heating to evaporate the water of crystallisation or remove the solid anhydrous precipitate from the slurry. This harvested Glauber's salt must be dehydrated prior to marketing.

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