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Aeolian control on the deposition of high altitude lacustrine basins in the Middle East: The case of Lake Neor, NW Iran

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ABSTRACT

Lake Neor is the largest lacustrine basin in the high mountains of the Middle East, at 2500 m altitude in the Alborz belt. This lake of Holocene age is a shallow, fresh water body of glacial origin with ca 4 km^2 surface area and a 40 km^2 drainage area. Its sedimentary sequence comprised of peat and gyttja consists of >10 m infill, which is fairly thick for such a lake. Autochthonous organic matter is limited in and around the lake except for small areas at the northern and southern ends. Inorganic constituents of the infill sediment include a significant amount of fine-grained calcite, dolomite and mica particles that are exotic to the catchment. They do not occur in the source rocks, as the drainage area of the lake is composed of only andesites and trachyandesites of Eocene age. In addition, the uppermost part of the infill includes abundant fine-grained charcoal particles derived from large forest fires perhaps derived as far as the Mediterranean region. As shown by the present meteorological records, the sediment of Lake Neor is under aeolian control during dust storms; this is leading to a considerable amount of deposition air-borne particles. The infill of some lakes, particularly those in highlands, may have contain an important aeolian component and thus they cannot be used directly for the interpretation of the evolution of the palaeogeography without taking into consideration the role of dust storms on deposition.

1. Introduction

Aeolian impact and dust storms that are the results of strong winds are common earth-surface processes for both sediment transportation and deposition. Particles can be moved long distances by, for example, winds from central Africa to Arctic regions and they can be deposited either by trapping or settling in various places depending heavily on wind direction (Nickling, 1994; Sleewaegen et al., 2002). As a part of climate, particularly in dry periods, dust storms have modified environment and impacted civilisations (Roberts et al., 2011; Albani et al., 2015; Sharifi et al., 2015). At present, central Asia, the Sahara and the Middle East are the regions most affected by wind storms (www.earthobservtory.nasa.gov/naturalhasards) (Fig. 1). When considering extensive sand dunes and loess deposits in the geological record, lakes should include a considerable amount of aeolian deposits. However, their amount, particularly in large lakes located on lowlands, could be negligible as the drainage areas of such lacustrine basins are also large and can provide much alluvial sediment. In addition, distinguishing aeolian sediments in lakes from ordinary lacustrine sediments is extremely difficult as there are no strict criteria (An et al., 2012). On the other hand, aeolian effects on deposition in lakes with small drainage areas cannot be negligible as a major part of their infill could be provided by dust storms. Because high altitude or highland lakes are generally small, their drainage areas are often limited (Stoch, 2006). Lake Neor, to be introduced in this study, is a good example of a high altitude lake located in a dusty region of the Middle East (Figs. 1 and 2).

The term "high altitude lake" is widely used, but it is not well described. Here we use the lower boundary of the alpine zone as the limit for highland lakes for the Middle East region, as it corresponds to the timberline (Noroozi et al., 2008). The alpine zone, according to ecological variations, is generally over 2000 m a.s.l.

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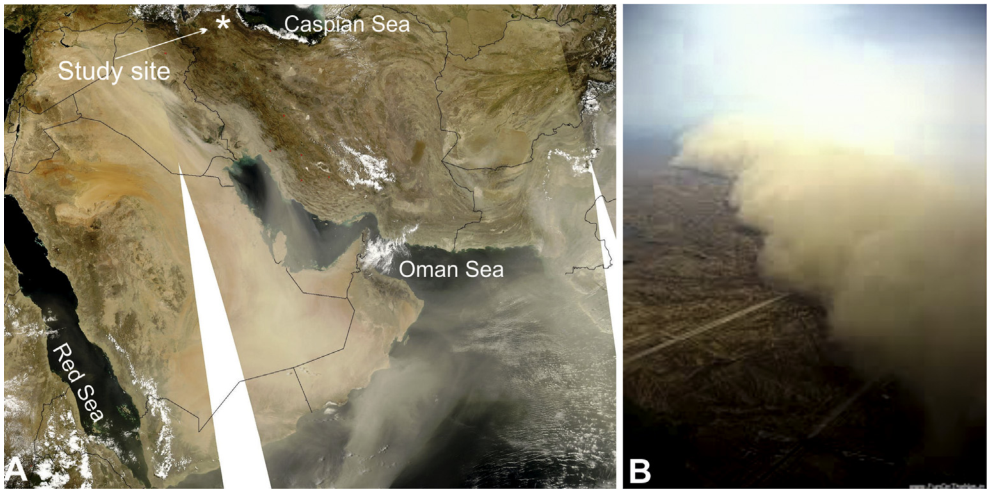

Fig. 1. Dust plumes in southern part of the Middle East. A) a day with moderate dust (8 March 2008) at the Gulf of Aden (www.earthobservatory.nasa.gov), B) view from ground of a usual dust storm on 22 April 2014 in Qatar (QatarCare News letter, 23 April of 2014).

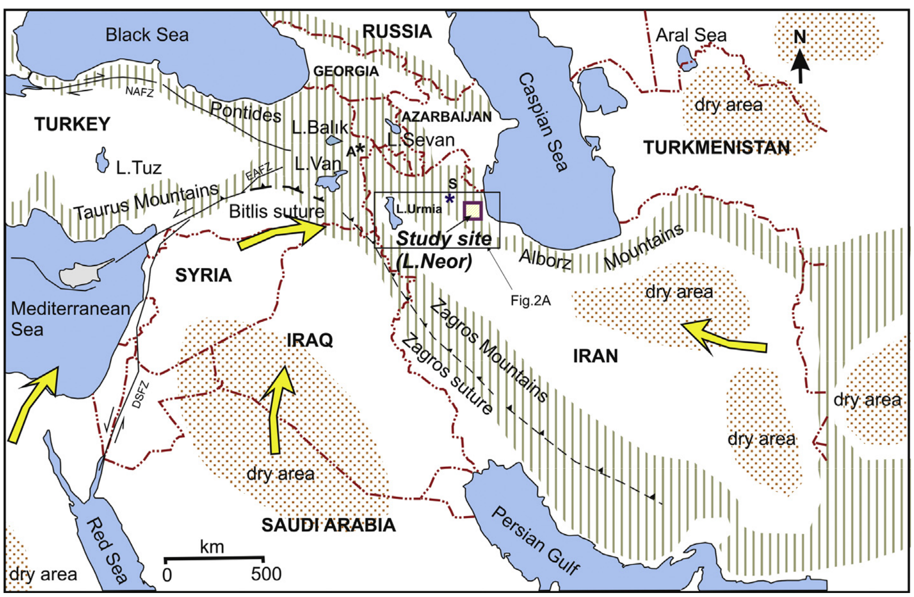

Fig. 2. Location of the study site and main tectonic elements of the region. Note that the each mountain belt represents more than one tectonic complex. Large arrows show dominant directions of dust storms (Kutiel and Furman, 2003; Anonymous, 2005). DSFZ Dead Sea Fault Zone, EAFZ East Anatolian Fault Zone, NAFZ North Anatolian Fault Zone, A Mount Ağrı, S Mount Sabalan.

with slight variations depending on latitude and humidity (Troll, 1973). With regard to high-altitude lakes, these conditions are mainly associated with glaciers, but flank collapses like landslides, alluvial deposits and debris cones may also play important roles. Although rare, lakes in karst or tectonic basins, and those associated with discontinuous tongues of permafrost, are not unusual. High altitude lakes are relatively small basins except for a few larger ones in the Andes (lakes Titicaca and Poopo), and in the Himalayas on the Tibetan plateau (lakes Pangons Tso, Bangong Co, Tsongmo and Aksayqin Hu). Such lakes in the alpine zone are proxies for the understanding of permafrost characteristics of the cold regions (e.g. Giralt et al., 2004; Liu et al., 2010) and for atmospheric depositions (e.g. Tait and Thaler, 2000; Rogora et al., 2001; Clow et al., 2002; Mosello et al., 2002). However, a large knowledge gap exists concerning sedimentation in high altitude lakes. The aim of this paper is to present sediment characteristics, particularly typical aeolian grains in the basin and the role of dust storms on deposition in high altitude lakes, using Lake Neor as a case study located at ~2500 m on the Alborz Mountains in NW Iran (Figs. 2 and 3).

2. General setting

The northern part of the Middle East (including Eastern Turkey and northwest Iran) forms a crossing point of four major mountain belts called the Pontides, the Taurides, the Alborz and the Zagros (Fig. 2). This mountainous region includes large volcanic centres, high plateaus and well-studied large lakes such as L. Van, L. Urmia, L. Sevan (Kelts and Shahrabi, 1986; Mohajjel and Taghipour, 2014; Stockhecke et al., 2014 and references therein). Also, many small, high-altitude lakes occur here (name of a city in eastern Turkey is “Bingöl”, which means one thousand lakes), but only Lake Neor and Lake Balık amongst them include significant sediment infill. The latter (Fig. 2) is a relatively large fresh water body (54 km^2) at

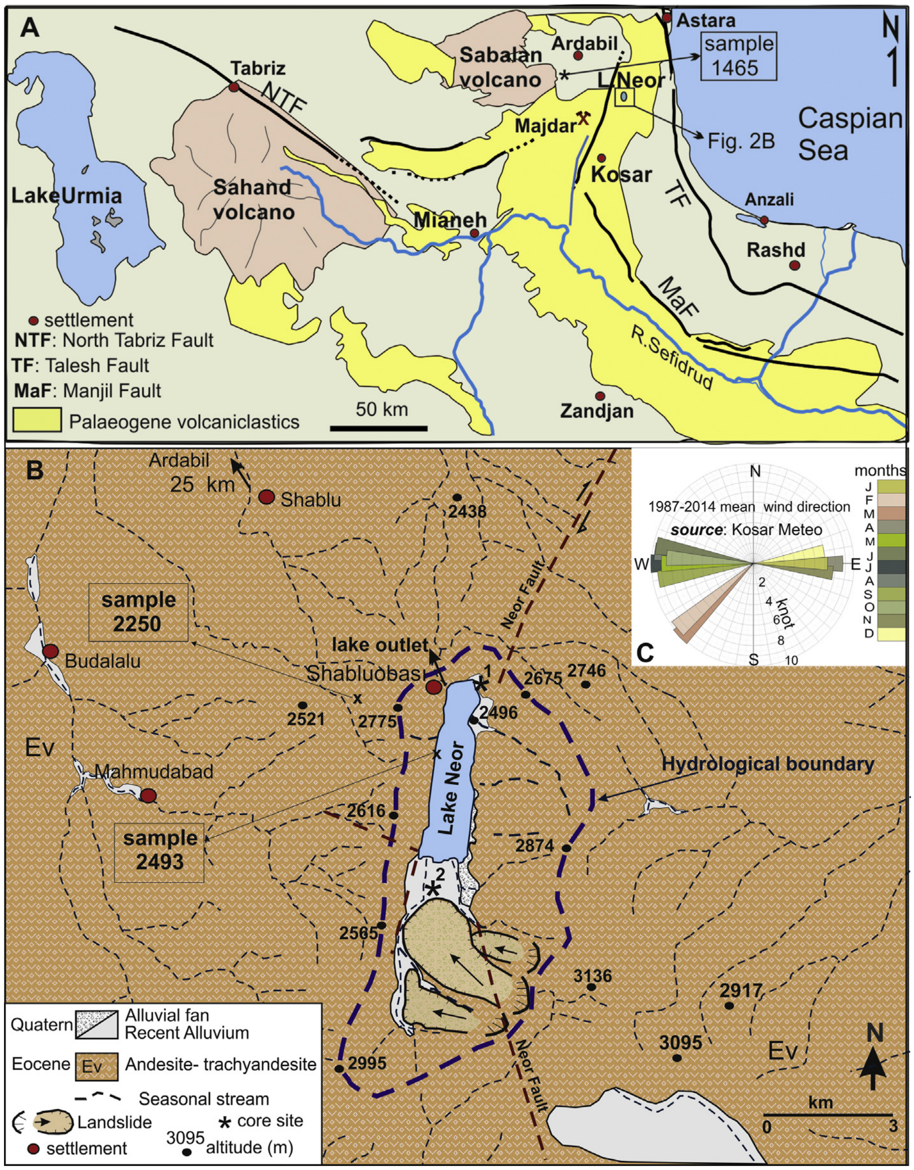

Fig. 3. A) The main geological and geographical elements of the northwestern Iran. B) Drainage area of Lake Neor and some elevations in its surrounding. The landslide here has been mapped by the satellite image. Neor Fault is from Clark et al. (1977). 1, 2 core sites of previous studies (see Fig. 4 for details). X for pollen sampling. C) Monthly wind directions of the last 27 years in the high Alborz. See Fig. 3A for site of the meteorology station.

2100 m a.s.l., but too deep (37 m) for sampling by piston corer. The present study focuses on L. Neor as it is shallow (3 m).

Western Asia and the Middle East are regions so affected by dust storms that in some days the Sun is not visible because of dense particles in the air (Kutiel and Furman, 2003; Akbari, 2011) (Figs. 1 and 2). Moreover, due to the presence of very fine detritus and high turbulence in the atmosphere, the ozone layer could be affected by large storms even if their contributions are not comparable with anthropogenic effects (Washington et al., 2003). Long-term observations indicate that the principal sources of the dust in southwestern Asia are desert areas in Saudi Arabia and Iraq and to a lesser extent the Sahara, Egypt and the central part of Iran (Modaihsh, 1997; Rifaat et al., 2007) (Fig. 2). Therefore, the Middle East is one of the few convenient regions to research the aeolian control on lacustrine sedimentation. Due to common dust storms, many settlements have been affected (Anonymous, 2005; Esmaili et al., 2006; Rifaat et al., 2007; Akbari, 2011; Gerivani et al., 2011) (Figs. 1 and 2). Lake Neor, the study site, is a perfect example for our purpose as its drainage area is small and consists of only one type of rock, andesite (Figs. 2 and 3). The catchment of Lake Neor is only 45 km^2 on a plateau-like mountain top at an altitude of between 3150 and 2500 m a.s.l. (Fig. 3). It has fairly smooth topography except for a relatively large landslide (Fig. 3). The western part of the catchment is relatively steep and narrower than the other sides. Therefore, it is possible to say that the main sediment source of the lacustrine basin is on the eastern margins, as made clear by the presence of some alluvial fans (Figs. 3 and 4). The simplicity and homogeneity of the sediment sources are important because exotic grains or minerals are more easily detected in the lacustrine basin.

3. Geographic and geological settings

The northern part of the Middle East, including eastern Turkey, northwest Iran, Georgia, Armenia and Azerbaijan, are regions of strong relief combined with broad high plateaus and large volcanic centres (Ağrı, Sabalan, Sahand), including some deep valleys, long

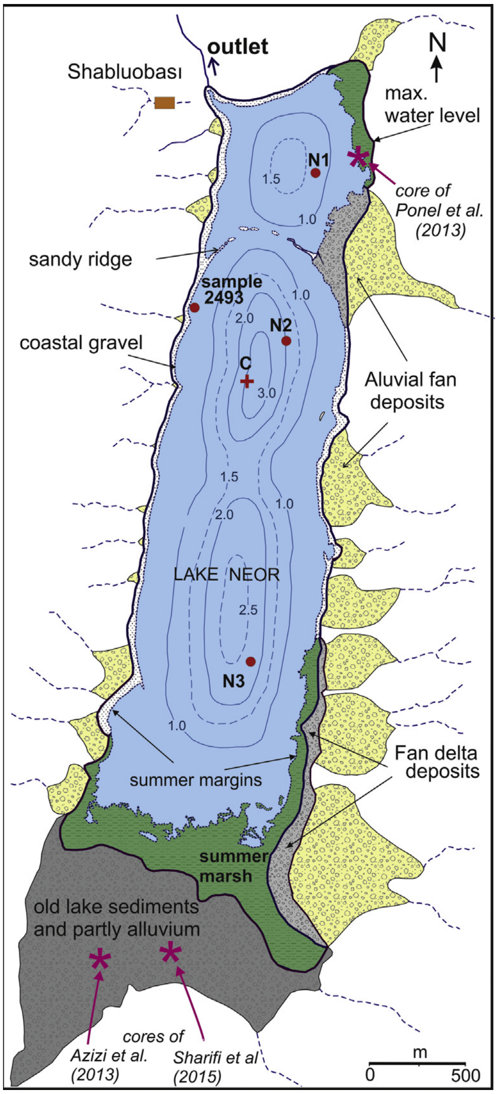

Fig. 4. Bathymetry and marginal sediments of Lake Neor: N1–3 and C sample sites (see text for details). Note that the lake is splitting in two parts when water level is down in autumn, but becomes one large lake in spring and early summer. Depth is in meter.

streams and large lakes (Fig. 2). Mean elevation is around 1600–1800 m a.s.l. However, some peaks are over 4500 m, e.g. 5160 m Mount Ağrı in the eastern Taurus and 4810 m Sabalan in the Alborz (Fig. 2). On some high summits, especially in the northern parts of Alborz, glaciers still exist and furthermore relicts of ancient glaciers can be found (Ferrigno, 1991). From these relicts, it is possible to say that glacial processes had a significant influence on the morphology of that region some time ago. Present-day morphology is essentially a result of continent–continent collision between the Anatolian (Turkey) subplate and/or the Eurasian and Arabian plates along the Bitlis and Zagros sutures and the consequent intracontinental deformation (Şengör and Kidd, 1979) (Fig. 2). The region is therefore characterized by several sub-regions with differing morphological characteristics. The Pontides and the Alborz in the north, and the Taurus and the Zagros in the south, are composed of tectonically juxtaposed volcano-sedimentary sequences that belong to different continents (Fig. 2). The age of the rock units ranges from Precambrian up to Middle Eocene. Cretaceous–Eocene Tethyan ophiolites and ophiolitic mélanges, occurring within an accretionary prism, form the basement in the region. The Oligocene–Early Miocene time interval corresponds to a period of tectonic quiescence and major transgression during which the area was invaded by sea from the south to the north. After that, mostly in the Late Miocene, the basement, forming an accretionary prism and overlying sedimentary cover, was intensely deformed. Continental basins formed and filled with fluvial sediments. The deformation has resulted in the shortening and uplift of the region that is distinguished by its unique landscape (Şengör and Kidd, 1979; Dewey et al., 1986). During the Pliocene-Quaternary, many volcanic centres including Mount Ağrı and Mount Sabalan, very large stratovolcanoes, have evolved in front of the suture zones as post-collisional magmatism (Shiran, 2013) (Fig. 2).

The geology of the Alborz belt has been studied and mapped previously in detail (Clark et al., 1975, 1977; Babahan and Rahimzade, 1988; Khodabandeh et al., 1990). According to these studies, the northern part of the Alborz belt and the drainage area of Lake Neor and its surroundings are composed of mainly andesites and trachyandesites with minor tuffaceous volcanoclastics of the Eocene, which were described as the Karaj Formation (Clark et al., 1975, 1977; Aftabi and Atapour, 2000) (Fig. 3). So, pre-collisional and post-collisional volcanics are found together in that region, providing correlation possibilities (Aftabi and Atapour, 2000; Shiran, 2013). One of the prominent characteristics of the Karaj Formation distinguishing it is the presence of mineralisation belts (Vasigh and Zamani, 2010). During the Quaternary the Alborz belt underwent strong glaciations and then developed the present physiography (Ferrigno, 1991; Tahouni, 2004).

Lake Neor lies in a simple depression near the mountain top (Fig. 3). Some previous studies have interpreted its origin as a graben, based on the presence of a possible strike-slip fault, i.e. the Neor Fault (Fig. 3) (Madadi et al., 2004; Karimdoust and Ardebili, 2012). However, no typical imprints of a tectonic landform occur.

4. Lake Neor

Lake Neor is a relatively small (4 km^2), narrow and long, freshwater body situated in the Alborz Mountains of NW Iran (37° 99′ N, 48° 36′ E), at an elevation of about 2500 m above sea-level (Fig. 2). The lake is dammed probably by old diamictites and partly by alluvial fans. It has a maximal water depth of 3.5 m, with a natural outlet (Fig. 4). No regular flowing water reaches the lake; thus precipitation is the only water source (Figs. 3 and 4). Due to overflows in winter and spring based on snow melting, the lake level rises 1 m and some coastal features become drowned (Fig. 5). It is surrounded by a narrow belt of coastal gravel formed by the interaction of alluvial fans and the lake water (Fig. 4). A small part at the southern end of the lake is covered by a sedge marsh; however it is mostly flooded in winter. The old lake sediment here has been cored recently by Azizi et al. (2013) and Sharifi et al. (2015) (Fig. 4).

There are no significant aquatic plants in the lake. The surrounding area is covered by a low steppic vegetation (that belongs to the Irano-Touranian floristic region; Ghahremaninejad et al., 2012) in early summer and so the valley is used for grazing. Overgrazing leads to the destruction of the vegetation, which is especially rich in endemics, and erosion (Ghahremaninejad et al., 2012). Many people come here for recreational activities (Nejad, 2015). This activity traditionally includes cooking over fire. Trout is the only other economic value of the lake.

No meteorological stations exist near the lake. Climatic detail can only be obtained from the closest settlement (Ardabil), which is at a much lower elevation, 1200 m. According to information collected from local people, the area receives much snow that sometimes reaches a thickness of 1 m, although summits are bare because of strong winds. The lake freezes from late December to mid-April. The minimum and maximum temperatures around the

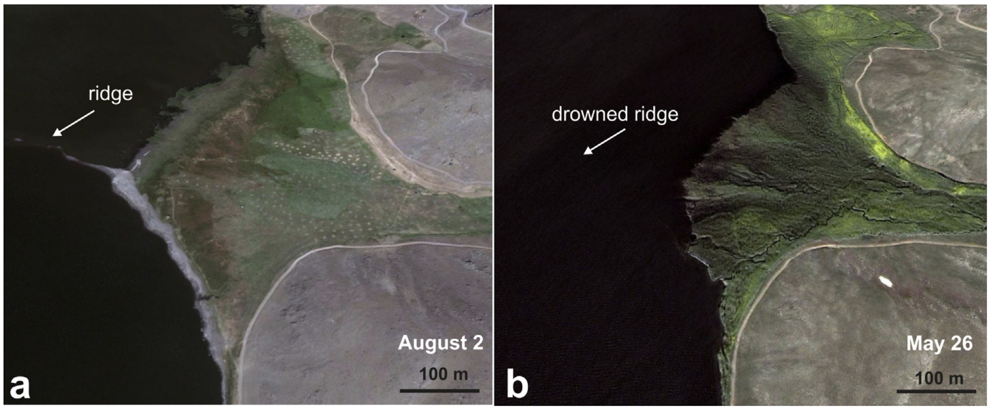

Fig. 5. Appearance and drowning of an alluvial fan based on annual water level oscillations. a) gravelly ridge, fan delta and alluvial fan at the low water-level (on August 2, 2013), b) drowned ridge and fan delta at a high water-level of May 26, 2012.

lake have been measured −37 °C in January and +39.5 °C in July, respectively (Nejad, 2015). In some years, ice thickness can reach 50 cm. However, the last few years' winters had less snow and were milder, as also seen in Ardabil (Table 1). The average annual precipitation in the lake area is given as 460 mm (much higher than Ardabil) in a recent article (Nejad, 2015).

5. Data acquisition

Lake Neor has become a popular tourist destination recently in Iran (Nejad, 2015) and so water quality is continuously controlled by the Ardabil Office of the Directorate for Environment Protection of Iran (Table 2). Surprisingly, no reliable data exist on the limnological properties of the lake based on measurements, except for water chemistry, in spite of the abundance of websites and some palynological studies (Azizi et al., 2013; Ponel et al., 2013; Sharifi et al., 2015). Therefore, the lacustrine basin and its surroundings had to be mapped first using satellite images and then geological formations controlling the deposition were described (Figs. 3 and 4). The elevations provided on Fig. 2 are from the topographic map at a scale of 1/25.000.

Three bulk samples (N1-3) and a sediment core (C) obtained from the lake centre are the main materials for this study. N1-3 samples are from bottom surface sediments taken by a dredge in the early summer of 2013, while the core C is a 60 cm long and 5 cm diameter piston core provided in autumn of the same year (Fig. 3). Core (C) was divided into six parts from bottom (C1) to top (C6) and in each part ~10 cm of sediment was averaged together for analyses (Table 4). During the campaign, the lake depth was measured at sampling points and results have been used when preparing the bathymetric map of the lake by ArcGIS (Fig. 4). Not only the surface area but also the depth of the lake is fairly small, although it is known to have been previously larger and deeper (Nejad, 2015). The maximum depth is 3.50 m at the centre of the lake (Fig. 4). The sediment samples were analysed at the laboratories of Mineral Research and Exploration (MTA, Ankara, Turkey) for mineralogy and geochemistry (Tables 3 and 4) and of Ankara University for sedimentological proxies by standard techniques (XRD, XRF, optical microscopy, etc). Loss-on-Ignition data (LOI) were obtained by the combustion of 5-cm^3 sediment samples in a furnace at 550 °C. Percentages were calculated relative to the dry sediment, with organic matter, carbonate and residual ash forming 100%. Grain-size of sediment samples was determined by using both Malvern Mastersizer 2000 and sieving at MTA Labs in Ankara. Radiometric age data of two recent works on this lake (Azizi et al., 2013 and; Ponel et al., 2013) have been used for interpretation.

5.1. Palynological method

Five samples (2 ml for each) from core C and the three modern samples of mud (3 ml) were analysed. The Ardabil sample at 1465 m was taken along a small river, the sample at 2250 m in a spring in a meadow with some trees, and the Ardabil sample at 2493 m on the NW shores of Lake Neor (Figs. 3 and 4).

The sediment samples were soaked in 10% tetra-sodium pyrophosphate solution to deflocculate the sediment. The samples were then treated with cold hydrochloric acid (first at 10% and then pure), cold hydrofluoric acid (32%), followed by a repeated cold hydrochloric acid treatment, in order to eliminate carbonates, quartz and fluorosilicate gels, respectively. Finally, the samples were sieved through 125 and 10 μm nylon meshes. In addition, samples from core C underwent a density separation with sodium polytungstate at 2.4. Then the residues were mounted on glass

Table 1
Meteorological records of the last three years at Ardabil. Source is http://www.ncdc.noaa.gov/ghcnm/.

	Year	Months												Mean
		1	2	3	4	5	6	7	8	9	10	11	12	
Temp.°C	2011	−1.4	−1.5	3.7	9.8	14.7	17.5	21	17.8	14.6	10.3	0.7	0.9	9.0
	2012	−0.4	−1.1	1.5	12.2	15.9	18.1	18.5	20.2	15.1	13.4	7.4	3	10.3
	2013	3	4.5	7.9	9.3	12.9	16.8	17.7	17	16.8	9.6	6.7	−4.3	9.8
Precip (mm)	2011	19.04	42.66	23.36	33.01	36.57	10.4	1.52	7.6	14.74	31.49	38.86	11.18	270.4
	2012	19.03	3.8	42.15	28.19	76.21	24.38	18.53	3.05	10.41	0.76	36.84	18.52	281.9
	2013	19.55	24.13	16	31	54.35	27.94	0	22.6	0	2.03	31.23	32.52	261.4

Table 2
Water characteristics of Lake Neor in different months of the last seven years (from Ardabil Office of the Iranian Environment Bureau). Note the difference on 22 August 2008.

	Date	10.5.2007	24.6.2007	16.7.2007	14.8.2007	17.9.2007	14.1.2007	22.8.2008	26.5.2010	23.9.2010	21.6.2012	26.9.2012	06.5.2013	17.6.2014
TDS	mg/l	239	240	243	263	283	272	164	239	240	231	230	230	274
EC	µs/cm	345	354	350	370	397	298	348	345	354	247	351	355	390
DO	mg/l	5.5	6.7	7.9	6.7	6.8	8.9	9	5.5	6.7	5.3	6.4	6	7.9
Transparency	NTU	11	50	27	90	55	42	20	11	50	11	37	31	34
pH		8.65	8.62	8.9	8.75	8.7	8.9	7.5	8.65	8.62	8.67	8.65	8.6	8.96
Water temp	°C	16	19	21.5	16	17	5.5	–	16	19	17	18	17.5	16.5
NO3	mg l	1.2	0.8	1.4	1.7	2.8	3.8	0.1	1.2	0.8	1	0.8	10.8	3.5
NH3	mg l	0.19	0.23	0.17	0.88	0.01	0.43	–	0.19	0.23	0.12	0.21	0.49	0.01
$MgCaCO_3$	3/l	95	95	130	155	120	100	–	95	95	95	100	125	120
Na	mg l	34.5	34.5	18.4	13.8	34.5	41.4	–	34.5	34.5	32.2	27.6	16.1	34.5
Mg	mg l	7.3	7.3	9.5	13.3	10.9	7.3	–	7.3	7.3	7.3	9.7	10.9	9.7
Ca	mg l	26	26	36	40	30	28	–	26	26	26	24	32	32
SO_4	mg l	0	0	0	0	0	9.6	1	0	0	0	0	0	0
Clorites	mg l	17.7	14.1	10.6	28.3	17.7	21.2	–	17.7	14.1	14.1	10.6	7.1	17.7
Bicarbonate	$mgCaCo_3$,l	183	183	189.1	183	213.5	189.1	–	183	183	183	183	183	213.5
Fecal cloroform	N/ml	0	7	4	21	0	0	–	0	7	0	3	23	0
Total cloroform	N/ml	0	240	9	93	3	0	–	0	240	0	3	23	3
COD	mg/l	18.8	15.2	35.8	83.5	74.2	108	34	18.8	15.2	18.2	19.6	31.5	60
BOD	mg/l	4	4	14	5	8	8	17	4	4	5	9	9	8
P	mg/l	0.1	0.3	0.9	0.3	0.6	0.4	–	0.1	0.3	0.1	0.3	0.1	0.3

slides in glycerol. The initial addition of *Lycopodium* tablets allowed the estimation of concentrations (number of palynomorphs per ml of wet sediment).

A light microscope at ×400 magnification and at ×1000 for special identifications was used to count the palynomorphs. Pollen atlases and the pollen reference collection at Brunel University London were used to identify pollen and spores. The identification of type HdV 119 is based on photos in Pals et al. (1980). This type is an unknown non-pollen palynomorph that was suggested in Van Geel et al. (2003) to be of zoological origin.

Percentages were calculated on the terrestrial sum (median of 344 terrestrial pollen grains), which represents pollen from plants growing on land, and the diagrams were plotted using the Psimpoll software, version 4.27 (Bennett, 2007). Due to the high concentration of organic debris (also found as a problem in the core in the bog; Ponel et al., 2013), only the concentration of the most abundant palynomorphs is shown along the sequence of core C: microcharcoals, fungal spores, *Glomus* (a fungal spore typical of soil erosion) and t. 119, alongside pollen. The results of pollen analysis of core C are plotted as histogram bars alongside the three surface samples.

6. Results

6.1. Drainage area and sediment sources

The only lithology of the catchment is andesite-trachyandesite lavas intercalated with some coarse-grained pyroclastic layers of the Eocene (Fig. 3A,B). However, the volcanics of not only Eocene but also Plio-Quaternary, in the Alborz Mountains have an andesitic character and it is difficult to differentiate them from each other (Aftabi and Atapour, 2000; Shiran, 2013) (Fig. 3A). The Eocene volcanics have been well analysed as some of them include Fe- and Cu-rich ore deposits, e.g. the Majdar bed 19 km southwest of the lake (Vasigh and Zamani, 2010). From these analyses, it is possible to compare the composition of lake sediments and their sources and the results indicate a strong resemblance of major elements between source rocks and lake sediment (Tables 3 and 4).

6.2. Lake morphology and the depositional environments

According to our detail mapping and field measurements, Lake Neor is a 4100 m long and 950 m wide water body when at its maximum extent in early summer due to snow-melt. However, it becomes smaller in late summer and/or early autumn forming marshes at northern and especially southern ends (Fig. 4). At that time, the lake is divided into two parts closed to the outlet by a sandy ridge toward the west from the eastern margin (Figs. 4 and 5). The bathymetry indicates that the lake has a more or less flat bottom topography with a 3.5 m depth maximum (Fig. 4). At cm-scale, however, three depressions are visible, possibly formed by the progradation of the alluvial fans. The sandy ridge is exposed when the lake level decreases (Fig. 4). The main depositional environments in and around the lake are summer marshes in the north and the south and a small fluvial plain (alluvium) at southern side, alluvial fans at eastern and western margins and the lacustrine basin itself (Fig. 4). In addition, some boulder-size clasts within the alluvial fan deposits at the western margin suggest that snow avalanches provide sediment to the basin.

6.3. Water characteristics

According to our graphical calculations using 2012 and 2013 values, Lake Neor has a maximum water volume of 9.10^6 and minimum of 72.10^3 m^3. Local people have witnessed that it has

Table 3
Relative mineral composition of the lake sediments based on XRD analyses. XXXX very abundant, XXX abundant, XX present, X rare.

	Feldspars	Quartz	Calcite	Hematite	Pyrite	Dolomite	Micas	Simectites	Palygorskite	Amorph. matter
C6	xxxx	xxx	xx	xx	–	x	–	xxxx	X	xx
C5	xxxx	xxx	xx	x	x	xx	–	xxxx	x	xx
C4	xxxx	xxxx	xxx	–	–	xxx	–	xxx	–	xxx
C3	xxxx	xxx	xxx	xx	–	xx	–	xxxx	–	x
N2	xxxx	xxx	xx	xx	xx	xxx	–	–	–	x
C1	xxxx	xxxx	–	xx	xx	xxx	x	xxx	–	x
N1	xxxx	xxx	xx	–	–	x	–	xx	–	xx
N2	xxxx	xxx	xx	–	–	x	–	xx	–	xx
N3	xxxx	xxx	xx	–	–	x	–	xx		xx

Table 4
Major and some minor element compositions of lake sediments (C1–6, N1–3), source rock (Majdar beds from Vasigh and Zamani, 2010) and major elements of dust samples collected from town Ardabil. Note that some elements could not be detected due to detection limit of facilities and/or not analysed (Tl and LOI_{550} in C 1–6).

Sample no		C6	C5	C4	C3	C2	C1	N3	N2	N1	Majdar n = 13	Ardabil dust, n = 7
SiO_2	%	58.9	58.7	43.3	58.1	39.2	61.1	54.01	57.18	57.20	**56.56**	**37.29**
Al_2O_3	%	19.2	19.8	11.9	18.2	12.1	15.4	17.64	17.95	18.09	**15.42**	**9.37**
Fe_2O_3	%	5.57	4.51	14	5.48	8.03	6.3	6.40	6.11	5.11	**7.17**	**4.84**
CaO	%	4.7	5.4	19.2	6.48	32.7	5.8	2.71	3.58	4.71	**5.35**	**17.45**
MgO	%	1.01	0.816	1.08	1	1.14	1.38	1.67	1.33	0.89	**2.55**	**4.52**
Na_2O	%	4.59	4.95	–	4.43	–	2.82	1.31	2.57	3.04	**1.17**	**0.57**
K_2O	%	4.29	4.2	3.77	4.26	4.14	4	4.54	5.42	5.29	**1.82**	**1.44**
Cr_2O_3	%	–	–	0,0043	–	–	0,0196	0.00	0.00	0.00	–	**0.03**
TiO_2	%	0.782	0.738	1.55	0.809	1.07	1	0.77	0.82	0.79	**0.77**	**0.67**
MnO	%	0,0793	0,0622	0.289	0,0727	0.28	0,0783	0.13	0.11	0.08	**0.40**	**0.08**
P_2O_5	%	0.503	0.457	–	0.486	0.457	0.593	0.52	0.66	0.71	**0.28**	**0.27**
SO_3	%	0.143	0,0886	2.83	0.458	0.496	1.23	0.21	0.20	0.19	–	–
Cl	%	0.011	0,0081	0,0447	–	–	0,0215	0.00	0.00	0.00	**0.00**	–
V_2O_5	%	–	–	0,0074	–	–	0,0252	0.02	0.02	0.02	–	–
LOI	%	–	–	–	–	–	–	9.83	3.82	3.82	–	**22.83**
Ga	ppm	11	13	–	13	13	17	19	20.1	19.6	–	–
As	ppm	6	6	23	2	10	7	12.1	11.4	11.2	**860.85**	–
Br	ppm	6	4	530	12	58	75	2	1.5	0.9	–	–
Sr	ppm	838	862	1220	764	1420	859	482.5	722	822.9	**534.92**	–
Nb	ppm	16	14	43	–	38	22	22.5	15.4	12.2	**10.92**	–
Sn	ppm	47	43	154	45	120	77	1.5	1.4	2	–	–
Tl	ppm	5	4	–	–	–	–	1	1.6	1.5	–	–

never been totally closed or emptied because of natural morphology and climatic conditions. Hence, water chemistry would have remained more or less the same for years previous to its record between 2007 and 2014 (Table 2). As fish farming and sporting activities mostly take place at the northern margin near the outlet, they do not much affect the water quality. Even in different seasons, water chemistry (Eh, pH, DO) remains constant (Table 2).

Water temperature is rarely over 21 °C. The only exception is values measured on 22 August 2008 from water in the lake at that time (Table 2). Local people informed us that large dust storms occurred at the end of the summer in 2008. However we could not verify from the Ardabil Office of the Environment Protection whether the chemical anomaly of lake water resulted from a dust storm, an anthropogenic factor, another natural event or even a measurement artefact.

6.4. *Sediments and lithofacies*

The mapping and sample examinations indicate that two granulometric types of deposit occur in and around Lake Neor: A) coarse-grained marginal sediments mainly formed by alluvial fans, fan deltas, runoff and avalanches from the catchment; and B) fine-grained basinal sediments deposited from suspension. They were mapped based on depositional mechanisms and environments (Fig. 4).

Fan-delta deposits: These are the most common lithofacies in the area formed by alluvial fans prograding into standing water (Nemec and Steel, 1988). Seven mapable fan deltas occur on the eastern side with four on the western side of the lake (Fig. 4). Alluvial fans that represent the fan-delta plains are gravel-rich, but delta fronts or fan deltas themselves are sand-rich depositional environments. Sand grains commonly consist of quartz and feldspar, while gravel-size clasts are fragments of andesite rocks. The boundary between delta plain and delta fronts is apparently sharp, not only in grain-size but also in surface inclination from 3 to 5° for the alluvial fans to 7–9° for the fan deltas. This results from wave action and annual oscillation of water level.

Coastal gravels: These are mixed sediments of pebble- and sand-size grains on the margins, mostly on the western side. They were formed in the lower beach zone by wave actions under the control of annually fluctuating water level. This lithofacies is the distal part of fan-delta deposits. The only difference is the abundance of clean sandy sediments. In addition, the lithofacies randomly include some cobble-size clasts, over 20 cm in diameter, particularly on the western margins. The presence of such relatively coarse-clasts indicates that snow avalanches have occurred from time to time together with ordinary gravity and sheet flows. The steep slopes of the backshore here are suitable environments to generate such mass transport events. This process is not unusual for fan-delta environments (Nemec and Steel, 1988).

Sandy ridge: This is both a sediment accumulation and also a morphological formation between the eastern and western margins towards the north of the lake (Fig. 4). It is a ca 1 m high, 250 m wide and over 500 m long, crescent-like ridge that is exposed in late summer (Figs. 4 and 5). Its outer surface consists of gravelly sand (no information is available about its inner part). At first sight, its spatial position suggests that it was formed by sediments of alluvial fan 7 as a spit. However, the relatively small lake size and limited water depth do not seem to be sufficient for the generation of strong waves to create such a large ridge.

Basinal deposits: This lithofacies includes all kinds of sediments (organic, inorganic, clastic and chemical) deposited in the lacustrine environment (Fig. 4). Previous studies mentioned a sediment thickness of at least 8 m in the southern and northernmost parts of the lake (Azizi et al., 2013; Ponel et al., 2013; Sharifi et al., 2015) (Figs. 3 and 4). However, we obtained only a 60 cm core from the middle of the lake to see the deposition from suspension (Fig. 4). According to its physical appearance when it was first recovered, the sediment (core C and surface samples N1–N3) is a viscous and somewhat plastic, peat-like, brownish mud. This sediment consists of relatively fine-grained (very fine sand, silt and clay) muds. However, their grain-size and amount varies in different areas of the lake bottom. The mean grain-size of the sediments in the axial part of the lake is between 15 and 90 μm (N2-3; Figs. 4 and 6).

6.5. Sediment composition

In this section, detailed analyses of basinal sediments are presented. The mineralogical constituents of core and bottom surface sediments (C 1–6, N1-3) described by XRD method are consistent with quartz (Q), feldspar (F), smectites (S) and to lesser extent opaque matter (Table 3). This is a common mineral composition for andesite and trachyandesite. However, the relative abundance of rock-forming minerals Q, F, and S are significantly different in some samples (Table 3). The abundance of smectites depends on a wide alteration of the source rocks (Vasigh and Zamani, 2010). The exotic minerals here, compared with the original composition of source rocks (andesite, trachyandesite), seem to be calcite, dolomite, mica and palygorskite. Relative abundance of calcite and dolomite is very apparent, despite the latter two are minor in the sediments (Table 3). Hematite and pyrite have been found at Majdar ore deposits (Vasigh and Zamani, 2010), and they might be derived from the catchment. Moreover, the diagenetic formation of pyrite within lacustrine sediment is well known (Manning et al., 1994).

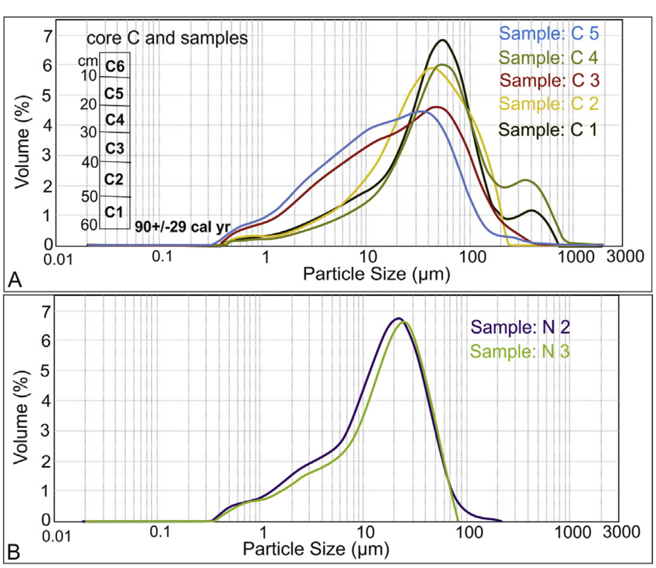

Fig. 6. Grain-size distributions of Lake Neor basinal deposits; A) grain-size of core sediment (C); note that each sample represents a 10 cm interval of the core. The calibrated age (^{14}C) is from Ponel et al. (2013) for 64–65 cm depth (see Fig. 4 for core site), B) grain-size of bottom surface sediments (N2–N3). Note the strong similarity of grain-size distribution.

The geochemical composition of basinal sediment samples (C1–6 and N1–3) is listed in Table 4 with columns for Majdar and Ardabil dust. The correlative distributions of some elements are in Fig. 7. The Majdar column on the right side shows the average of 13 samples of the source rocks collected from the Majdar area and analysed by Vasigh and Zamani (2010) (Fig. 3A, Table 4). As result, silica content of some basinal sediments (N1–3, C 1,5,6) are about 57–61% and they are close to those of Majdar samples (=equivalent to source rocks). Surprisingly, silica content of samples C4 and C2 are very low (39–43%) resembling silica content of the modern Ardabil dust (Table 4). Vertical distribution of some elements shows strong negative correlation with Si, Al, K and particularly Ca, Mg, Fe, Ti, Mn (Fig. 7). In addition, the distribution of S, As, Br, Sn in the sediments is of the same order, whereas the presence of Na, P, Nb, V, Cl, Ga, Tl does not show any regularity (Fig. 7). From Table 4 and Fig. 7, it is clear that not only silica but also Al_2O_3, Fe_2O_3, CaO, Na_2O, TiO_2, Sr and Sn values of these layers (50–40 and 30–20 cm; Figs. 6A and 7) are significantly different from others. The most apparent constituent is CaO that reaches between 19.2 and 32.7%. However, the average in other samples and also in the source rock is only around 3–5% (Table 4, Fig. 7). It must be dependent on the presence of abundant calcite and dolomite minerals within these layers (Table 3).

Minor element content of the basinal samples displays differences between various core depths and also surface samples, i.e Br, As and Sr contents at 20–30 cm (C4) and 40–50 cm (C2) levels are apparently higher than others (Table 4; Figs. 6A and 7). Another important compositional characteristic of the lacustrine deposits (N1–3) is the high volume of organic matter (unfortunately they could not be analysed in core samples; Table 4), but it is somewhat reflected in the charcoal concentration in the palynological analyses (Figs. 8 and 9).

6.6. Palynological results

Core C: the concentration of the five palynomorphs decrease upwards. The values of microcharcoals are especially high in general, including a peak of 2 million per ml at the base and of 5 million per ml at 15 cm depth. The top sample at 5 cm depth is clearly different with low values for the five palynomorphs. Note the proportionally low values in pollen from 12,000 to 3000 grains per ml. The data suggest intensive erosion from the drainage basin, as well as trapping of dust.

Pollen analyses in surface samples: the diagram (Fig. 9) is dominated by non-arboreal pollen, with a clear shift from very high values of sedges (Cyperaceae) including even broken stamina in the lake centre (core C) and lake side (Ardabil 2403 m), to high values of grasses (Poaceae) in the two steppe samples especially, that are at the lowest altitude (the village of Ardabil at 1465 m). The arboreal values are generally low reflecting the very open landscape around the lake. The Ardabil sample at 2250 m has more tree pollen because of the local presence of willows along the river. Distant pollen transport that can be expected in any mountainous area above the tree line include deciduous *Quercus*, *Carpinus betulus*, *Alnus* and *Fagus* amongst others. They are derived from the Hyrcanian forest <20 km to the east (Ghahremaninejad et al., 2012; Ponel et al., 2013). The few pollen grains of *Olea* are probably from further away in the Manjil area (150 km to the south – southeast) where they are intensively cultivated. Similar occurrences of *Olea* above the tree line have been found in the detailed study made in the Pyrenees Mountains (Cañellas-Boltà et al., 2009). Other trees

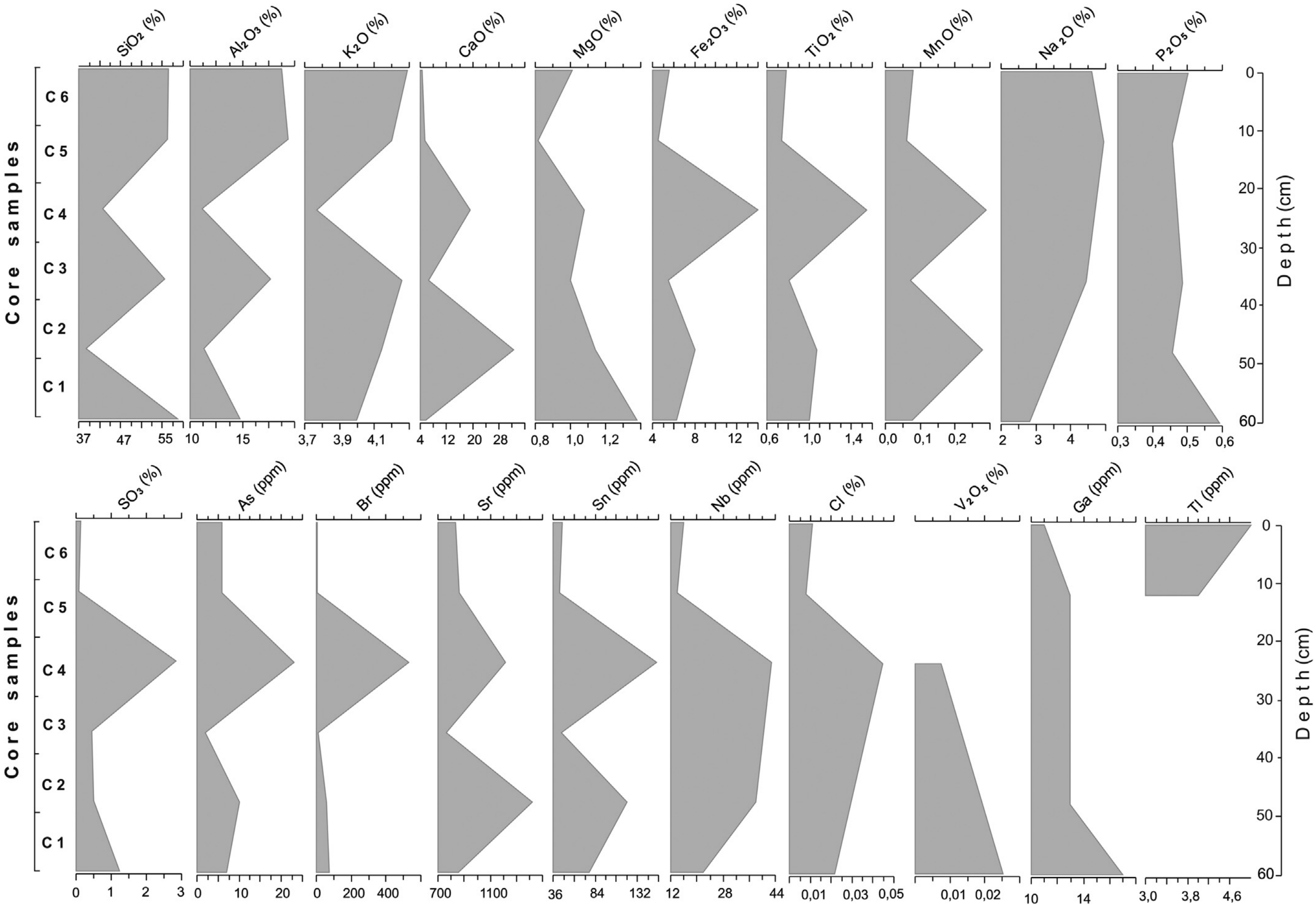

Fig. 7. Comparison of some major and minor element distributions along the core. Note that silica, aluminium and potassium are in negative correlation with each other.

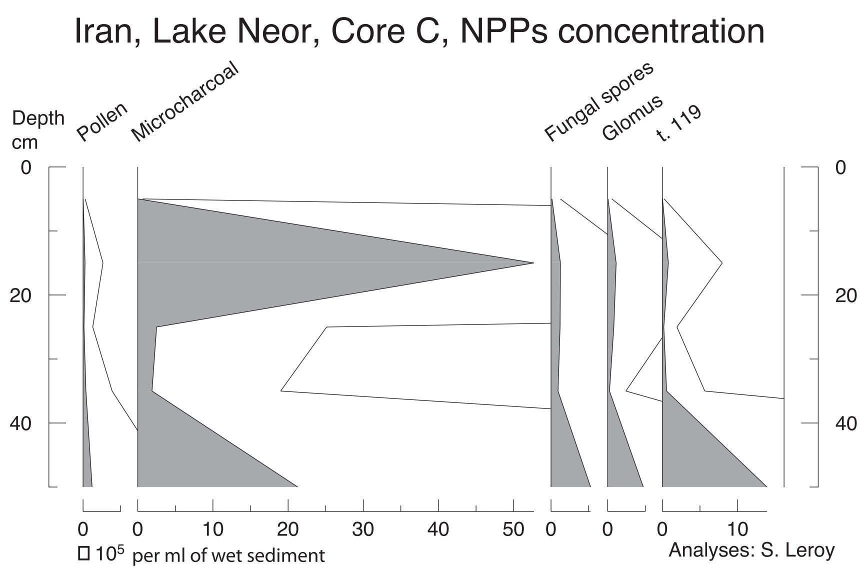

Fig. 8. Non Pollen-Palynomorphs concentration of Core C in Lake Neor.

such as *Pistacia* are most likely transported from the west. This phenomenon of pollen transport upslope is very well known and may have a significant effect on pollen assemblages of open landscape above the tree line (Fall, 1992).

Grazing indicators are *Plantago*, *Podospora*, *Sordaria* and *Sporormiella*. *Trichuris*, a parasite of animals including ovine, has also been found (Ejarque et al., 2011; Brinkkemper and van Haaster, 2012). The aquatic plant pollen and fern spores are scarce. Ranges

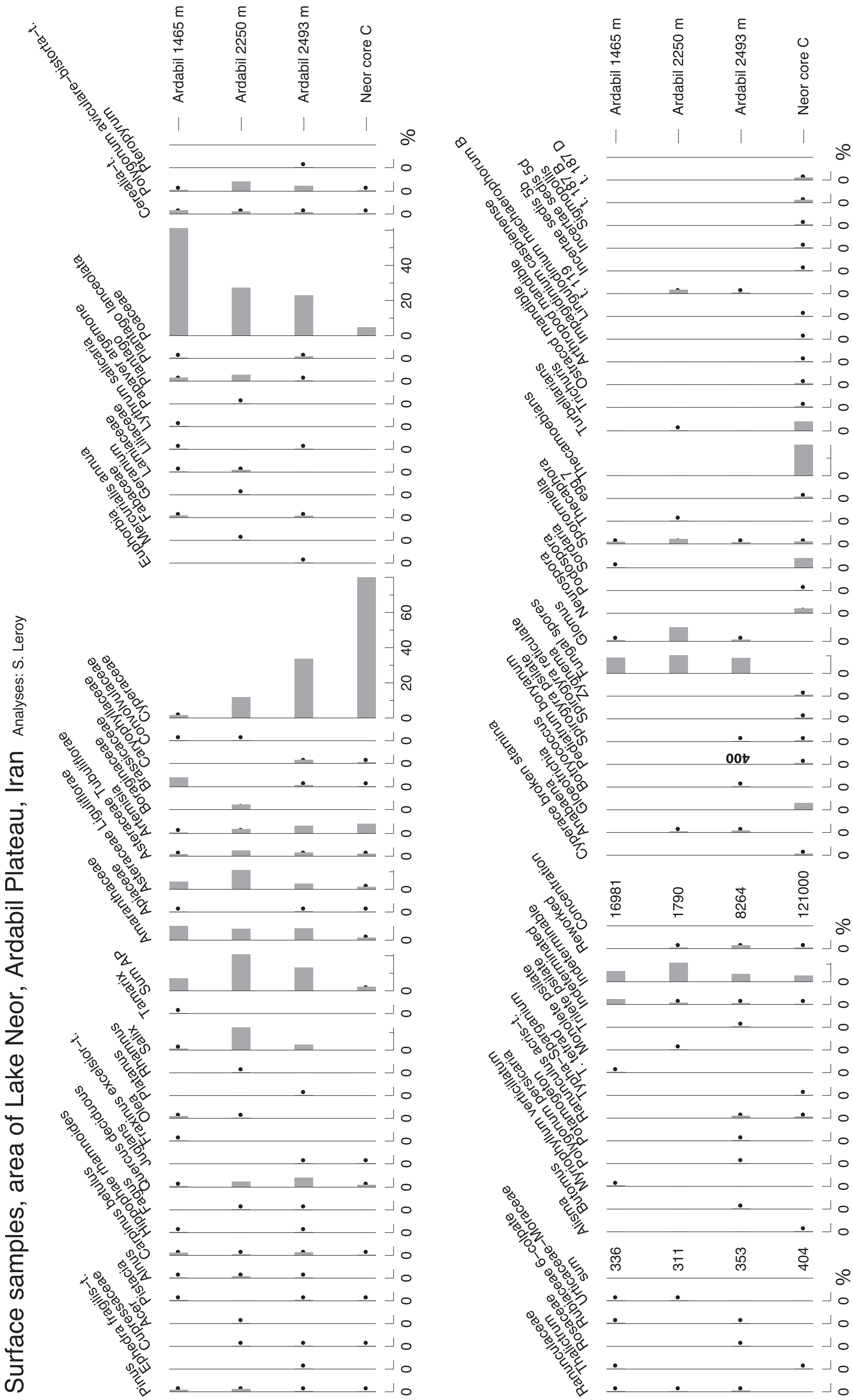

Fig. 9. Palynological content (in percentages) of surface sediment in Lake Neor and from its surrounding. See Fig. 3A for sample sites.

of shallow water algae (Zygnemataceae) and of fungal spores (especially coprophilous) are found. The extreme abundance of *Glomus* in core C sample in comparison to the other three surface samples, points to a focussing of this soil erosion indicator in the lake centre. Neor C sample had two dinoflagellate cysts, typical of the Caspian Sea (*Impagidinium caspienense* and *Lingulodinium machaerophorum* form B; Marret et al., 2004), probably transported by birds (Leroy and Albay, 2010).

7. Discussion

Lake Neor is an exception among high-altitude lakes as it has a relatively large surface area (4 km^2) and more importantly, has a thick infill of >10 m formed during the last 13 ka (Azizi et al., 2013; Sharifi et al., 2015). It is the largest lake at the highest altitude (~2500 m) in the Middle East (Figs. 2–4). The origin, infilling, and evolution of this lake are briefly discussed.

7.1. Origin of the lake

The formation of the lacustrine depression and/or the origin of Lake Neor are not clear. It has been widely interpreted as a simple graben (Madadi et al., 2004; Karimdoust and Ardebili, 2012). However, the Neor Fault, the closest tectonic fracture, has been inferred as a long transform line, not an ordinary normal fault, first by Clark et al. (1975, 1977) and later by Babahan and Rahimzade (1988). During our fieldwork, we could not detect any structural signs in the lake area, like fault breccia, slickenside, slip surface or shifted alluvial fan or a river valley, except for a steep slope at the western lake margin (Fig. 4). Some other studies consider the lake as a cirque-like depression, most probably based on glacial features in the Alborz belt (Tahouni, 2004; Ghahremaninejad et al., 2012). The geometry of the lake and presence of a wide sandy ridge at the northern part of it (Figs. 3 and 4) suggest that glacier-related conditions were effective in the formation of the first depression. Hence, most probably Lake Neor developed as an ice-scour lake in the Late Pleistocene. In the following time period, a relatively thick infill (>10 m) for high-altitude lakes could have been formed there with 0.61 mm y^{-1} rate of deposition in the last 13 ka (12,885 cal. BP; Azizi et al., 2013). According to dates obtained (Ponel et al., 2013), the upper 283 cm of the lacustrine-fill was deposited in the last 6235 ± 57 cal. BP, pointing at a sedimentation rate of 0.48 mm y^{-1}, while the uppermost 65 cm of the infill is only 90 ± 29 cal. old. The recent sedimentation rate of Lake Neor seems to be also very high, even double that of some similarly-sized European lakes (i.e. Mosello et al., 2002; Gasiorowski, 2008). We suggest that the high rate of deposition is a result of aeolian input to the lake basin.

7.2. Deposition and lake evolution

The infill of Lake Neor mainly consists of gravelly marginal deposits derived from alluvial fans and fan-deltas, alluvium as stream deposits at the southern end of the lake and basinal deposits. Fig. 10 shows generalised sources and depositional types of the sediments in Lake Neor.

The extensive facies of the basin-fill is the basinal deposits. Interestingly, the distribution of these sediments in the lake is more or less monotonous, even thicker at the southern end than elsewhere (core of Azizi et al., 2013 in Fig. 4). Nevertheless, the general gradient of the lake basin is towards the north (Fig. 3). It is expected that such sediments should have been at depocentre primarily in the north in an ordinary alluvial- or fluvial dominated-lacustrine deposition. Another significance of the basinal deposits of Lake Neor is that they are relatively rich in organic matter (3.8–9.8% LOI_{550}, Table 4). Basinal deposits, not only the upper 60 cm

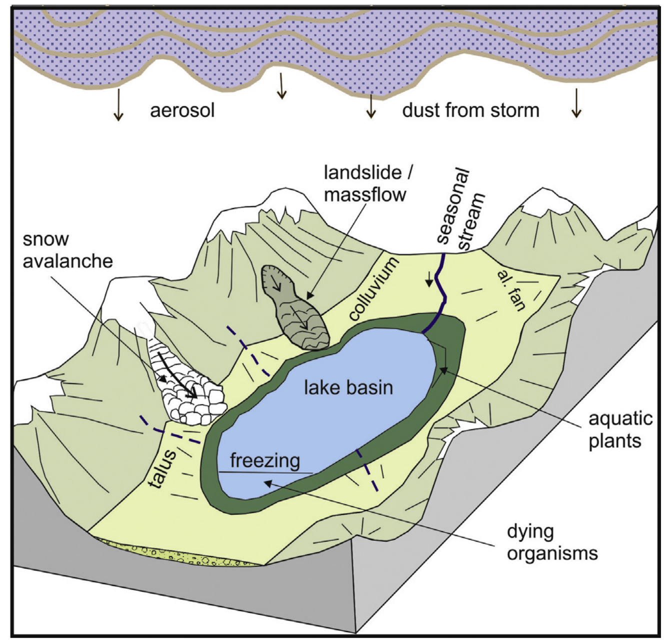

Fig. 10. A conceptual model for the allochthones and autochthonous sources for the high altitude lacustrine sediments.

examined by this study, but also the whole infill obtained from previous works (Azizi et al., 2013; Ponel et al., 2013), were described as gyttja and/or brownish peat. The organic matter of the lake at the upper part of the infill consists of abundant micro-charcoals (Fig. 8). Similar detritus has also been described previously in the lower 3 m of the infill (Fig. 7 in Azizi et al., 2013). However, the drainage area of the lake is barren except for some seasonal plants. On the other hand, an extremely high content of LOI_{550} in Ardabil storm dust and very abundant microcharcoal (10–125 μm) in the lacustrine sediment, are very distinctive (Table 4, Fig. 8). When considered together, these results suggest that organic matter within the lake sediment has been transported from outside by aeolian storms. The origin of the aeolian organic matter must be fine particles of charcoals, which were produced after large forest fires and possibly some burning by shepherds for better grazing. Recent research indicates that the Holocene was already characterized by extensive forest fires (Vannière et al., 2011; Christopoulou et al., 2013; Albani et al., 2015 and references therein). Decisively, the presence of some special minerals, i.e. calcite, dolomite, mica, palygorskite, in the basinal sediment that are exotic to the source rocks, supports aeolian transportation by dust storms (Table 3). In addition, major and minor element distributions through the infill shows a successive pattern parallel to that of the micro-charcoal concentration (Figs. 7 and 8). From here it is possible to determine that most of the sediment particles of the infill, i.e. charcoal, some carbonate minerals (calcite and dolomite), mica and many others have been transported here during dust storms. Aeolian-dominated deposition seems not to have been continuous but consisted of repetitive events as they were represented in Figs. 7 and 8. Such hazardous events are still very common in the Middle East and the whole of northern Iran, as a part of daily life (Anonymous, 2005; Esmailli et al., 2006; Akbari, 2011; Gerivani et al., 2011; Hojati et al., 2012; Keramat et al., 2013) (Fig. 1). A recent study showed dust storms are useful for plants and agriculture in the country (Ezzati, 2011).

The thickest sediment sequence of Lake Neor seems to be deposited as mire or gyttja at the south end of the basin, instead of the lake basin centre (Fig. 4). That part of the basin behaves as a sediment trap preventing particle transportation to the lake centre from the south (Figs. 3 and 4). Two important publications concluded that Middle East and west Asia have undergone dry intervals after the Last Glacial period based on existence of some aeolian input within sediment of that mire (Azizi et al., 2013; Sharifi et al., 2015). However, a mire is a kind of "wetland" growing only in wet climate. In addition, aeolian dust is a common particle in mire and they produce a fertilizing effect on the growth of plant organisms (Ezzati, 2011; Bao et al., 2012). Fig. 3C proves also that storm-generating winds are common around Lake Neor in year round. When considering all these facts together, the interpretation that aeolian input in the sediment would represent past dry periods as suggested by Sharifi et al. (2015) is not immediately obvious.

Like many other high-altitude lakes, L. Neor is covered by a 50–75 cm thick ice layer in winter. It means that during the wintertime a stable environment occurs in the lake. However no evidence for any diagenetic formation is known at that time. It is expected that some organisms, i.e. aquatic plants, may degrade and enter into inorganics enriching the muddy sediments as shown previously (Manning et al., 1994; Spadini et al., 2003). Briefly, sources of sediments of that lake could be summarized as streams, alluvial fans, snow avalanches, organisms, aerosols, air-falls (dust), and possibly, diagenetic processes. Storm dust in particular is a significant source of Lake Neor (Fig. 10). When regarding the limited drainage area of that lake, dust storms could be more important than would be expected in the history of a lake. Based on the very high sedimentation rate, a sorted grain-size distribution through the infill and abundance of exotic particles in the sedimentary sequence, it is assumed that half of the whole basinal sediments, at least, had been formed by aeolian input. For a precise description, further studies are needed.

8. Conclusions

Lake Neor is a high-altitude lacustrine basin. Its distinctiveness is of having a relatively thick (ca 10 m) infill, whereas its drainage area is limited (ca 40 km^2). The provenance of the lacustrine sequence formed mainly by basinal deposits was studied by facies analysis. The gravelly marginal deposits derived from alluvial fans and fan deltas surround the basinal deposits like a thin ring (Figs. 4 and 5). The prominent characteristics of the basinal deposits which are represented by organic-rich mud, gyttja and peat are 1 – associated with fine-grained clastic grains, generally 10–80 μm in dimension, 2 – the presence of mineral grains exotic to the source rocks of the drainage area, i.e. calcite, dolomite, mica, palygorskite, and 3 – the relative abundance of organic matter in the sediment, especially microcharcoal particles (Figs. 6–8, Tables 3 and 4). The localisation of the minerals and charcoal particles in some layers is another key result. They all suggest that deposition in Lake Neor has been mainly controlled by dust storms blowing predominantly from the west, south and southwest (Figs. 2 and 3). Local and regional meteorological data, in addition to the results of relevant investigations, support these directions. The charcoal particles within the sediment are also indicators of intensive fires in the Middle East and Mediterranean region during the Holocene. Based on core data and their correlations, it is possible to say that the intensity of fires has increased in the last century.

Together with the Middle East, some other parts of the northern hemisphere currently suffer from dust emissions (Goudie and Middleton, 1992; Clow et al., 2002; Kutiel and Furman, 2003; Rifaat et al., 2007). Although deposition from dust on the earth is not negligible, i.e. 270 μg m^{-3} in 2009 and 6–8 g m^{-2}.month^{-1} in central Iran (Givehchi et al., 2013; Hojati et al., 2012), only rare research focuses on its role on lacustrine deposits (Tait and Thaler, 2000; Rogora et al., 2001; Mosello et al., 2002). However, the basinal deposits of Lake Neor undoubtedly indicate that aeolian processes, specifically deposition from dust storms, are a significant control on lacustrine sequences.

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