Palaeoenvironmental evolution of late Miocene lacustrine deposits at Zahle (Bekaa Valley, Lebanon)

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Abstract

Neogene non-marine sedimentary rocks of the Bekaa Valley (Lebanon) are microfossil rich and show minimal lateral facies changes and post-depositional diagenetic alteration across continuous exposures. In this paper, we analyse the sedimentary facies and microfossils of three closely-spaced stratigraphic sections near the town of Zahle. The sedimentary sequence is divided, from base to top, into three intervals: (1) a massive conglomerate unit interpreted as
alluvial fan deposits, (2) fossiliferous yellowish marls and limestone interpreted as perennial lacustrine deposits, and (3) an organic-rich marlstone intercalated with volcanic ash horizons interpreted as a palustrine interval representing an overall shallowing sequence. Intervals 2 and 3 contain a diverse microfossil assemblage comprising charophytes, terrestrial molluscs, a freshwater bivalve, ostracods as well as fish and mammal remains. The palaeoenvironmental characteristics and evolution of these lacustrine deposits are inferred through facies analysis and through comparison of microfossil tolerances with the ecological requirements of their nearest living relatives. Results suggest that during the Miocene the Bekaa Valley was occupied by a relatively shallow, stable, oligotrophic freshwater or slightly oligohaline lake that evolved to a very shallow eutrophic lake with a dense palustrine vegetation belt. The palaeolake ultimately regressed to the south due to climatic changes and tectonic stresses leaving the lacustrine deposits exposed in the area of Zahle as an erosional surface.

**Keywords:** Neogene, lacustrine, Middle East, microfossil, sedimentology, palaeoecology.

1. Introduction

Neogene continental sedimentary rocks of Lebanon are well exposed in the Bekaa valley, especially in its eastern margin along paths and roads. These deposits show minimal post-depositional diagenetic alteration with lateral extension north-eastwards from the town of Zahle to the Chmistar village. In the area of Zahle, this sedimentary sequence displays a discontinuous vertical succession divided into three distinct intervals (Fig. 1).

The Neogene rocks of Zahle were first studied by Dubertret (1945, 1955) who identified and described the stratigraphic sequence. Dubertret (1945) defined this interval as a rock
sequence of conglomerates passing upwards into marl deposits rich in gastropods and
intercalated with thin layers of lignite. Dubertret (1945) suggested a Messinian (latest Miocene)
age for these deposits, yet without any palaeontological support. He used an imprecise
lithostratigraphic correlation with similar stratigraphic sequences localised at the north of the
same sedimentary basin. In agreement with Dubertret’s suggestion, biostratigraphically relevant
fossils from this lacustrine marl interval were first reported by Kansou (1961), who discovered a
_Hipparion_ horse tooth near the town of Zahle. A new fossil site with _Hipparion_ teeth was
discovered by Malez and Forsten (1989) in a southern locality near the village of Kefraya.
_Walley_ (1996) redefined these deposits in more detail naming them informally as the Zahle
Formation. According to this author this rock unit is composed of three intervals with different
lithologies; 1) thick deposits of conglomerates and breccia at the base passing upward to a 2)
marl interval alternated with thin layers of limestone and lignite which is topped by 3) another
interval of conglomerates. Little palaeontological work has been performed in the area during the
last thirty years due to the Lebanese civil war and other international conflicts. A
palaeontological analysis of rodent remains found in the area of Zahle has been recently
performed by López-Antoñanzas et al. (2015). According to those authors the lacustrine deposits
of Zahle, yielding the widely distributed taxon _Progonomys_, can be correlated with the European
Mammal Neogene zones MN 10 or MN 11 (late Miocene, 9.9–7.6 Ma; Gradstein et al., 2012).
However, a new micropalaeontological study based on charophytes from the same deposits
suggests older ages (Sanjuan and Alqudah, 2018). _Lateef_ (2003) assigned absolute ages of 10.4 ±
0.37 Ma and 10.87 ± 0.31 Ma (early late Miocene) to a basalt unit located northern and laterally
and above the lacustrine deposits of Zahle, which is in agreement with recent biostratigraphic
data based on rodents and charophytes.
In contrast to the amount of stratigraphic data available from these deposits, information about sedimentology, palaeoecology and palaeoclimate is scarce. In order to characterize the palaeoenvironmental conditions and the palaeoecological evolution of these non-marine deposits, four field campaigns were performed from autumn 2016 to spring 2017 in the area of Zahle (Fig. 1). Three sections were studied in detail from the sedimentological viewpoint (facies analysis) and sampled systematically for microfossils. Hundreds of well-preserved fossils including molluscs, charophytes, ostracods and vertebrate remains were obtained from the studied sections. The large amount of well-preserved fossil remains and the good exposure of facies lay the basis for the palaeoecological reconstruction presented herein, shedding new light on the palaeoenvironmental characteristics of the lake, its sedimentological and limnological evolution, as well as the regional climatic conditions. This work also aims to create an inventory of Neogene microfossils of Zahle since the complete study area is under a high urbanization pressure threatening the outcrops and the fossil sites.

2. Geological setting

The Bekaa Valley represents a tectonic basin bounded by two anticline-systems representing the two mountain chains in Lebanon, i.e. the Mount Lebanon Mountain range in the west and the Anti-Lebanon Mountains in the East. The origin of the Bekaa Valley is related to tectonic folding and uplift of the aforementioned mountain ranges as a consequence of the collision between the joined African-Arabian and the Eurasian Plates during the Late Cretaceous (Lateef, 2007 and references herein). This tectonic phase is referred to as the Syrian Arc Event. While the mountain ranges formed subaerially exposed islands at that time, the synclines
represented epicontinental seas along the southern Neo-Tethys margin that accumulated thick marine sedimentary sequences (Alqudah et al., 2014). The Late Cretaceous to middle Eocene time was characterised by successive episodes of emergence and submergence due to alternating compressive and extensive movements, leading to variations in the sedimentation patterns across the Bekaa basin (Ponikarov, 1967; Lateef, 2007). During the early Palaeogene, parts of the anticlines emerged forming longitudinal islands oriented NE-SW. Palaeocene and lower/middle Eocene rocks are composed of chalky limestone beds and marls deposited in a shallow marine environment. During the late Eocene to Oligocene, the collision between the African-Arabian and Eurasian plates caused further uplift of the Lebanese geological structures and continental sedimentation commenced in the Bekaa Valley (Beydoun, 1999; Lateef, 2003). However, this regional uplift and the continentalization of the valley have never been dated precisely.

Biostratigraphic studies based on nannofossils suggest that the first inversion and elevation of northern Mount Lebanon occurred between latest Maastrichtian to Early Paleocene time (C. Müller et al., 2010). These authors dated a second elevation phase during the pre-Early Miocene.

This second tectonic phase resulted in a flexural subsidence in the northern part of the Middle East leading to a major progradation of the marine facies (Alsharhan and Nairn, 1997). As a consequence of high tectonic activity, the intense erosion of the uplifted areas resulted in high rates of synorogenic deposition (mainly conglomerates related to alluvial fan deposits) within the Bekaa Basin and other Levantine basins during the early Miocene (Lateef, 2007). The Dead Sea transform fault formed probably in the middle to late Miocene favouring the development of extensive volcanism in the region, further uplift of the Lebanon and Anti-
Lebanon Mountains and deepening of the proto-Bekaa Valley (Ponikarov, 1967). Macro-
geomorphic features studied by Gomez et al. (2006) suggest that this uplift phase was 
asymmetric between the Mt. Lebanon and Anti Lebanon ranges. This tectonic event increased 
the accommodation space infilled by more synorogenic alluvial and lacustrine deposits. 
Lacustrine systems occupying large parts of the basin became the dominant sedimentary 
environments during the middle to late Miocene. Younger uplift and tilting occurred during the 
Pliocene and Quaternary in the Syrian Coastal Range and some areas of Lebanon (Gomez et al., 
2006).

3. Materials and Methods

Fossil remains were recovered from three stratigraphic sections closely related that can 
be correlated in the field, covering the lower, middle and upper parts of the Neogene deposits of 
Zahle (Figs. 1 and 2). The section 1 is located at the lower part of the lacustrine sequence (base 
of the section: 33°51’22.2”N, 35°53’39”E, top of the section: 33°51’15.12”N, 35°53’49”E). The 
overlying section 2 is situated about 250 m westwards to the previous section (base of the 
section: 33°51’14.69”N, 35°53’55.65”E, top of the section: 33°51’13.1”N, 35°53’55.69”E). The 
upper section 3 follows a path located about 500 m westward of the previous section (base of the 
section: 33°51’05.95”N, 35°54’14.95”E, top of the section: 33°51’02.77”N, 35°54’22.96”E).

Microfossils were obtained from twelve samples (Z-0 to Z-11) of grey/yellowish 
lacustrine marls collected from the aforementioned sections (Fig. 2). About 2 kg of sediment per 
sample were disaggregated in solution composed of water, hydrogen peroxide and Na₂CO₃ and 
later sieved using sieves with five different mesh sizes, i.e. 1.0 cm, 0.85, 0.65, 0.35 and 0.25 mm.
Microfossils were picked out under a light microscope. The relative amount of microfossils picked out from the samples is based on a semi-quantitative visual estimation (Table 1). Selected fossils were photographed and studied using a scanning electronic microscope MIRA 3LMU at the Central Research Science Laboratory of the American University of Beirut and at the Department of Earth Sciences, University College London. Thin-sections, about 30 µm in thickness, were prepared from rock samples from selected limestone beds in order to describe the microfacies. The material here studied and illustrated is housed in the Geology Museum of the American University of Beirut (acronym AUBGM).

4. Depositional Environments

The studied sections overlie an Eocene nummulitic limestone bed dipping 50º East. The Neogene deposits dip 30º East and can be divided into three basic types of facies assemblages: 1) alluvial fan clastic facies deposits, 2) perennial lake marl and limestone beds, and 3) palustrine organic-rich marls.

4.1. Alluvial fan clastic deposits

Clastic deposits are located at the base of section 1. This interval is about 30 m thick and consists of massive clast-supported oligomict conglomerates (Figs. 3C and 4). Deposits are poorly sorted and lack sedimentary structures. Clasts are subrounded in shape and variable in size ranging between 5 to 40 cm in diameter. All clasts are composed of nummulitic limestone suggesting that the clasts’ source rock is the underlying Eocene nummulitic limestone.
Conglomerates become less massive at the top of the section showing more concentrated clasts and becoming alternated with metre-scale silty intervals rich in ostracods (Fig. 3C).

The massive and structureless conglomerates located at the base of section 1 are related to debris flow deposits in an alluvial fan context (Boggs, 2011). The increase of clast concentration at the upper part of the interval together with the presence of silt suggests a progressive change from debris to stream flow sedimentary processes. Moreover, the presence of ostracods in silty deposits indicates that sedimentary processes occurred in a subaquatic context. The abundant supply of sediment in the area is a consequence of high tectonic activity, i.e. fault displacement, during the first stages of the lacustrine system.

4.2. Lacustrine marl and limestone beds

This soft rock interval comprises the upper part of section 1, the complete section 2 and base of section 3. In general marls and sandy marls are arranged forming monotonous beds, metre-scale in thickness, light grey to yellowish in colour and alternated with limestone and few lignite layers (Fig. 3D-E and Fig. 4). These deposits are very rich in fossil remains of gastropods, charophytes and ostracods. Small gastropods of the family Hydrobiidae are especially abundant in most of the intervals, representing by far the dominant fossils of the three stratigraphic sections (Fig. 3E, Table 1).

Several cycles of a characteristic facies succession formed by marls at the base passing upwards to silts and topped with limestone can be observed in the sections 1, 2 and base of section 3. Marls are organised in grey to yellowish sets of beds ranging in thickness from 0.3 to 1 m. They show diffuse lamination and contain abundant and well-preserved fossil remains,
mainly gastropods and charophytes. Silty marls contain a few organic-rich dark-grey horizons which are 5–10 cm thick showing poorly preserved comminute plant debris. No edaphic features have been observed underlying these layers in section 1. Limestone layers are represented by low-cemented wackestone–packstone, generally light grey in colour and forming irregularly tabular beds of 20–50 cm in thickness. The most common components of these limestone intervals are gastropods shells, frequently dissolved and forming a secondary moldic porosity (Fig. 3A–B). Microfossil content is very diverse composed of gastropods, charophytes, ostracods, bivalves, fish otoliths and vertebrate remains. Freshwater gastropods belonging to Hydrobiidae family are especially abundant along with the ostracod Cyprideis sp.

The vertical succession of facies changing from monotonous fossiliferous marls with some lignite horizons grading upwards to wackestone–packstone limestone intervals can be interpreted as the increasing abundance of calcareous organisms in the shallower and well-illuminated lacustrine environments. The marls were probably deposited in more distal and deeper lacustrine facies than the limestones. Despite the high content of fossils in the marl interval, the facies show some intervals of diffuse lamination and they contain a few lignite horizons with comminute plant fragments suggesting that the lake bottom was occasionally anoxic, hindering bioturbation and preserving the plant remains (Gierlowski-Kordesch, 2010). Moreover, no edaphic features have been observed underlying these lignite horizons indicating that plant remains were probably transported from the lakeshore and sank in the deeper areas forming an allochthonous assemblage on the lake bottom. Microfossils are well-preserved and do
not show signs of fragmentation suggesting that fossils were buried *in situ* or after minor transport, although the lack of juvenile ostracod valves in sample Z-6 suggests that higher-energy conditions, which led to the winnowing of the smaller and lighter juvenile valves, must have prevailed during at least some of the interval represented by the sediment record. Fossils occur in both marls and limestones and from the sedimentological viewpoint they correspond to biogenic carbonate producers. The presence of charophyte gyrogonites and thalli suggest that the lake bottom was well-oxygenated and well-illuminated. Dissolved gastropod shells are related to secondary diagenetic processes. The absence of ripples and broken shells in almost all sections 1 and 2 suggests that the depositional environment was relatively quiet, without the action of strong waves or currents. The presence of limestone layers indicates a change of the environmental conditions. The predominance of wackestone and packstone fabrics indicates moderate energy sedimentation (Boggs, 2011).

### 4.3. Palustrine organic-rich marls

These deposits are mainly located at the upper part of section 3 (Fig. 4). Marls and marly siltstones are organised in yellowish or dark grey beds ranging in thickness from 0.3 to 0.5 m. These deposits are mostly made of tabular beds, sometimes with erosive bases (Fig. 3F). They contain abundant organic matter rich marl intervals forming lignite of 5–10 cm in thickness, some volcanic ash intervals, burrowing structures, root traces and a high diversity of fossils, mainly gastropods (Fig. 3G). This palustrine facies could be classified in the type facies number 7 (organic-rich marlstone and clays) described by Alonso-Zarza (2003) and Alonso-Zarza and Wright (2010). Large numbers of the mollusc shells do not occur in life position, although well-preserved specimens are concentrated in some intervals. Large broken gastropod shells mostly
belong to the species *Melanopsis buccinoidea*, which occasionally forms accumulations of about 5–10 cm thickness (Fig. 3H).

Dark-grey coloured marls and silty marl intervals with abundant lignite horizons suggest a higher concentration of organic matter (plant remains) deposited in locally anoxic conditions. The presence of edaphic structures, which are particularly abundant below the lignite horizons, indicate that plant remains were not transported (autochthonous taphoflora) and the plant community grew *in situ* in the lake shores forming occasionally peat swamps (Gastaldo et al., 1995). Sedimentological characteristics suggest that sediments of section 3 were deposited under extremely shallow lake conditions at the lake margin where halophytic plants grew forming local peat swamps. Small fossils are well-preserved, while large gastropod shells are fragmented and occasionally form coquinas. This evidence suggests that shells were exposed to an energetic environment, probably subjected to wave activity at the lake shore or re-working episodes due to water level fluctuation and/or periodic exposures. The abundance of ash intervals in this section may indicate an increase of the volcanic activity in the area.

5. **Micropalaeontology**

5.1. **Characeae**

Charophytes represent a group of aquatic plants living in freshwater or brackish water conditions (Krause, 1997). Their biomineralised fructifications (gyrogonites and utricles) frequently fossilize and have been traditionally used as biostratigraphic markers of non-marine
deposits (Soulié-Märsche, 1989). The usefulness of charophytes lies in their sensitivity to palaeoenvironmental change and specific habitat requirements (Gierlowski-Kordesch, 2010).

Hence, fossil charophytes have been used as a palaeoecological proxies specially in Neogene and Holocene non-marine deposits providing valuable information about palaeosalinities, water level fluctuation and changes in trophic status (García and Chivas, 2006; Martín-Closas et al., 2006; Soulié-Märsche et al., 2010; Sanjuan and Alqudah, 2018). Recent studies involving experimental cultures have been developed with the aim to use geochemistry (trace-elements and oxygen isotopes) to reconstruct palaeosalinities and palaeotemperatures (Dux et al., 2015) and to find links between gyrogonite morphology and ecological parameters such as temperature and light irradiance (Sanjuan et al., 2017). Moreover, species-specific palaeoenvironmental constraints have been defined for Mesozoic and Cenozoic fossil charophytes based on sedimentological and taphonomical analyses (Villalba-Breva and Martín-Closas, 2011; Sanjuan and Martín-Closas, 2012; Vicente et al., 2016).

Charophyte gyrogonites belonging to five taxa have been recognised in the lacustrine deposits of Zahle, i.e. *Nitellopsis (Tectochara) merianii*, *Lychnothamnus barbatus* var. *antiquus*, *Chara microcera*, *Chara cf. globularis* and *Sphaerochara* sp. Three of these taxa have been recently described and illustrated by Sanjuan and Alqudah (2018).

*Nitellopsis (Tectochara) merianii* (Grambast and Grambast-Fessard, 1954) Grambast and Soulié Märsche, 1972 occurs abundantly and well preserved in three samples from section 1 and one sample from section 2 (Fig. 5, Table 1). This fossil species is considered the ancestor of the living species *Nitellopsis obtusa* (Desv. in Loisel.) Groves (Soulié-Märsche et al., 2002; Sanjuan and Martín-Closas, 2015). These authors linked both species to an evolutionary lineage that
ranges from the latest Eocene (late Priabonian) to the Quaternary. *N. obtusa* is a boreal species that is exclusively distributed in deep and shallow large, cold lakes of northern Europe, Asia and North America (Corillion, 1972; Soulié-Märsche et al., 2002). In these permanent lacustrine habitats *N. obtusa* forms large and dense meadows of up to 2 m height covering the lake ground. It thrives in oligotrophic/mesotrophic alkaline waters in depths over 4 m (Krause, 1985; Soulié-Märsche et al., 2002). Gyrogonites of *Lychnothamnus barbatus* var. *antiquus* Soulié-Märsche, 1989 occur in three samples of section 1 (Fig. 5, Table 1). The typical depth range of the living species *Lychnothamnus barbatus* in Europe is from 2 to 8 m where it forms dense meadows of up to 1 m high plants (Krause, 1985). This species has been traditionally related to cold and oligotrophic freshwaters usually associated to phreatic origin from northern Europe (Krause, 1997; Soulié-Märsche and Martín-Closas, 2003). However, recent studies performed in central-western Poland concluded that *L. barbatus* can also thrive under eutrophic conditions (Pelechaty et al., 2017). Specimens of *Chara cf. microcera* Grambast and Paul, 1965 have been extracted from two samples at the base of section 1 (Fig. 3, Table 1). Although there is no living representative of this species, previous micropalaeontological studies suggested that this extinct species grew in perennial freshwater lakes (Sanjuan et al., 2014). Many specimens of *Chara cf. globularis* Thuiller, 1799 have been recovered from a large number of samples through the sections. It appears abundantly at the top of section 3, especially in samples Z-10 and Z-11 (Fig. 5, Table 1). *Chara globularis* lives in permanent or temporary shallow bodies of water. This species has a strong tolerance to eutrophication and is able to survive in areas with low light irradiance and very cold water temperatures, even resistant to lakes with frozen surfaces (Bailly and Shaefer, 2010). Few gyrogonites of *Sphaerochara* sp. occur in sample Z-10 (Fig. 5, Table 1). Gyrogonites are medium in size, 630 µm high and 533 µm wide (mean values), spheroidal in...
shape showing nine convolutions in lateral view displaying a characteristic ornamentation formed by large and regularly spaced tubercles arranged along the spiral cells (Fig. 5O–Q). No ecological requirements can be deduced for this species since it does not have extant representatives. Corticated charophyte stems (thalli) belonging to genus Charaxis sp. appear in many samples suggesting that charophyte meadows were growing in situ (Table 1).

5.2. Molluscs

Non-marine molluscs are widely used as palaeoenvironmental indicators (e.g. Ložek, 1964; Goodfriend, 1992; Ciangherotti et al., 2007; Salvador et al., 2016; Neubauer et al., 2017; Harzhauser and Neubauer, 2018). Many extant relatives of species found in the fossil record are typical of very specific ecological conditions (e.g. Glöer, 2002; Welter-Schultes, 2012).

Nine freshwater gastropod species have been recovered from the studied stratigraphic sections. Many well-preserved shells of Valvata saulcyi Bourguignat, 1853 have been picked out from marls in section 3 (Fig. 6A–C, Table 1). This living species thrives in slowly running headwaters of rivers, ponds, springs, channels and lakes on muddy-sandy bottoms to hard grounds, as well as in ditches with stagnant water, preferably with aquatic vegetation. The species is tolerant of (slight) salinity increases and eutrophication (Germain, 1921; Yıldırım, 1999; Şereflişan et al., 2009; Bößneck, 2011; Van Damme and Kebapçı, 2014). A large number of opercula belonging to Bithynia sp. have been extracted from many samples throughout the
sections (Fig. 6D–E, Table 1). Species of this genus dwell in moving and standing water bodies, also in temporarily drying water bodies, on muddy bottoms, rock or plants (Welter-Schultes, 2012). Shells of *Melanopsis buccinoidea* Olivier, 1801 have been recovered from three samples from sections 2 and 3 (Fig. 6F, Table 1). Adult specimens can attain 5 cm in height, and they have been spotted also in some intervals at the top of section 3 (Fig. 3H). This species, nowadays native to the Middle East, dwells in various freshwater habitats, including streams, ponds, springs, pools and swamps (Van Damme, 2014).

Three species of mud snails (Hydrobiidae) have been recovered from the three studied sections. *Semisalsa* sp. is abundant in many samples (Fig. 6G–H, Table 1). This genus has a broad ecological amplitude occurring in brackish water environments, estuaries, salt lakes and non-tidal lagoons, coastal rivers, as well as in freshwater springs, wells, ponds and lakes (Bank and Butot, 1984; Glöer, 2002). Many specimens of *Pseudamnicola* sp. have been recovered abundantly in all the samples from section 1 (Fig. 6I, Table 1). Species of *Pseudamnicola* dwell in coastal streams, lakes, ponds, low river courses, springs and thermal springs (Szarowska, 2006; Glöer et al., 2010; Delicado et al., 2015). Hundreds of shells of *Islamia* sp. have been picked out from almost all the samples studied being the most abundant microfossil recovered (Fig. 6J–K, Table 1). Living species of *Islamia* are found in subterranean waters and springs, occasionally also in rivers and lakes (Bodon et al., 2001; Arconada and Ramos, 2006; Radea et al., 2017).

Few specimens of *Radix* sp. have been recovered from samples Z-10 and Z-11 (Fig. 6L, Table 1). Species of the genus *Radix* are found in standing or slowly moving waters often rich in vegetation (Welter-Schultes, 2012).
Two species of Planorbidae have been obtained from the three studied sections. *Gyraulus cf. piscinarum* Bourguignat, 1852 occurs in low numbers in all the sections becoming more abundant at the top of section 3 (samples Z-7 and Z-9) (Fig. 6N–O, Table 1). This species dwells in swamps and slowly flowing, vegetated waters (Heller, 2009). Few specimens of *Gyraulus cf. hebraicus* Bourguignat, 1852 has been recovered from three samples (Fig. 6M, Table 1). Seddon (2014) suggests that this species thrives in ponds and vegetated rivers.

Three species of terrestrial microgastropods have been extracted from section 3. A relatively large number of *Carychium* sp. shells occur in samples Z-8, Z-9 and Z-11 (Fig. 6P, Table 1). Living *Carychium* species require humid or wet conditions and are found in forests, meadows and swamps among leaf litter, under decaying wood and between stones (Welter-Schultes, 2012). Few specimens of *Vertigo cf. antivertigo* Draparnaud, 1801 have been picked out from samples Z-8, Z-10 and Z-11 (Fig. 6Q, Table 1). This hygrophilous species dwells in swampy meadows, along river and lake margins and in regularly flooded areas, mainly among rotting plant material. This species needs permanent moist habitats and it cannot thrive in places subjected to temporary droughts (Welter-Schultes, 2012). *Vertigo* is at present a widespread genus of humid habitats or regions, chiefly in the Northern Hemisphere. Members of *Vertigo* occur both in subarctic woodland of Norway and, much more rarely, in American tropics (Stworzewicz, 2009). Few shells of *Strobilops* sp. occur in sample Z-11 (Fig. 6R, Table 1). Extant species of *Strobilops* live in decaying logs and dead leaves in moderately humid forests (Pilsbry, 1927). No record of this genus has been found after the Pliocene in Europe since it became extinct in Europe before the first major glaciation.
One species of bivalve of the family Sphaeriidae, *Pisidium cf. moitessierianum* Paladilhe, 1866, has been extracted from samples Z-5, Z-6, Z-8 and Z-9 (Fig. 6S–U, Table 1).

This species requires slowly moving, well-oxygenated hard water over clean, unpolluted substrates varying from fine mud to sand. It dwells in lowland rivers, canals and large lakes with moderately moving water (Welter-Schultes, 2012).

5.3. *Ostracods*

Ostracods are small aquatic crustaceans that secrete bivalved shells made of low-Mg calcite. They are common in most types of water of circum-neutral to alkaline pH and their shells are often abundant and well preserved in Neogene sediments (e.g. Anadón et al., 2002; Rodriguez-Lazaro and Ruiz-Muñoz, 2012). Non-marine ostracods are sensitive to a range of environmental variables, including the size, depth and energy level of the waterbody, hydrochemistry, water temperature, dissolved oxygen concentration, trophic status and predation (Mesquita-Joanes et al., 2012) and they have excellent potential as palaeoenvironmental indicators (Anadón et al., 2002). Some species also display well-characterized ecophenotypic responses to environmental variations, especially hydrochemistry and variations in size and morphology may thus provide complementary palaeoenvironmental information (Boomer et al., 2003). Ostracods grow by moulting, up to eight times prior to adulthood. Because the different moult stages have contrasting hydrodynamic properties, the size distribution of moults within a stratigraphic interval can indicate whether a fossil assemblage has been subjected to post-mortem reworking by current action (Whatley, 1983; De Deckker, 2002). Adult ostracod carapaces often disarticulate into the constituent valves following death. Although different species show
variable tendency to such disarticulation, the presence of large numbers of articulated carapaces
within a fossil assemblages suggests low-energy conditions at the time of deposition and/or high
rates of sediment accumulation and hence rapid burial (De Deckker, 2002).

Four ostracod species have been recovered from the studied sections, which are, in order
of decreasing abundance, *Cyprideis* sp., *Cypris pubera* O.F. Müller, 1776, *Candona cf. angulata*
G.W. Müller, 1900 and *Strandesia* sp.

Large numbers of *Cyprideis* sp. occur in samples Z-5, 6, 7 and 8 (Fig. 7A-N, Table 1). In
samples Z-5, 7 and 8, adults and juvenile moults were recovered, whereas in Z-6, juvenile moul
tages were rare. Valves and carapaces were common in all samples. A few individuals display
moderately prominent nodes, but most are un-noded. The specimens from Zahle closely
resemble the widespread and well-known species *Cyprideis torosa* (Jones, 1850). This species
evolved in the Neogene or early Pleistocene and is at present common in marginal marine and
athalassic saline waters (Gliozzi et al., 2017). It is extremely euryhaline, tolerating a wide range
of salinities from around 0.5 to 60 psu or more, although its optimum ranges appears to be in
more dilute waters, from about 17 to 20 psu (Wouters, 2017). In athalassic environments, it is
generally restricted to waters with an alkalinity to calcium ratio less than unity, i.e. waters whose
anion composition is dominated by chloride or sulphate (De Deckker and Lord, 2017). The
species is generally found in shallow waters, <10 m deep (Pint et al., 2012), and is tolerant of a
wide range of dissolved oxygen concentrations, with the ability to tolerate dysaerobic conditions
(Pint and Frenzel, 2016). The species is able to tolerate water temperatures from at least 5 to
20°C, although it is more productive at higher end of this range (Ruiz et al., 2013) and requires a
temperature of at least 14 to 15°C for the eggs to hatch (Heip, 1976; Frenzel et al., 2012).
Cyprideis torosa shows strong salinity-driven ecophenotypic response in valve size (Boomer et al., 2017), noding (Frenzel et al., 2012) and sieve pore morphology (Frenzel et al., 2017); variations in these characteristics in fossil shells have been used for palaeosalinity reconstructions (De Deckker and Lord, 2017). Preliminary morphological observations of specimens from the Zahle sequence are consistent with salinity values greater than about 8.5 to 9.5 psu based on lengths of adult female left valves (0.95 ± 0.04 mm, n = 31: cf. Fig. 5 in Boomer et al., 2017) and about 8 to 9 psu based on the predominance of non-noded valves. However, these interpretations derive mainly from works on C. torosa in a marginal marine context (Van Harten, 2000; Keyser, 2005; Frenzel et al., 2012). Athalassic lakes may have contrasting ionic composition to marginal-marine environments, in which the relationship between shell morphology and salinity differs (Boomer et al., 2017).

Firm identification of Miocene Cyprideis is problematical because of the close similarity in valve features of C. torosa to several other proposed species, all of which are now extinct. These are C. agregentina Decima, 1964, C. ruggieri Decima, 1964 and C. crotonensis Decima, 1964; together with C. torosa, they make up the Cyprideis torosa-group. Whether these represent truly distinct species or are simply a manifestation of intraspecific variability within C. torosa remains unresolved (Ligios and Gliozzi, 2012; Gliozzi et al., 2017). Based on comparison of a few specimens with the detailed morphological descriptions in Gliozzi et al. (2017), the Zahle material shows similarity with C. ruggieri (Elsa Gliozzi, pers. comm. 2018). However, determinations of more specimens from Zahle are needed to confirm this and, for the moment, the species is left in open nomenclature.
Most important for paleoenvironmental reconstruction is whether the ecophenotypical responses developed for living *Cyprideis torosa*, especially the quantitative morphological transfer functions based on valve size, sieve pore morphology and degree of noding, can be applied to Neogene material such as that from Zahle. Grossi et al. (2015) have shown that adult valve size and sieve pore morphology of Messinian *C. agrigentina* appear unrelated to salinity inferred from palaeoecology and geochemistry, whereas the convergence of our results based on valve size and noding, suggest that the relationships described for *C. torosa* may hold for the species found in the Zahle sequence. However, given the uncertainties about the identification of the material from Zahle, and the ionic composition of the palaeo-lake, the paleoenvironmental significance of *Cyprideis* morphology should be treated with caution pending further investigations.

*Cypris pubera* (Fig. 7O) is a minor component of three samples, present as adult and juveniles shells, although there are too few specimens to comment conclusively on the ontogeny.* Cypris pubera* is widely distributed across Europe and the Middle East, and most commonly found in shallow water; it can tolerate elevated salinity up to about 4 psu and is described as mesothermophilic (Meisch, 2000), associated with July and January air-temperature ranges of 8 to 28˚C and -31 to 14˚C, respectively (Horne et al., 2012).

*Candona cf. angulata* (Fig. 7Q) is present in small numbers in Z-5. The adult valve resembles *C. angulata* in outline, but too few specimens were recovered to be certain about the identification or to comment on the ontogeny: the juvenile candonids in this sample are assumed to belong to the same species as the adult specimen. *Candona angulata* prefers brackish water and is often found in coastal lakes with some input of seawater. It is found in waters with salinity
from 0.2 to 14 psu and often co-occurs with *Cyprideis torosa* which is mesothermophilic 
(Meisch, 2000), and associated with July and January air-temperature ranges of 16 to 25°C and - 
5 to 17°C, respectively (Horne et al., 2012).

*Strandesia* sp. (Fig. 7P) is represented by a single specimen in sample Z-1. The specimen 
clearly belongs to the group of species of *Strandesia* that display protuberances on the dorsal 
margin of the right valve: however, this specimen could not be identified to species level.

5.4. Other microfossils

Other biogenic structures such as an indeterminate bone fragments, a crocodile tooth, few 
rodent teeth related to the extinct genus *Progonomys* (pers. comm. Isaac Casanovas and Raquel 
López-Antonanzas), fish otoliths related to the Cichlidae and Gobiidae families (pers. comm. 
Werner Schwarzhans) and many fish teeth have been extracted from the studied sections (Table 
1).

6. Discussion

6.1. Microfossil taphonomy and palaeoecology
The lacustrine deposits from Zahle yielded a large and diverse number of microfossils (charophytes, molluscs, ostracods and vertebrate remains) that display a characteristic vertical succession and facies association, providing valuable information for the understanding of the palaeoenvironmental evolution of the palaeolake through time. In general, two microfossil assemblages can be distinguished in agreement with the facies succession, i.e. one assemblage from lacustrine marls (top of the section 1, section 2 and base of the section 3) and one from the palustrine marls (upper part of section 3).

Seven species of aquatic gastropods have been recognised in marls from these three sections. Three hydrobiid species (*Semisalsa* sp., *Islamia* sp., and *Pseudamnicola* sp.) represent the dominant fossils in these deposits, accompanied by *Gyraulus* cf. *piscinarum*, *Gyraulus* cf. *hebraicus*, *Valvata saulcyi* and *Bithynia* sp. (Table 1). Living representatives of *Semisalsa* and *Pseudamnicola* have broad ecological requirements and live in brackish or freshwater water environments (estuaries, rivers, springs, ponds and lakes). Similarly, species of *Islamia* are found in a wide array of habitats, ranging from subterranean waters and springs to lakes and rivers. The presence of the freshwater bivalve *Pisidium* moitessierianum suggests that well oxygenated, calm and alkaline waters conditions prevailed in the palaeolake. The charophyte assemblage in these deposits is dominated by the species *Nitellopsis* (*Tectochara*) merianii which appears abundantly in samples from the section 1 (Table 1). Other species appear less abundantly also in sections 1, 2 and base of the 3 i.e. *Lychnothamnus barbatus*, *Chara microcera* and *Chara* cf. *globularis* (Table 1). The occurrence of the fossil species *Nitellopsis* (*Tectochara*) merianii and *Lychnothamnus barbatus* var. *antiquus* is significant from the palaeolimnological viewpoint. The two taxa represent the ancestors of the extant boreal species *Nitellopsis* obtusa and *Lychnothamnus barbatus*, respectively. The predominance of *Nitellopsis* (*T.*) merianii suggests
permanent and relatively deep (2–8 m deep), oligotrophic lake conditions (fig. 8). The ostracod assemblage is dominated by *Cyprideis* sp., which is especially abundant in section 2. Notwithstanding uncertainties about the identification of this ostracod species, the ostracod assemblage may suggest moderate-depth (<10 m), possibly dysaerobic and oligohaline water with a low alkalinity/Ca ratio, but with the strong caveat that these inferences, which are based on living *Cyprideis torosa*, may not apply to the Miocene-age material. The rise in the number of *Cyprideis* sp. carapaces in the second section may suggest an increase in lake salinity reflecting either in response to more arid conditions or as a result of a hydrographic change from an open to a closed lake system. Mollusc shells are well preserved, showing only few signs of abrasion. Charophytes gyrogonites show their original mineralogical constituents (endocalcine and ectocalcine), without any trace of dissolution or corrosion occurring in association with fragments of charophyte stems (thalli). This evidence suggests that the fossil assemblages from sections 1 and 2 were buried *in situ* or after short-distance transport.

The sedimentological, micropalaeontological and taphonomic analyses suggest that marls and limestones were deposited in a permanent fresh or oligohaline, relatively shallow, oligotrophic and alkaline lake with a soft muddy bottom.

A dramatic change of the microfossil content can be observed in the upper part of section 3. Terrestrial microgastropod shells of *Carychium* and *Vertigo* are relatively abundant. In addition, the gastropods *Semisalsa* and *Pseudamnicola* disappear in this interval while other aquatic groups related to stagnant conditions and vegetated waters (*Valvata, Radix* and *Gyraulus*) appear or increase in number (Table 1). Similarly, charophyte species related to perennial-deep and oligotrophic lacustrine conditions present in sections 1 and 2 such as *N. (T.*)
*merianii* and *L. barbatus* are absent in this palustrine interval. On the other hand, *Chara cf. globularis*, which has a wide ecological amplitude, shows a considerable increase. No ostracod carapaces have been found in the upper part of section 3. Although this may imply that conditions were unfavourable to ostracods at this time, this seems surprising given the abundance of remains of other aquatic fauna, suggesting instead that it may be the result of taphonomic effects.

Shells of large gastropods appear fragmented especially in the uppermost part of the section, and some specimens of terrestrial gastropods show signs of abrasion (Fig. 6Q). In contrast, no signs of dissolution or abrasion have been observed in gyrogonites of *Chara cf. globularis*. Hence, while charophytes and some gastropod species (*Islamia, Valvata, Radix* and *Gyraulus*) thrived *in situ*, larger aquatic and terrestrial gastropods were transported.

The sedimentological, micropalaeontological and taphonomic analyses indicate that rocks at the top of section 3 were deposited in very shallow, eutrophic conditions at a vegetated lake margin. The presence of broken shells intervals forming coquinas suggests that the lake margin was subjected to current or wave activity or subaerial exposure related to water level fluctuations (fig. 8).

6.2. Tectonic implications

Tectonic activity represents, along with the climate, a key parameter controlling the lake topography, hydrology (open/closed), the mechanisms of water supply and the sources of chemical constituents affecting the water chemistry (Alonso-Zarza and Wright, 2010).
The position of the lake and its morphology was controlled by the location and rates of movement of the Yammouneh fault located about 3 km westward in the same area (north extension of the Dead Sea transform fault). The vertical change of facies described here may respond to tectonic pulses of the fault during the Miocene. Clastic alluvial fan deposits located at the base of section 1 clearly indicates a period of erosion and transport due to the very high tectonic activity. The sedimentological characteristics of the overlying carbonate deposits, i.e. marls and limestone related to perennial-lake conditions, suggest that the tectonic activity decreased. A fossil charophyte assemblage recovered from the base of these lacustrine deposits containing biostratigraphically relevant taxa suggest that the establishment of the palaeolake took place during the early-middle Miocene (Sanjuan and Alqudah, 2018). The presence of palustrine marls and organic-rich clays in section 3 may indicate that the fault remained inactive in the region during the last stage of the palaeolake sequence.

6.3. Palaeoclimate implications

Little is known about the climatic and palaeoenvironmental evolution of Lebanon during the Miocene. The fossil assemblage recovered from lacustrine deposits of Zahle may shed light on the palaeoclimatic setting of the Bekaa Valley and the Eastern Mediterranean region during the late Miocene. However, the palaeoenecological evidence presented here suggests reconstructions based on the various fossil groups are, to some degree, contradictory.

Several of the fossil taxa recovered from the Zahle sequence provide information about past temperatures. The two charophyte species recorded in section 1, i.e. *N. (T.) merianii-obtusa* and *Lychnothamnus barbatus*, are considered boreal taxa growing mainly in north European cold-water lakes (Corillion, 1972). The dominant species *N. merianii-obtusa* grows in permanent
lakes with an average summer water temperature of 16 Cº (Larkin et al., 2018). This seems surprising, however, given the widespread evidence that the late Miocene, although cooler than the earlier part of the Miocene, was warmer than present. However, *N. (T.) merianii-obtusa* is a fossil species, and its ecology is only inferred from a related extant species. Although *Lychnothamnus barbatus* is living today, it is possible that its ecological preferences have changed since the Miocene. In contrast, several species of the aquatic molluscs suggest a much warmer climate, since they are still living in the Zahle region today, and this region is presently characterized by a hot-summer Mediterranean climate. The ostracod taxa found within the Zahle sequence have broad temperature tolerances, although they are not inconsistent with warmer temperatures, and would thus tend to support the climatic inferences drawn from the aquatic molluscs.

All of the groups of aquatic fossils (charophytes, aquatic molluscs and ostracods) include elements that are tolerant of elevated salinity; this is especially true for the ostracods. Elevated salinity in athalassic lakes is often associated with a more arid climate: although the dissolution of evaporitic rocks within a lake catchment can also contribute to elevated salinity, the absence of evaporites from the Zahle region suggests that climate was the more likely control. The land snails from the upper part of the section 3 point to a shift toward a humid environment and thus suggest less dry conditions as today.

Data from elsewhere within the Near East, NE Africa and the Arabian Peninsula, point to a regionally-complex pattern of climate in the late Miocene. Kingston and Hill’s (1999) reconstructions of the late Miocene vegetation on the Arabic Peninsula included wooded grasslands, consistent with more humid conditions. Palynological analysis from central and western Turkey indicated that this region was dominated by relatively open, grass-dominated
habitats (Akgün et al., 2007), with a climatic cooling and a shift from subtropical to warm temperate conditions at the transition between the middle and late Miocene in central Anatolia, although accompanied by a significant decrease in precipitation (Akkiraz et al., 2011). Griffin (2002) reconstructed more arid conditions in North-eastern Africa during the late Miocene. Globally, the late Miocene witnessed a significant cooling after the mid-Miocene climate optimum, but it was still considerably warmer than today (Herbert et al., 2016). Reconstructions of global vegetation for the Tortonian suggest warm-temperate mixed forests to temperate deciduous forests for the Levantine region (Pound et al., 2011).

7. Conclusion

Non-marine Neogene deposits in the western margin of the Bekaa Valley (Lebanon) near the village of Zahle have been analyzed from the sedimentological and micropalaeontological viewpoints. Three stratigraphic sections were raised with the aim to ascertain the palaeoenvironmental evolution of the area. Facies analysis of the three studied sections indicates that the western margin of the basin was occupied by an alluvial fan that evolved vertically into a perennial lake grading upwards into palustrine conditions. The well-preserved microfossil assemblage recovered from lacustrine and palustrine deposits of Zahle shed new light about the limnological characteristics of this paleolake. During the Miocene the south of the Bekaa Valley was flooded by a perennial, relatively shallow and oligotrophic freshwater lake that evolved to a very shallow and eutrophic lake with a dense palustrine vegetation belt. Ostracod assemblage suggests that oligohaline conditions may prevailed in some periods. However, the absence of evaporite bedrock in the valley’s catchment area suggests that climatic change were
the main factor controlling the salinity of the paleolake. The increase of salinity was probably related to higher evaporation rates during dry periods. Later on, this perennial lake changed into very shallow conditions were eutrophic and palustrine vegetated margins prevailed. In these conditions the lake was subjected to water table fluctuations and episodes of subaerial exposure probably related to changes in the hydrologic budget or climatic changes affecting the Valley during the Miocene. The subsequent high tectonic activity in the area displaced the basin depocenter towards the south leaving the studied deposits exposed along the south western margin of the Valley. The fossil assemblages are somewhat ambiguous indicators of palaeotemperature. Despite some fossil indicators of cold temperatures similar to those of present-day boreal environments, most of the evidence is consistent with temperatures being broadly similar to those of the present-day Zahle region, following a climatic deterioration in the region during the middle-late Miocene. Of course, it is difficult to provide a general overview of the basin and climate evolution based solely on sedimentological/palaeontological analyses of one limited area. Additional data from other localities along the Bekaa Valley are required to expand our knowledge of basin and climate evolution as well as tectonic activity. Unfortunately, the present political situation renders field campaigns in the eastern areas of the basin close to the Syrian border is not advisable for safety reasons.

Acknowledgments

This study was funded by the URB project of the American University of Beirut entitled: “Fossil Charophytes from Lebanon” (Project number AUB-23936). Peter Glöer and Adrienne Jochum are thanked for sharing ideas on the identifications of some of the gastropods. We acknowledge Isaac Casanovas, Raquel López-Antoñanzas and Werner Schwarzhans for their
help in the identification of vertebrate remains and Elsa Gliozzi and Dave Horne for invaluable discussions about the ostracods. We are also very thankful to Rania Shatila (Central Research Science Laboratory of the American University of Beirut) and Jim Davy (Department of Earth Sciences, University College London) for their help and technical support during the SEM sessions. T.A.N. was supported by an Alexander-von-Humboldt Scholarship for Postdoctoral Researchers. Carles Martin-Closas and two anonymous reviewers greatly improved the manuscript.

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Figure Captions

**Figure 1.** Geological sketch of the western part of the Bekaa Valley, Lebanon showing the location of studied section (modified from Sanjuan and Alqudah, 2018).

**Figure 2.** Geological map showing the detailed location of the three stratigraphic sections near the town of Zahle. A. section 1, B. Section 2, C. Section 3 (modified from Dubertret, 1945).

**Figure 3.** A–B. Microfacies of wackestone–packstone with abundant dissolved gastropod shells (D.S) from a limestone interval at the top of the Zahle section 1 (sample ZL). C–H. Field photos of the stratigraphic sections. C–E. Section 1. C. Base of the lacustrine sequence in Zahle, see the location of sample Z-0 between conglomerate channels (CGL). D. Marls of the lacustrine sequence, see the location of sample Z-1. E. Detail of the dominant facies at the base of the section, high concentration of microgastropods (G.S). F–H. Section 3. F. Dark grey marls at the top of section 3, see the location of sample Z-1. G. Detail of section 3 showing edaphic structures (root marks, R.M) underlying a lignite horizon (L.H). H. Detail of section 3 showing an interval of accumulations of broken large gastropod shells or shell-debris (G.S) of *Melanopsis buccinoidea.*

**Figure 4.** Stratigraphic logs for sections 1, 2 and 3 of the lacustrine deposits of Zahle showing their correlation and their facies associations. Z-0 to Z-11 represent the stratigraphic position of samples extracted for microfossils. ZL refers to the stratigraphic position of the sample recovered for microfacies analysis.

**Figure 5.** Charophytes from lacustrine deposits of Zahle. A–C: *Nitellopsis* (*Tectochara* merianii; sample Z-2 (A. apical view n°2017019 AUBGM, B. lateral view n°2017003 AUBGM,
C. basal view n°2017026 AUBGM). **D–F:** *Lychnothamnus barbatus* var. *antiquus*; sample Z-2

(D. apical view n°2017011 AUBGM, E. lateral view n°2017014 AUBGM, F. basal view n°2017012 AUBGM). **G–J:** *Chara microcera*; sample Z-1 (G. apical view n°2017002 AUBGM, H. lateral view n°2017002 AUBGM, I. lateral view n°2017003 AUBGM, J. basal view n°2017005 AUBGM). **K–N:** *Chara cf. globularis*; sample Z-1 (K. apical view n°2017007 AUBGM, L. lateral view n°2017008 AUBGM); sample Z-8 (M. lateral view n°2019001 AUBGM, N. basal view n°2019002 AUBGM). **O–Q:** *Sphaerochara* sp.; sample Z-10 (O. apical view n°2019003 AUBGM, P. lateral view n°2019004 AUBGM, Q. basal view n°2019005 AUBGM).

**Figure 6:** Molluscs recovered from Miocene lacustrine deposits of Zahle. **A–C:** *Valvata saulcyi*; all from sample Z-8 (A. n°2019006 AUBGM, B. n°2019007 AUBGM, C. n°2019008 AUBGM). **D, E:** *Bithynia* sp. (opercula); both from sample Z-8 (D. n°2019009 AUBGM, E. n°2019010 AUBGM). **F:** *Melanopsis buccinoidea*; sample Z-6 n°2019011 AUBGM. **G, H:** *Semisalsa* sp.; both from sample Z-5 (G. n°2019012 AUBGM, H. n°2019013 AUBGM). **I:** *Pseudamnicola* sp.; sample Z-4 n°2019014 AUBGM. **J:** *Islamia* sp.; sample Z-5 n°2019015 AUBGM. **K:** *Islamia* sp.; sample Z-1 n°2019016 AUBGM. **L:** *Radix* sp.; sample Z-10 n°2019017 AUBGM. **M:** *Gyraulus cf. hebraicus*; sample Z-8 n°2019018 AUBGM. **N:** *Gyraulus cf. piscinarum*; sample Z-5 n°2019019 AUBGM. **O:** *Gyraulus cf. piscinarum*; sample Z-1 n°2019020 AUBGM. **P:** *Carychium* sp.; sample Z-8 n°2019021 AUBGM. **Q:** *Vertigo cf. antivertigo*; sample Z-8 n°2019022 AUBGM. **R:** *Strobilops* sp.; sample Z-11 n°2019023 AUBGM. **S–U:** *Pisidium cf. moitessierianum* (left valves), all from sample Z-6 (S. n°2019024 AUBGM, T. n°2019025 AUBGM, U. n°2019026 AUBGM).
**Figure 7.** Ostracods from lacustrine deposits of Zahle. **A:** *Cyprideis* sp., female, external lateral view of right valve; sample Z-7 n°2019027 AUBGM. **B:** *Cyprideis* sp., female, internal lateral view of right valve; sample Z-7 n°2019028 AUBGM. **C:** *Cyprideis* sp., female, external lateral view of left valve; sample Z-7 n°2019029 AUBGM. **D:** *Cyprideis* sp., female, internal lateral view of left valve; sample Z-7 n°2019030 AUBGM. **E:** *Cyprideis* sp., male, external lateral view of left valve; sample Z-7 n°2019031 AUBGM. **F:** *Cyprideis* sp., male, internal lateral view of left valve; sample Z-7 n°2019032 AUBGM. **G:** *Cyprideis* sp., male, external lateral view of right valve; sample Z-7 n°2019033 AUBGM. **H:** *Cyprideis* sp., male, internal lateral view of right valve; sample Z-7 n°2019034 AUBGM. **I:** *Cyprideis* sp., female, dorsal view of carapace; sample Z-7 n°2019035 AUBGM. **J:** *Cyprideis* sp., male, dorsal view of carapace; sample Z-7 n°2019036 AUBGM. **K:** *Cyprideis* sp., female, external lateral view of right valve, noded form; sample Z-0 n°2019037 AUBGM. **L:** *Cyprideis* sp., female, external lateral view of left valve, noded form; sample Z-5 n°2019038 AUBGM. **M:** *Cyprideis* sp., male, external lateral view of left valve, noded form; sample Z-8 n°2019039 AUBGM. **N:** *Cyprideis* sp., male, external lateral view of right valve, noded form; sample Z-5 n°2019040 AUBGM. **O:** *Cypris pubera*, external lateral view of left valve; sample Z-6 n°2019041 AUBGM. **P:** *Strandesia* sp., external lateral view of right valve; sample Z-1 n°2019042 AUBGM. **Q:** *Candona cf. angulata*, male, left valve; sample Z-5 n°2019043 AUBGM.

**Figure 8.** Palaeoenvironmental model summarizing the distribution of microfossils in the Zahle palaeolake. The main stratigraphic logs (section 1, 2 and 3) are represented in numbers. Not to scale.
Table 1. List of microfossils and their relative abundance recovered from lacustrine deposits of Zahle in the western margin of the Bekaa Valley. This table is based on a semi-quantitative visual estimation of the fossils. Vertical position of samples represents their relative stratigraphic position, which is indicated in the figure 4.
Legend

- Pliocene - Recent (Alluvial)
- Zahle Formation (Lacustrine marl)
- Miocene (Conglomerate)
- Eocene (Nummulitic limestone)
- Upper Cretaceous (Limestone)
- Lower Cretaceous (Marl)
- Jurassic (Limestone)

- Village
- Section
- Road
- Faults
- Dipping
- Elevation point (m)

Figure 1

Figure 2
Figure 2
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<td>Chara cf. globularis</td>
<td>Valvata saulcy</td>
<td>Pseudanomnicola sp.</td>
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</tr>
</tbody>
</table>

Relative abundance (number of specimens per sample)  
- 1-25  
- 26-100  
- >100

Vertical position of samples represents their relative stratigraphic position, which is indicated in Figs. 6, 7 and 8.