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A new high-resolution pollen sequence at Lake Van, Turkey: Insights into penultimate interglacial-glacial climate change on vegetation history

Pickarski, Nadine[1] and Litt, Thomas[1]

[1] *University of Bonn, Steinmann Institute for Geology, Mineralogy, and Paleontology, Bonn, Germany*

Correspondence to: Nadine Pickarski (pickarski@uni-bonn.de)

Abstract

A new detailed pollen and oxygen isotope record of the penultimate interglacial-glacial cycle, corresponding to the Marine Isotope Stage (MIS) 7-6 (c. 242.5-131.2 ka before present), has been generated from the 'Ahlat Ridge' (AR) sediment core at Lake Van, Turkey. The presented record displays the highest temporal resolution for this interval with a mean sampling interval of ~540 years.

Integration of all available proxies shows three intervals of effective moisture, evidenced by the predominance of forested landscapes (oak-pine steppe forest), which can be correlated with MIS 7e, 7c, and 7a. The warmest stage in terms of highest temperate tree percentages is MIS 7c, while the amplitude of MIS 7e appears to be truncated by a shift to colder/drier climatic conditions. The detailed comparison between the penultimate interglacial complex (MIS 7) to the last interglacial (Eemian, MIS 5e) and the current interglacial (Holocene, MIS 1) provides a vivid illustration of possible differences of successive climatic cycles. Intervening periods of open steppe landscape correlate with MIS 7d and 7a, favouring local erosion and detrital sedimentation. The predominance of steppe elements during MIS 7d indicates very cold/dry climatic conditions. In contrast, the occurrence of more temperate tree percentages throughout MIS 7b points to relatively mild conditions, in agreement with atmospheric CO_2 concentration and oxygen isotope records.

Despite the general dominance of dry/cold desert-steppe vegetation during the penultimate glacial (MIS 6), this period can be divided into two parts: an early stage (c. 193-157 ka BP) with pronounced oscillations in tree percentages, and a later stage (c. 157-131 ka BP) with lower tree percentages and subdued oscillations. The occurring vegetation pattern is analogous to the MIS 3 to MIS 2 division during the last glacial in the same sediment sequence. Furthermore, we are able to identify the MIS 6e event (c. 179-159 ka BP) as described in marine pollen records, which indicates cooler but relatively wetter climate conditions during the penultimate glacial.

In comparison with long European pollen records, speleothem isotope records from the Near East, and global climate parameters (e.g., insolation, atmospheric CO_2 content), the new high-resolution Lake Van record presents an improved insight into regional vegetation dynamics and climate variability in the eastern Mediterranean region.

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1. Introduction

The long continental pollen record of Lake Van (Turkey) contributes significantly to the picture of long-term interglacial-glacial terrestrial vegetation history and climate conditions in the Near East (Litt et al., 2014). Based on a lower time resolution, the 600,000 year old record already shows a general pattern of alternating periods of forested and open landscapes that clearly responds to the Milankovitch-driven global climatic changes (Berger, 1978; Martinson et al., 1987). In that study, the Lake Van pollen record has demonstrated the potential ecological sensitivity for paleoclimate investigations that bridge the southern European and Near East climate realms. Since then, high-resolution multi-proxy investigations of the Lake Van sedimentary record allow the systematic documentation of different climatic phases throughout the last interglacial-glacial cycle (Pickarski et al., 2015a, 2015b).

To date, little attention has been focused on characterizing terrestrial sedimentary archives beyond 130 ka BP. In particular, the detailed vegetation response to climatic and environmental changes in the Near East during the penultimate interglacial-glacial cycle (Marine Isotope Stage (MIS) 7 to 6) is not being thoroughly investigated.

In this context, we present new high-resolution pollen and oxygen isotope data from the 'Ahlat Ridge' composite sequence over the penultimate interglacial-glacial cycle (between c. 242.5-131.2 ka BP). We have added our recent results to the already available low-resolution palynological and isotope data from Lake Van published by Litt et al. (2014) and Kwiecien et al. (2014). This enables us to provide new detailed documentation of multiple vegetation and environmental changes in the Near East by a centennial-to-millennial-scale temporal resolution of ~180 to 780 years. Our record is placed in its regional context by the comparison with several archives from the Mediterranean region, e.g., Lake Ohrid (between Former Yugoslavian Republic of Macedonia and Albania; Sadori et al., 2016), Ioannina basin (NW Greece; Frogley et al., 1999; Roucoux et al., 2011, 2008; Tzedakis et al., 2003a), Tenaghi Philippon (NE Greece; Tzedakis et al., 2006, 2003b), and Yammoûneh basin (Lebanon; Gasse et al., 2015, 2011).

In this presented study, we want to address the following questions:

(I) What kind of regional vegetation occurs during the penultimate interglacial complex (MIS 7)? Is the regional vegetation pattern of the MIS 7e comparable to the last interglacial (Eemian, MIS 5e) and current warm stage (Holocene, MIS 1)?

(II) What processes characterize the climatic and environmental responses during MIS 6? Is this vegetation history similar to the millennial-scale variability recorded during the last glacial (MIS 4-2) in the same sequence?

(III) Does the Lake Van vegetation history correlate with other existing long pollen records from southern Europe? What are the influencing factors of environmental change in the Near East?

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Site description

Lake Van is situated on the eastern Anatolia high plateau at 1,648 m asl (meter above sea level; Fig. 1) in Turkey. The deep terminal alkaline lake (~3,574 km², max. depth >450 m) occupies the eastern continuation of the Muş basin developed in the collision zone between the Arabian and Eurasian plates at ~13 Ma (Reilinger et al., 2006). Regional volcanism of Nemrut and Süphan volcanoes (at 2,948 m asl and 4,058 m asl, respectively, Fig. 1b), subaquatic hydrothermal exhalations and tectonic activities are still active today, evident by the M 7.2 Van earthquake occurred on October 23, 2011 (Altiner et al., 2013).

The present-day climate at Lake Van is continental (warm dry summer and cool wet winter), with a mean annual temperature of >9°C and mean annual precipitation between 400 and 1000 mm yr^{-1} (Climate-data.org, 1982-2012; Table 1). In general, eastern Anatolia receives most of its moisture in winter from the eastern Mediterranean Sea. 'Cyprus cyclones' generated in the Mediterranean Sea or penetrating from the North Atlantic are steered by the mid-latitudes westerlies and reinforced eastward along the northern Mediterranean coast (Giorgi and Lionello, 2008). At Lake Van, rainfall decreases sharply from south-west (c. 816 mm a^{-1} in Tatvan) to north-east (c. 385 mm a^{-1} in Van; Table 1) due to orographic effects of NWW-SEE running Bitlis Massif parallel to the southern shore of the lake (Fig. 1).

Due to the diverse topography at Lake Van, local variations in moisture availability and temperature are quite pronounced, reflected in the modern vegetation distribution. At present, the vegetation cover at Lake Van has been altered by agricultural and pastoral activities. However, the southern mountain slopes are characterized by an open deciduous oak shrubs and parklike steppe-forest containing *Quercus brantii*, *Q. ithaburensis*, *Q. libani*, *Q. robur*, *Q. petraea*, *Juniperus excelsa*, and *Pistacia atlantica*, which is also known as the Kurdo-Zagrosian vegetation. In contrast, the northern catchment area at Lake Van is dominated by a dwarf-shrub steppes of *Artemisietea fragrantis anatolica*, also referred to as the Irano-Turanian steppe and desert vegetation (Zohary, 1973).

2. Material and methods

2.1 Ahlat Ridge composite record

The sediment archive 'AR' (Ahlat Ridge; 38.667°N, 42.669°E at c. 357 m water depth, Fig. 1) was collected during the drilling ICDP campaign (International Continental Scientific Drilling Program) 'PALEOVAN' in summer 2010 (Litt and Anselmetti, 2014; Litt et al., 2012). The c. 219 mcblf (meter composite below lake floor) record contains a well-preserved partly laminated or banded sediment sequence, intercalated by several volcanic and event layers (e.g., turbidites; Stockhecke et al., 2014b). For further detailed description of the Lake Van lithology, we refer to Stockhecke et al. (2014b).

In this paper, we focus on a 54.7 m long sediment section from 112.74 to 58.09 mcblf representing the time span from c. 241.39 - 131.21 ka BP. In this section, we combine new pollen and isotope data with those already obtained from the low-resolution pollen record (Litt et al., 2014) and oxygen isotopes data derived from bulk sediments ($\delta^{18}O_{bulk}$; Kwiecien et al., 2014).

2.2 Chronology

The analytical approaches applied for the Lake Van chronology have previously been published in detail in Stockhecke et al. (2014a). Main results of the construction of the age-depth model are briefly summarized here.

For the investigated period, the age model is based on independent proxy records, e.g., on high-resolution X-ray fluorescence (XRF) measurements (Kwiecien et al., 2014), total organic carbon (TOC; Stockhecke et al., 2014b), and pollen data (Litt et al., 2014). The chronology was improved by adding two paleomagnetic time markers (relative paleointensity minima, RPI), analyzed by Vigliotti et al. (2014), at ~213-210 ka BP (Pringle Fall event; Thouveny et al., 2004) and at ~240-238 ka BP (Mamaku event; Thouveny et al., 2004). In addition, three reliable $^{40}Ar/^{39}Ar$ ages of single crystal dated tephra layer at c. 161.9 ± 3.3 ka BP (V-114 at 71.48 mcblf), c. 178.0 ± 4.4 ka BP (V-137 at 82.29 mcblf), and c. 182 ka BP (V-144 at 87.62 mcblf; Stockhecke et al., 2014b) are used to refine the age-depth model. For the final chronology of this presented period, the composite record was correlated by using eight 'age control points' derived from visual synchronization with the speleothem-based synthetic Greenland record ($GL_{T\text{-}syn}$ from 116 to 400 ka BP; Barker et al., 2011).

2.3 Palynological analysis

For the new high-resolution pollen analysis, 193 sub-samples were taken at 20 cm intervals. The temporal resolution between each pollen sample, derived from the present age-depth model, ranges from 180 to 780 years (mean temporal resolution c. 540 years).

Sub-samples of 4 cm^3 were prepared using the standard palynological procedures by Faegri and Iversen (1989), improved at the University of Bonn. This preparation includes treatment with KOH (10 %, hot), HCL (10 %, cold), HF (39 %, cold), acetolysis mixture (hot), and ultrasonic sieving to concentrate the palynomorphs. In order to calculate the pollen and micro-charcoal (>20 µm) concentrations (grains cm^{-3} and particles cm^{-3}, respectively), tablets of *Lycopodium clavatum* spore (Batch no. 483 216, Batch no. 177745) were added to each sample (Stockmarr, 1971). In all spectra, the average of ~540 pollen grains was counted in each sample using a Zeiss Axio Lab.A1 light microscope. Terrestrial pollen taxa were identified to the lowest possible taxonomic, using the recent pollen reference collections of the Steinmann-Institute, Department of Paleobotany and Beug (2004), Moore et al. (1991), Punt (1976), Reille (1999, 1998, 1995). Furthermore, we followed the taxonomic nomenclature according to Berglund and Ralska-Jasiewiczowa (1986).

Pollen results are given as a percentages and concentration diagram of selected taxa (Fig. 2). This includes the total arboreal pollen (AP; trees & shrubs) and non-arboreal pollen (NAP; herbs) ratio (100 % terrestrial pollen sum). In order to evaluate sea-surface conditions, dinoflagellate cysts and green algae (e.g., *Pseudopediastrum boryanum, P. kawraiskyi, Pediastrum simplex, Monactinus simplex*) were counted on the residues from preparation for palynological analyses. Percent calculation, cluster analysis (CONISS, sum of square roots) to define pollen assemblage zones (PAZ), and construction of the pollen diagram was carried out by using TILIA software (version 1.7.16; ©1991–2011 Eric C. Grimm).

2.4 Oxygen isotope analysis

Stable oxygen isotope measurements ($\delta^{18}O_{bulk}$) were made on bulk sediments samples with an authigenic carbonate content of ~30 % ($CaCO_3$). Similar to the pollen analysis, 193 sub-samples were taken for the new high-resolution isotope record at 20 cm interval within the penultimate interglacial-glacial cycle. Before measurements, the samples were dried at c. 40°C for 2 days and homogenized by a mortar. The isotope analyses were carried out at the Leibnitz-Laboratory, University of Kiel, using a Finnigan GasBenchII with carbonate option coupled to a DELTAplusXL IRMS.

All isotope values are reported in per mil (‰), relative to the Vienna Pee Dee Belemnite (VPDB) standard. The standard deviation of the analyses of replicate samples is 0.02 ‰ for $\delta^{18}O_{bulk}$.

3. New data from the Lake Van sequence

3.1. The high-resolution pollen record

The new palynological results from the penultimate interglacial-glacial cycle are presented in Fig. 2. In addition, the main characteristics of each pollen zone and sub-zone and the interpretation of their inferred dominant vegetation types are summarized in Table 2.

The low-resolution pollen sequence, shown in Litt et al. (2014), has already been divided into six pollen assemblage superzones (PAS IIIc, IV, Va, Vb, Vc, VI). This study followed the criteria for the classification of the pollen superzones as described in Tzedakis (1994 and references therein). Based on the new detailed high-resolution pollen sequence compared to the record in Litt et al. (2014), the PAS IV, Va and Vc can now be further subdivided into 13 pollen assemblage zones (PAZ).

The pollen diagram provides a broad view of alternation between regional deciduous forested and open steppic landscapes. The three main forested phases (PAZ Va1, Va3, Vc2, and Vc3), where total arboreal vegetation reaches percentages above 30 %, are predominantly represented by deciduous *Quercus* (max. ~56 %), *Pinus* (max. ~26 %), *Betula* (max. ~8 %), and *Juniperus* (max. ~7 %). Mediterranean sclerophylls, e.g., *Pistacia* cf. *atlantica*, are only present sporadically and at very low percentages. During open non-forested periods, the most significant herbaceous taxa are the steppe elements Chenopodiaceae

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(max. ~7 %), *Artemisia* (max. ~56 %), and further herbs, such as Poaceae (max. ~54 %), Tubuliflorae (max. ~13 %), and Liguliflorae (max. ~10 %).

Throughout the sequence, the total pollen concentration values vary between c. 1,700 and 52,000 grains cm^{-3} dominated mainly by steppic herbaceous pollen types. The highest tree concentration peaks occur during forested intervals in PAZ Va1, Va3, Vc2, and Vc3 (all above c. 5,000 grains cm^{-3}).

In total, six *Pediastrum* taxa were identified on Lake Van sediments. Fig. 2a presents only the most important *Pediastrum* species. The density of the thermophilic taxa *Pseudopediastrum boryanum* reaches maxima values (c. 5,500 coenobia cm^{-3}) during PAZ Vc2, whereas the cold-tolerant species *Pseudopediastrum kawraiskyi* occur during the PAZ IV4-2 (max. values c. 2,000 coenobia cm^{-3}).

Furthermore, we calculated dinoflagellate concentration (*Spiniferites* species; cysts cm^{-3}) in order to get additional information about environmental conditions of the lake water (Dale, 2001; Shumilovskikh et al., 2012; Fig. 2a). In this study, the concentration of dinoflagellates is high (500-2,000 cysts cm^{-3}) during non-forested periods, especially within PAZ IV1, IV3, IV5, Va2, and PAS Vb.

The microscopic charcoal concentrations range between 300 and ~3,000 particles cm^{-3} during non-forested phases when terrestrial biomass were relatively low (PAZ IV1-5, Va2, Vb and Vc1; Fig. 2a). During forested phases, the charcoal content reaches maxima values of c. 8,000 particles cm^{-3} (e.g., in PAZ Va3, Vc4-2).

3.2. The oxygen isotopic composition of Lake Van sediments

The general pattern of Lake Van isotope composition of bulk sediments shows very high amplitude. The $\delta^{18}O_{bulk}$ ranges from c. 5.9 ‰ to -4.6 ‰. Positive values occur between 250 and 244 ka, 238-222 ka, at 215 ka; 213-203 ka, 192-190 ka, 189-182 ka, and mainly between 171-157 ka and 141-134 ka BP. Negative isotope composition ($\delta^{18}O_{bulk}$ below 0‰) can be observed at ~241 ka; 221-216 ka; 202-194 ka; at ~181 ka, 178-171 ka, and between 156 and 155 ka BP.

Previous studies at Lake Van (e.g., Kwiecien et al., 2014; Lemcke and Sturm, 1997; Litt et al., 2012, 2009; Wick et al., 2003) have shown that the stable isotope signature of lake carbonates reflects complex interaction between both several regional climatic variables and local site-specific factors. Such climate variables are the moisture source, in this case the eastern Mediterranean Sea surface water and the storm trajectories coming from the Mediterranean Sea, as well as temperature changes. Furthermore, the lake water itself is related to the seasonality of precipitation (both rain and snowfall; water inflow) and evaporation processes in the catchment area. However, the Lake Van authigenic carbonate $\delta^{18}O_{bulk}$ values are primarily controlled by water temperature and isotopic composition of the lake water ($T+\delta^{18}O_w$; Kwiecien et al., 2014; Leng and Marshall, 2004; Roberts et al., 2008).

The $\delta^{18}O_{bulk}$ composition of the lake water becomes progressively more enriched during interglacial/interstadial periods and lighter during glacial/stadial stages (Fig. 3b). Sharp negative peaks at

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Termination III (T III at 241.4 ka BP) and at the transition from stadial to pronounced interstadial periods documents not only enhanced precipitation during winter months but also the significant contribution of depleted snow melt/glacier meltwater during the summer months (Kwiecien et al., 2014; Roberts et al., 2008).

4. Discussion

4.1 The penultimate interglacial complex (MIS 7)

The penultimate interglacial at Lake Van resembles other interglacial complexes (e.g., the last interglacial/interstadial complex, MIS 5; Pickarski et al., 2015a, 2015b) with three remarkable arboreal pollen peaks. Here, the first sub-stage MIS 7e is generally considered as the full interglacial. This general pattern of three warm phases (MIS 7e, 7c, and 7a) is separated by two intervening cold intervals (stadials; MIS 7d and 7b) comparable with the marine classification by Martinson et al. (1987).

Forested periods

The Lake Van pollen sequence shows three pronounced steppe-forested intervals within MIS 7 that display high moisture availability and/or warmer temperature (Fig. 2a, 3e). Here, the steppe-forest periods of MIS 7e (242.5-227.4 ka BP), MIS 7c (216.3-207.6 ka BP), and MIS 7a (203.1-193.4 ka BP) followed the classical vegetation pattern of early to late temperate stage. The vegetation succession starts with the colonization of open habitats by pioneer trees, such as *Betula*, followed by sclerophyllous *Pistacia* cf. *atlantica* and a gradual expansion of deciduous *Quercus*. The abrupt occurrence of the frost-sensitive *Pistacia* at the beginning of each forested interval indicates summer dryness due to higher temperature and evaporation regime, and mild winter temperature. Moreover, the fire activity rose at Lake Van when global temperature increased and the vegetation communities changed. It is clearly visible by high charcoal concentration up to 5,000 particles cm^{-3} (Fig. 3d). In addition, the most depleted (negative) $\delta^{18}O_{bulk}$ values occur at the base of each early temperate stage. This rapid change reflects intensified freshwater supply into the lake by melting of Bitlis glaciers in summer months and/or enhanced precipitation during winter months (Kwiecien et al., 2014; Roberts et al., 2008).

The climate optima of each forested interval are characterized by the maximum development of oak steppe-forests, where summer-green *Quercus* rises consistently above 20 %. In case of MIS 7e, the climate optimum occurs between c. 240 and 237 ka BP. Independent of environmental conditions around the lake, the presence of thermophilic algae (i.e., *Pseudopediastrum boryanum*), which occurred mainly during MIS 7e, displays warm and eutrophic conditions within the lake. In addition, the oxygen isotope composition of the lake water confirms the obvious climate change within the region. The gradual shift from depleted to enriched $\delta^{18}O_{bulk}$ values indicates a change towards warm climate conditions with high evaporation rates and/or decreased moisture availability (Kwiecien et al., 2014; Roberts et al., 2008). Here, positive $\delta^{18}O_{bulk}$ values at Lake Van are attributed to evaporative ^{18}O-enrichment of the lake water during the dry season. Furthermore, Kwiecien et al. (2014) described the relation between soil erosion processes and the vegetation cover in the catchment area. Our new high-resolution pollen record validates this hypothesis with high authigenic carbonate concentration (low terrestrial input) along with the increased terrestrial vegetation cover density during the climate optimum (Fig. 3c).

The ensuing ecological succession at Lake Van is documented by high percentages of dry-tolerant and/or cold-adapted coniferous species (e.g., *Pinus* and *Juniperus*) that suggests a cooling trend with summer-dry environment during the late stage (Fig. 2a, 3e). However, we are aware of the fact that pine pollen was mainly transported over several kilometers via wind into the basin. Nevertheless, the presented regional vegetation composition in the pollen spectra clearly illustrates a cooling/drying trend that appears during the time of minimum ice volume. In other words, before the substantial ice accumulation is evident in the marine MD01-2447 record (Desprat et al., 2006). In light of these insights, the MIS 7e vegetation succession shows a shift from temperate species to the predominance of conifer taxa. Similar features are recorded in the last interglacial stage (MIS 5e; 131.2-111.5 ka BP; Fig. 4), where the shift indicates higher continentality, in particular to high seasonal contrasts on land along with low moisture availability (Litt et al., 2014; Pickarski et al., 2015a).

Such pattern of forest succession, mentioned above, is not as clearly developed in each forested intervals. For example, MIS 7c does not show a clear *Pistacia* cf. *atlantica* phase or MIS 7a a distinct *Pinus* phase. Furthermore, the different amplitudes of the deciduous tree development, e.g., weak oak steppe-forest re-expansion during MIS 7a and 7e, mirrored significant variability in regional effective moisture content and/or temperature. These differences stem from the variety of factors, e.g., changes in orbital parameters reflected in insolation forcing. In the case of MIS 7a, the ice volume was larger than during MIS 7c (Desprat et al., 2006). Nevertheless, a possible explanation for high deciduous *Quercus* percentages in MIS 7a is the persistence of relatively large tree populations through the preceding stadial MIS 7b.

All three forested stages of the MIS 7 are clearly recorded in other long terrestrial pollen sequences from Lebanon and southern Europe: (I) the Yammoûneh record (Gasse et al., 2015), (II) the Tenaghi Philippon sequence (Tzedakis et al., 2003b), (III) Ioannina basin (Roucoux et al., 2008), and (IV) the Lake Ohrid sequence (Sadori et al., 2016). Fig. 5 shows that the Lake Van pollen record generally agrees with the vegetation development of the Mediterranean region. However, we have to take into consideration that most southern European sequences, e.g., the Ioannina basin, are situated near to refugial areas, in which temperate trees persisted during cold stages (Bennett et al., 1991; Milner et al., 2013; Roucoux et al., 2008; Tzedakis et al., 2002). For example, the Mediterranean sequences show the most floristically diverse and complete forest succession during the MIS 7c (Follieri et al., 1988; Roucoux et al., 2008; Sadori et al., 2016; Tzedakis et al., 2003b). In contrast, the Lake Van interstadial contains only the highest amplitude of deciduous *Quercus* (peaked at 212.6 ka BP) of the entire sequence. In fact, deciduous *Quercus* percentages reach the level of the last interglacial (MIS 5e) and the Holocene forested intervals, representing the most humid and temperate period at Lake Van (Fig. 4; Litt et al., 2014). Preliminary comparison with eastern Mediterranean pollen records suggest that the extent and the diversity of vegetation development is clearly controlled by insolation forcing and associated climate regimes (high summer temperature, high winter precipitation). Therefore, the difference in the deciduous *Quercus* percentages might have resulted from higher Mid-June insolation during MIS 7c relative to MIS 7e (similar to Holocene levels), despite lower atmospheric CO_2 content (c. 250 ppm, Fig. 5; Jouzel et al., 2007; Lang and Wolff, 2011; Petit et al., 1999; Tzedakis, 2005). However, we cannot recognize a clear interglacial-like vegetation succession within the MIS 7c with, e.g., the occurrence of the summer-drought-resistant specie *Pistacia* cf. *atlantica*. In this case, there does not seem any reason to define the MIS 7c as a full interglacial separate from MIS 7e.

Non-forested periods

The two stadial phases between the three forested intervals, MIS 7d (227.4-216.3 ka BP) and MIS 7b (207.6-203.1 ka BP), are characterized by: (I) extensive steppe vegetation when tree growth was inhibited either by dry/cold or low atmospheric CO_2 conditions, (II) high dinoflagellate concentration (probably a species which tolerate high water salinity conditions; Fig. 2a), and (III) high regional mineral input derived from the basin slopes (Fig. 3c).

Due to the strongest development of extensive semi-desert steppe plants (mainly Chenopodiaceae) and massive reduction of temperate tree (AP c. 5 %, Fig. 2), the MIS 7d suggests considerable climate deterioration and increased aridity. Furthermore, this stadial is marked by large ice volume and extremely low global temperatures, documented by low CO_2 concentration (c. 200 ppm, Fig. 5) values that are nearly as low as those of MIS 8 and 6 (McManus et al., 1999; Petit et al., 1999). Concerning the oxygen isotope record, the MIS 7d documents a significant change towards lighter $\delta^{18}O_{bulk}$ values (up to -3.8 ‰; Fig. 3b) that reflect reduced evaporation in the Lake Van catchment area. Such a cold and/or dry period within the entire interglacial complex can also be recognized in all pollen sequences from Lebanon and southern Europe. An exception is the Lake Ohrid record, which shows only a minor temperate tree decline (Sadori et al., 2016).

In contrast, the MIS 7b stadial recognizes only a slight and short-term steppe-forest contraction. Although the landscape at Lake Van was more open, moderate values of *Betula*, deciduous *Quercus* (up to 16 %) and conifers (*Pinus*, *Juniperus*) formed steppe vegetation with still patchy pioneer and temperate trees. The significantly larger temperate tree pollen percentages (AP c. 20 %) during the sub-stage 7b relative to MIS 7d point to milder climate conditions. In addition, the continuous heavier oxygen isotope signature confirms the assumption of milder conditions with 'higher' evaporation rates (Fig. 3b). Based on these results, the Lake Van pollen archive mirrored the trends seen in various paleoclimatic archives (Fig. 5). Indeed, a number of arboreal pollen sequences from the Mediterranean area and oxygen isotope records suggest that the North Atlantic and southern European region (i.e., Ioannina basin; Roucoux et al., 2008) did not experience severe climatic cooling during MIS 7b (Fig. 5; e.g., Bar-Matthews et al., 2003; Barker et al., 2011; McManus et al., 1999; Petit et al., 1999). In addition, the global ice volume remains relatively low during the MIS 7b in comparison with other stadial intervals with similarly low insolation values (e.g., Petit et al., 1999; Shackleton et al., 2000). Vostok ice-core sequence also records a relatively 'high' CO_2 content (c. 230 ppm) supporting a slight decline of temperature compared with MIS 7d (McManus et al., 1999; Petit et al., 1999).

Comparison of past interglacials at Lake Van

The comparison of the penultimate interglacial (MIS 7e) with the last interglacial (Eemian, MIS 5e; Pickarski et al., 2015a) and the current interglacial (Holocene, MIS 1; Litt et al., 2009) provides the opportunity to assess how different successive climate cycles can be (Fig. 4).

In general, all interglacial climate optima are characterized by the development of an oak steppe-forest, which indicates high effective moisture. A dense vegetation cover reduces physical erosion of the surrounding soils in the lake basin. Furthermore, the dominance of forested landscapes and productive steppe environment leads to enhanced fire activity in the catchment. However, all interglacial intervals at Lake Van recognize a delayed forest onset of c. 3,000 to 2,000 years, visible by the slow expansion of deciduous *Quercus*, based on summer-dry conditions (Litt et al., 2009; Pickarski et al., 2015a). In addition, the late temperate stage of both the penultimate and last interglacial is documented by continental environments with warm evaporative summer conditions and a higher seasonality due to the vegetation shift towards the predominance of *Pinus* (Pickarski et al., 2015a).

Despite the common vegetation succession from an early to late temperate stage, the three interglacial maxima differ significantly. One important difference of the last two interglacial vegetation assemblages is the absence of *Carpinus* during MIS 7e, compared to a distinct *Carpinus betulus* phase during MIS 5e (Pickarski et al., 2015a). In general, *Carpinus betulus* usually requires high amounts of annual rainfall, and relatively high annual summer temperature. However, deciduous *Quercus* is 'less' sensitive to summer droughts compared to *Carpinus betulus* and a decrease in humidity would favor the development of an oak steppe-forest. A change in temperature is difficult to assess because deciduous oaks at Lake Van include many species with different ecological requirements. Therefore, general 'cooler/wetter' conditions of the penultimate interglacial resulted in overall smaller abundance of temperate trees. Possible reasons for this development could be reduced Mid-June insolation (lower than Holocene level) and moderately lower interglacial CO_2 content (Lang and Wolff, 2011). Moreover, general lower temperature are commonly associated with the persistence of larger volumes of continental ice (Shackleton et al., 2000).

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Another important difference is the duration of each full interglacial period. According to Tzedakis (2005), the beginning and duration of terrestrial temperate intervals in the eastern Mediterranean region is closely linked to the amplitude of summer insolation maxima and less influenced by the timing of deglaciation. Based on this assumption, the climate optimum of the penultimate interglacial (c. 9.6 ka) is c. 4 ka shorter as the last interglacial interval at Lake Van (~13.5 ka, Pickarski et al., 2015a; Fig. 4).

4.2 The penultimate glacial (MIS 6)

Within the penultimate glacial stage (MIS 6; 193.4-131.2 ka BP), the general lower summer insolation (Berger, 1978; Berger et al., 2007), increased global ice sheet extent (McManus et al., 1999), and decreasing atmospheric CO_2 content (below 230 ppm; Petit et al., 1999; Fig. 5) are responsible for the enhanced aridity and cooling in eastern Anatolia. Such observed climate deterioration is evident by the dominance of semi-desert plants (e.g., *Artemisia*, Chenopodiaceae) and by the rapid decline in temperate trees (AP <20 %) during this time. High erosional activity (low Ca/K ratio) and decreasing paleofire activity (Ø ~1,400 particles cm^{-3}) result from low vegetation cover density with low pollen productivity (Fig. 2, 3). As an additional local factor, the strong deficits in available plant water were possibly stored as ice/glaciers in the Bitlis mountains during the coldest phases.

During 193 and 157 ka BP, high-frequency oscillations in tree percentages between ~1 and 18 % can be observed in the pollen record. Furthermore, the early penultimate glacial stage documents similar high-amplitude variations in $\delta^{18}O_{bulk}$ values (c. -4 to 6 ‰), compared to the isotope signature of MIS 7 (Fig. 3b). However, such rapid change in temperate plant communities, e.g. at ~189.4 ka BP, resembles the pattern of interstadial to stadial stages. It indicates unstable environmental conditions with rapid alternation of slightly warmer/wetter interstadials and cooler/drier stadials at Lake Van. This situation is also reflected in several Lake Van paleoenvironmental proxies. Here, the short-term expansion of trees and shrubs (deciduous *Quercus*, *Betula*, *Ulmus*, *Pinus*, and *Juniperus*; PAZ IV6, Fig. 2a, 3e) combined with rapid variations in the fire intensity (up to 6,000 particles cm^{-3}, Fig. 3e) and decreasing terrestrial input of soil material (Fig. 3c), point to short-term humid conditions and/or low evaporation within interstadials. Even if mean precipitation was low, the local available moisture was sufficient to sustain arboreal vegetation when low temperature minimized evaporation. Nevertheless, the landscape around the lake was still open and less extensive due to still high percentages of dry-climate adapted herbs.

In contrast, the period after 157 ka BP shows a great abundance of steppe elements with dwarf shrubs, grasses and other herbs (e.g., Chenopodiaceae, *Artemisia*, *Ephedra distachya*-type) along with lower temperate tree percentages (AP c. 1-8 %). The remaining tree values consist mainly of deciduous *Quercus*, *Pinus*, with some scattered patches of *Betula* and *Juniperus*. The combination of minor AP oscillation, high percentages of steppe plants (Fig. 2b), and reduced fire activity reflect a strong aridification and cold continental climate during the late penultimate glacial. In addition, a general low-amplitude variation of

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$\delta^{18}O_{bulk}$ values (c. -2 to 2 ‰; Fig. 3b) and local erosion processes (Fig. 3c) refer to a rather stable period with both widespread aridity (low winter and summer precipitation) and low winter temperature across eastern Anatolia.

The Lake Van record generally agrees with high-frequency paleoenvironmental variations in the ice-core archives and high-resolution terrestrial European pollen records (e.g. Ioannina basin, Lake Ohrid; Fig. 5) in terms of a general aridity and cooling throughout the penultimate glacial. Our sequence also share some features with stable isotope speleothem records from western Israel (Peqi'in and Soreq Cave; Ayalon et al., 2002; Bar-Matthews et al., 2003) concerning high $\delta^{18}O$ values that refers to dry climate conditions. Similar to the Lake Van $\delta^{18}O_{bulk}$ values, the Soreq and Peqi'in record also show distinct climate variability, especially at the beginning of the MIS 6 (Fig. 5). In addition, several high-resolution terrestrial records document a further period of abrupt warming events between 155-150 ka BP. In particular, the Tenaghi Philippon profile illustrates a prominent increase of up to 60 % in arboreal pollen, which coincides with increase rainfall at Yammoûneh (Gasse et al., 2015) and at Peqi'in Cave (Bar-Matthews et al., 2003).

Comparison of the last two glacial intervals at Lake Van

Compared to interglacial stages, forest vegetation cover was generally reduced during the glacial. The occurrence of high-frequency climate changes within the Lake Van sediments provides an opportunity to compare the vegetation history of the last two glacial periods. Fig. 6 illustrates that the first part of the penultimate glacial (c. 193-157 ka BP) resembles MIS 3, regarding pronounced millennial-scale AP oscillations and abruptness of the transition in the pollen record. The series of millennial-scale interstadial-stadial intervals can be recognized in both glacial periods. This variability is mainly influenced by the impact of North Atlantic current oscillations and the extension of atmospheric pattern, in particular, northward shift of the polar front in eastern Anatolia (e.g., Cacho et al., 2000, 1999; Chapman and Shackleton, 1999; McManus et al., 1999; Rasmussen et al., 2014; Wolff et al., 2010).

The longest and most distinct environmental variability occurs during MIS 6e (c. 179-159 ka BP), which can be further divided into six interstadials based on rapid changes in the marine core MD01-2444 off Portugal (Margari et al., 2010; Roucoux et al., 2011; Fig. 6). MIS 6e reveals a clear evidence of abrupt climate variability due to rapid alternation in the vegetation cover similar to the largest Dansgaard-Oeschger (DO) events 17 to 12 during MIS 3 (c. 60-44 ka BP; Pickarski et al., 2015b). Both intervals start at the point of summer insolation maxima. Here, the Northern Hemisphere insolation values reach interglacial level at the beginning of MIS 6e compared to the MIS 7e (Fig. 5). In contrast, the interstadial-stadial pattern during the late MIS 6 oscillated at lower intensities, similar to rates of change in the Dansgaard-Oeschger (DO) events during MIS 4 and 2, reflecting a general global climatic cooling.

Within the MIS 6e, the subdued temperate tree pollen oscillations consist mainly of deciduous *Quercus* and *Pinus*, range between ~1 % and ~15 %. In contrast, the identical AP composition oscillates between ~1 % and ~10 % during the orbitally equivalent MIS 3 (c. 61-28 ka BP). The different amplitude in arboreal pollen percentages in both glacial stages and a general dense temperate grass steppe during the MIS 6e is supported by more abundant summer moisture (Fig. 6). The general depleted isotope signature may result from summer meltwater discharge from local glaciers (e.g., Taurus mountains, Bitlis Massif) or by increased precipitation over the entire Mediterranean basin (Kallel et al., 2000). However, the presence of *Artemisia* and Poaceae makes it difficult to disentangle the effects of warming from changes in moisture availability in both glacials. Nevertheless, the occurrence of cold-tolerant taxa such as *Pinus*, *Ephedra distachya*-type, and the algae *Pseudopediastrum kawraiskyi* points to a general picture of cold but 'wet' climate conditions during MIS 6e than experienced during MIS 3.

Evidence for relatively humid but cold climate conditions during MIS 6e agrees with several other paleoclimate studies from the Mediterranean area. For example, the occurrence of open forest vegetation associated with wetter climate is indicated at, e.g., Tenaghi Philippon (Tzedakis et al., 2006, 2003b) and Ioannina (Roucoux et al., 2011). In addition, the stalagmites record from the Soreq Cave (Israel) shows an increase in precipitation (negative shift in the $\delta^{18}O$ values) in the eastern Mediterranean at ~177 and 166-157 ka BP (Fig. 5; Ayalon et al., 2002; Bar-Matthews et al., 2003). Furthermore, a pluvial phase is also inferred from a prominent speleothem $\delta^{18}O$ excursion in the Argentarola Cave (Italy) between 180 and 170 ka BP based on U/Th dating (Bard et al., 2002). This phase coincides with high runoff due to the deposition of the 'cold' sapropel layer (S6, c. ~176 ka BP) in the western and eastern Mediterranean basin (Ayalon et al., 2002; Bard et al., 2002). Finally, the progressive decline in effective moisture is a result of the combined effect of temperature, precipitation and insolation changes in the Lake Van region.

5. Conclusions

The new high-resolution Lake Van pollen record provides a unique sequence of the penultimate interglacial-glacial cycle that fills the gap in data coverage between the northern Levant and southern Europe.

All climate-related variables at Lake Van varied at interglacial/interstadial-glacial/stadial scale. During the MIS 7 complex, high local and regional effective moisture is evidenced by a dense temperate oak steppe-forest, high charcoal accumulation, and reduced physical erosion during the climate optima. Each warm stage is characterized by a succession of vegetation types: (I) pioneer and sclerophyllous taxa, (II) temperate tree expansion dominated by deciduous *Quercus*, (III) *Pinus*-dominated landscapes, and (IV) steppe vegetation. The comparison of past interglacials at Lake Van suggests wet and colder conditions during the penultimate interglacial, strong thermal and hydrological seasonal contrasts during the last interglacial, and a higher humidity during the Holocene climate optimum (at 6 ka cal. BP; Litt et al., 2009).

During the penultimate glacial, a strong aridification and cold climate conditions are inferred from open steppe vegetation that favors physical erosion and local terrigenous inputs. In particular, our record reveals a pattern of subdued but 'higher' temperate oscillations between 193-157 ka BP, followed by a period of lower tree variations and expansion of desert-steppe from 157-131 ka BP. A comparison between the last two glacials highlights differences in vegetation responses in eastern Anatolia. The first part of MIS 6 including the MIS 6e event may point to cooler but relatively wetter conditions than experienced during the MIS 3.

Finally, the eastern Mediterranean Lake Van pollen sequence is in line with data from long-term climate records from southern Europe and the northern Levant, in terms of vegetation changes, orbitally-induced fluctuations, global ice sheet waxing and waning, and atmospheric changes over the North Atlantic system.

Data availability: The pollen data set is available online at…. (www.pangaea.de).

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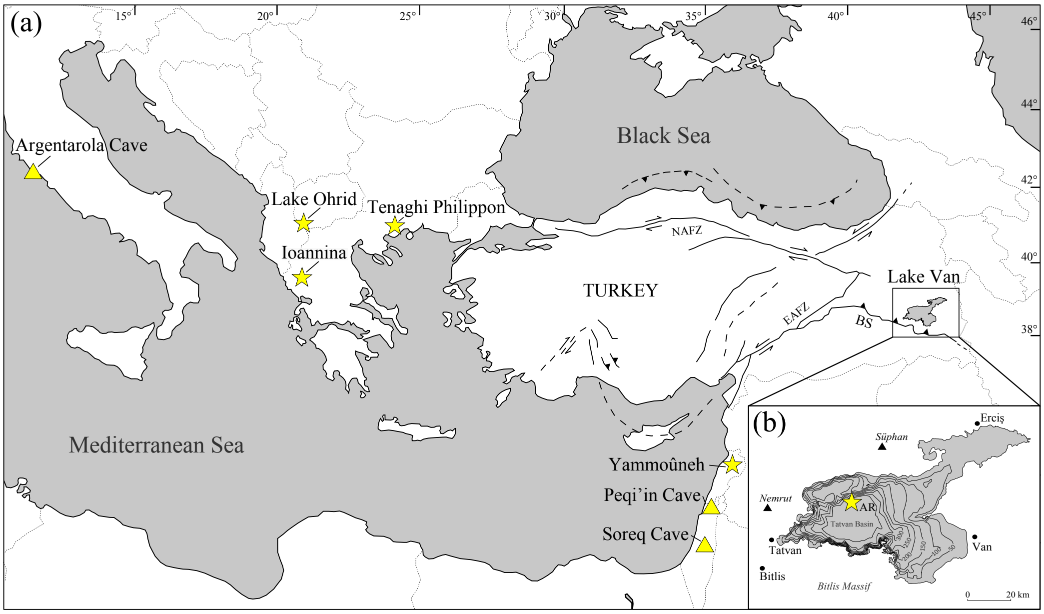
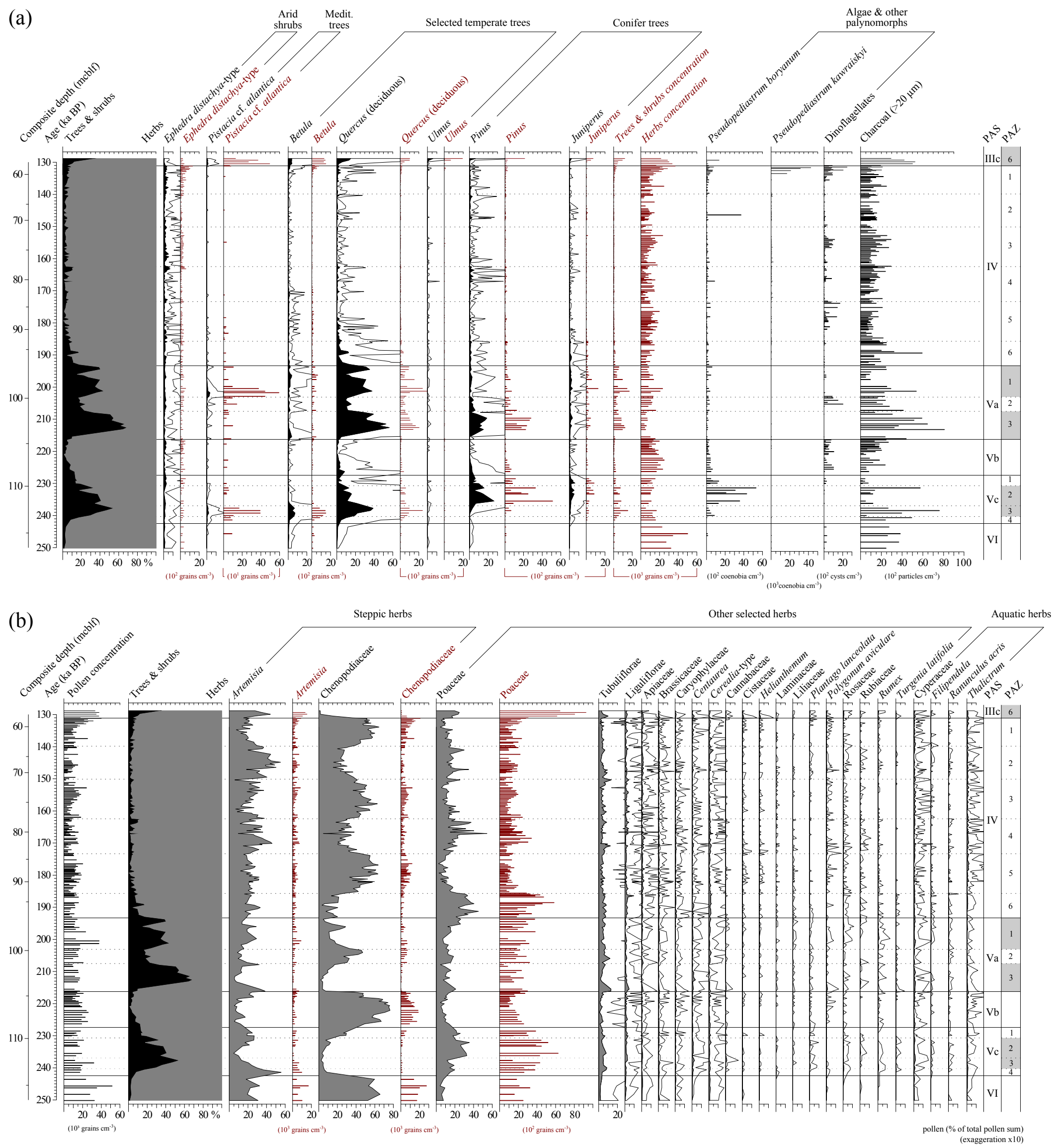


662 **Fig. 1:** Map of the eastern Mediterranean region showing major tectonic structures in Turkey (a) Location of key Mediterranean and Near East pollen sites (stars) and speleothem records (triangle) mentioned in the text. (b) Bathymetry of Lake Van including the Ahlat Ridge drill site (AR). The black triangle indicates the positions of the active Nemrut and Süphan volcanoes. NAFZ: North Anatolian Fault Zone; EAFZ: East Anatolian Fault Zone; BS: Bitlis Suture.



667 **Fig. 2:** Pollen diagram of Lake Van showing pollen percentages and concentrations of key taxa, plotted against composite depth (mcblf) and age (ka BP). (a) Summary curve of percentages total trees and herbs pollen, selected arboreal pollen percentages and pollen concentrations (red bars), spores of green algae (Pseudopediastrum boryanum, P. kawraiskyi, black bars), dinoflagellates (black bars), and charcoal particles (>20 µm, black bars); (b) Total pollen concentration, selected non-arboreal percentages and concentrations, and key aquatic herbs.

The diagram is separated by six pollen assemblages superzones (PAS), marked by major horizontal black solid lines, and 13 pollen assemblages zones (PAZ; grey dashed lines). Intervals characterized by steppe forest (AP >30 %) are indicated on the right (grey box) of each diagram. An exaggeration of the pollen curves (x10; white curves) is used to show low variations in pollen percentages.

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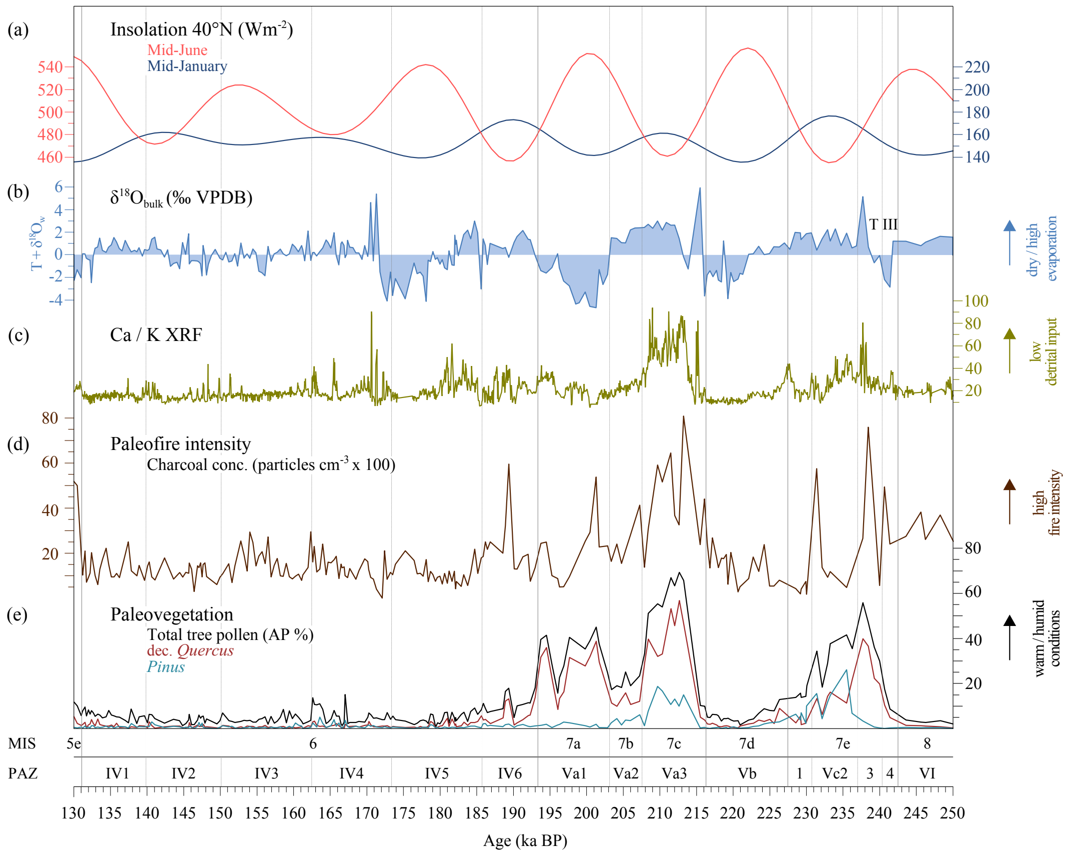

677 **Fig. 3:** Comparative study of Lake Van paleoenvironmental proxies during the penultimate interglacial glacial
678 cycle. (a) Insolation values (40°N, Wm^{-2}) after Berger (1978) and Berger et al. (2007); (b) Lake Van oxygen isotope
679 records $\delta^{18}O_{bulk}$ (‰ VPDB; new analyzed isotope data including the already published isotope record by Kwiecien
680 et al., 2014); (c) Calcium/potassium ratio (Ca/K) after Kwiecien et al. (2014); (d) Fire intensity at Lake Van (>20
681 µm, charcoal concentration in particles cm^{-3}); (e) Selected tree percentages (total arboreal pollen (AP), deciduous
682 *Quercus*, and *Pinus*) including the pollen data from Litt et al. (2014). MIS – Marine Isotope Stage; PAZ – Pollen
683 assemblage zone. Termination III (T III) at 241.4 ka BP is indicated.
684

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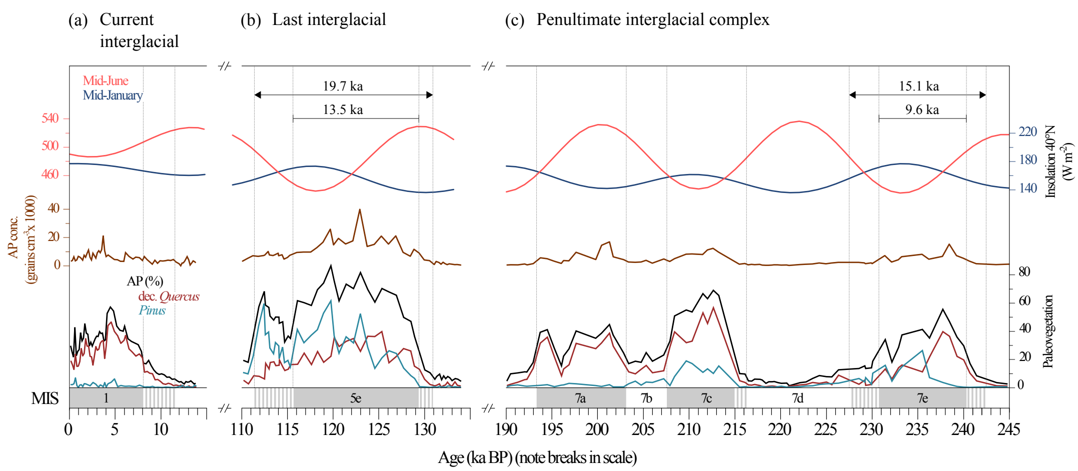

Fig. 4: Comparison of (a) Current interglacial (MIS 1; Litt et al., 2009) with (b) Last interglacial (MIS 5e; Pickarski et al., 2015a), and (c) Penultimate interglacial complex (MIS 7; this study) at Lake Van. Shown is the insolation values (40°N, Wm^{-2}) after Berger (1978) and Berger et al. (2007), the Lake Van arboreal pollen (AP) concentration (grains cm^{-3}, brown line), and the Lake Van paleovegetation (AP, deciduous *Quercus*, and *Pinus* in %). The grey boxes mark each steppe-forest intervals. Marine Isotope Stage (MIS) and the length of each full interglacial (MIS 5e, 7e, black arrows) are indicated.

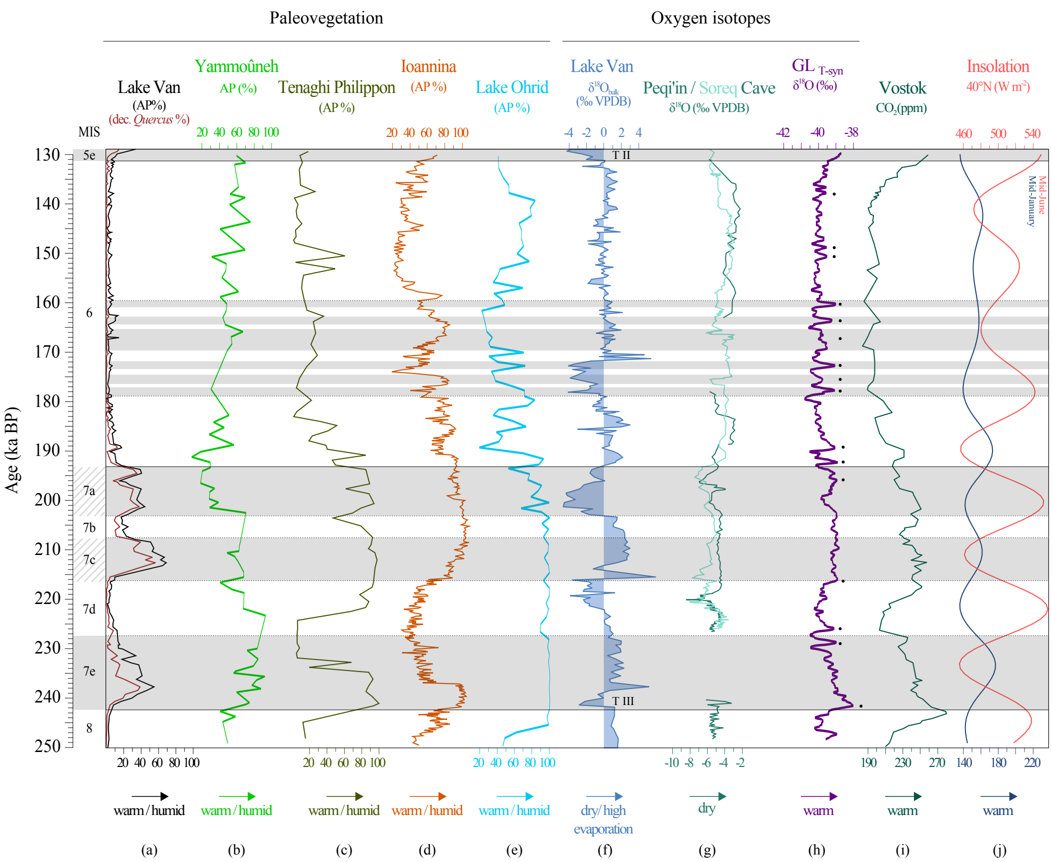

Fig. 5: Correlation scheme of Lake Van pollen record with terrestrial, marine and ice core paleoclimatic sequences. (a) Total arboreal pollen (AP %) and deciduous *Quercus* curve from Lake Van (this study); (b) Arboreal pollen percentages from Yammoûneh basin (Lebanon; Gasse et al., 2015); (c) Tree percentages of the Tenaghi Philippon record (NE Greece; Tzedakis et al., 2003b); (d) AP sequence from Ioannina basin (NW Greece; Roucoux et al., 2011, 2008); (e) Lake Ohrid pollen record (AP %; Macedonia, Albania; Sadori et al., 2016); (f) Stable oxygen isotope record of Lake Van ($\delta^{18}O_{bulk}$ data including the already published isotope record of Kwiecien et al., 2014); (g) Peqi'in and Soreq Cave speleothem records (Israel; M. Bar-Matthews & A. Ayalon, unpubl. data); (h) Synthetic Greenland ice-core record (GLT-syn; Barker et al., 2011); (i) Atmospheric CO_2 concentration from Vostok ice core, Antarctica (Petit et al., 1999); (j) Mid-June and Mid-January insolation for 40°N (Berger, 1978; Berger et al., 2007). Marine Isotope Stages is also shown (MIS; Martinson et al., 1987). Bands highlights periods of distinctive climate signature discussed in the text. Black dots mark significant interstadial periods. Terminations (T III and T II) are indicated.

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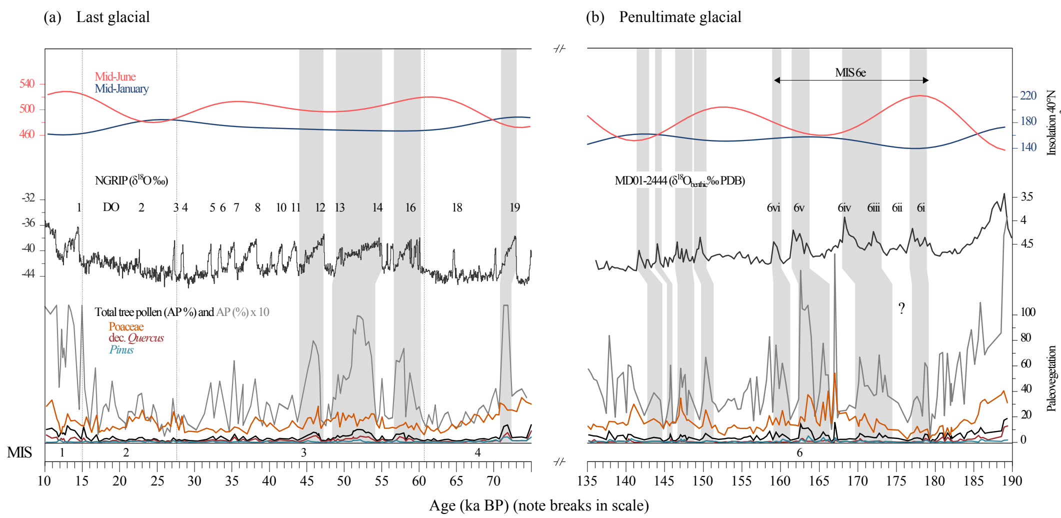

Fig. 6: Comparison of the (a) Last glacial period (MIS 4-2; Pickarski et al., 2015b) with the (b) Penultimate glacial (this study) characteristics at Lake Van. Shown is the insolation values (40°N, Wm^{-2}) after Berger (1978) and Berger et al. (2007), the δ^{18}O profile from NGRIP ice core (Greenland; NGRIP members, 2004) labeled with Dansgaard-Oeschger (DO) events 1 to 19 for the last glacial period, the δ^{18}O composition of benthic foraminifera of the marine core MD01-2444 (Portuguese margin; Margari et al., 2010) for the penultimate glacial, and the Lake Van paleovegetation with AP % (shown in black), AP in 10-fold exaggeration (grey line), Poaceae, deciduous *Quercus*, and *Pinus*. The grey boxes mark the correlation between the different paleoenvironmental records of pronounced interstadial oscillations. Marine Isotope Stage (MIS) and informally numbered interstadials of the MD01-2444 record are indicated.

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Tables:

Table 1: Present-day climate data at Lake Van (see Fig. 1 for the location; Climate-data.org; 1982-2012).

Station	Coordinates			Mean temperature (°C)			Mean precipitation (mm)		
	Latitude (°N)	Longitude (°E)	Altitude (m asl)	Jan.	July	Year	Jan.	July	Year
Bitlis	38°24’	42°60’	1536	-2.8	22.5	9.7	131	5	1059
Tatvan	38°30’	42°17’	1651	-2.5	21.3	9.0	89	6	844
Erciş	39°20’	43°22’	1691	-4.9	21.8	8.5	38	8	499
Van	38°27’	43°19’	1689	-3.7	21.2	8.9	37	5	409

Table 2: Main palynological characteristics of the Lake Van pollen assemblage superzones (PAS) and zones (PAZ) with composite depth (mcblf), age (ka BP), criteria for lower boundary, components of the pollen assemblage (AP: arboreal pollen, NAP: non-arboreal pollen), green algae concentration (GA: low <1,000; high >1,000 coenobia cm^{-3}), dinoflagellates concentrations (DC: low: <100; high: >100 cysts cm^{-3}), charcoal concentrations (CC: low: <2,000; moderate: 2,000-4,000; high: >4,000 particles cm^{-3}) and their inferred dominated vegetation type during the penultimate interglacial-glacial cycle. Marine Isotope Stages (MIS) after Martinson et al. (1987) were shown on the right.

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PAS	PAZ	Composite depth (mcblf)	Age (ka BP)	Criteria for lower boundary	Main palynological characteristics (minimum – maximum in %)	Dominant vegetation type	MIS
IIIc	6	57.20 - 58.09	129.1 – 131.21	Occurrence *Pistacia*	**AP:** *Betula* (2-4 %), dec. *Quercus* (1-13 %), *Ephedra distachya*-type (0-3 %), *Ulmus* (0-2 %), *Juniperus* (0-1 %), *Pinus* (0-1 %), *Pistacia* cf. *atlantica* (0-1 %) **NAP:** *Artemisia* (16-49 %), Poaceae (7-25 %), Chenopodiaceae (2-52 %) **GA:** Low **DC:** Low **CC:** Moderate to high	Steppe taxa become less widespread, giving way to open grassland	5e
IV	1	58.09 - 63.25	131.21 - 139.87	Chenopodiaceae >40 %	**AP:** Low AP (2-8 %); increased frequencies of *Ephedra distachya*-type (1-5 %); deciduous *Quercus*, *Betula*, *Pinus*, and *Juniperus* are abundant at low level **NAP:** Chenopodiaceae (39-64 %) show high values at the top of sub-zone, while *Artemisia* (8-29 %) abundances rapidly decline; still moderate Poaceae percentages **GA:** Low **DC:** Low **CC:** Low to moderate	Open desert steppe vegetation	6
	2	63.25 - 71.50	139.87 - 150.14	Chenopodiaceae <40 %	**AP:** Low AP (1-7 %); temperate trees are present at low level **NAP:** Expansion of *Artemisia* continues and peaks in the middle of the sub-zone (54 %); Chenopodiaceae percentages drop to 15-41 %; moderate Poaceae values (11-34 %), **GA:** Low with a single peak at 146.4 ka BP (c. 3,700 coenobia cm^{-3}) **DC:** Low **CC:** Low	Productive dwarf shrub steppe vegetation	
	3	71.50 - 77.72	150.14 - 162.49	Chenopodiaceae >40 %; decrease *Quercus*	**AP:** Deciduous *Quercus*, *Betula*, *Pinus*, and *Juniperus* are continuously present at low level (AP 2-8 %); increase of *Ephedra distachya*-type (1-6 %) **NAP:** Predominance of Chenopodiaceae (33-62 %); *Artemisia* (6-38 %) shows moderate values with increasing trend towards the top, Poaceae continuously present at ~13 % **GA:** High to low at the end of the sub-zone **DC:** Low to high **CC:** Low to moderate	Open desert steppe vegetation	
	4	77.72 - 83.84	162.49 - 173.38	Chenopodiaceae <40 %; increase *Quercus*	**AP:** Low AP (1-14 %); relatively moderate contents of deciduous *Quercus* (0-3 %); slight decrease of *Betula* (0-2 %), while *Pinus* (0-5 %) and *Juniperus* (0-1 %) percentages increase towards at the end of the sub-zone **NAP:** Predominance of *Artemisia* (10-46 %) and Poaceae (8-54 %); Chenopodiaceae abundances (5-40 %) are reduced within this sub-zone **GA:** Low to high **DC:** Low **CC:** Low with moderate peaks at the end	Fluctuation between open desert-steppe and grassland scattered with temperate trees	
	5	83.84 - 93.51	173.38 - 185.74	Chenopodiaceae >40 %	**AP:** AP (1-9 %) decrease continuously throughout the sub-zone; mainly by deciduous *Quercus* (0-4 %)	Change from grassland to desert steppe	

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PAS	PAZ	Composite depth (mcblf)	Age (ka BP)	Criteria for lower boundary	Main palynological characteristics (minimum – maximum in %)	Dominant vegetation type	MIS
					NAP: Base marked by a pronounced expansion of Chenopodiaceae (33-64 %); *Artemisia* continues from previous sub-zone with max. 32 %, while Poaceae decrease (3-18 %) **GA:** Low **DC:** Low to high towards the top **CC:** Low	vegetation at the end of the zone	
	6	93.51 - 97.02	185.74 - 193.36	Decrease *Quercus*; increase Poaceae	**AP:** General reduction of AP percentages throughout the sub-zone; still abundant: deciduous *Quercus* (1-31 %), *Betula* (0-2 %), and *Ulmus* (<1 %); conifer trees maintain moderate values with small oscillations; disappearance of *Pistacia* cf. *atlantica* **NAP:** Pronounced increase of Poaceae (21-45 %) values; steppic herbs continue to be moderate **GA:** Low **DC:** Low **CC:** Low to moderate, peak at 189.4 ka BP	Open grasslands with scattered temperate trees	
Va	1	97.02 - 99.88	193.36 - 203.11	Increase AP; peak *Pistacia*	**AP:** High AP (24-44 %) percentages mainly of deciduous *Quercus* (8-38 %), increasing values of *Betula* (0-4 %), *Pinus* (0-3 %), and *Juniperus* (0-3 %); peak of *Pistacia* cf. *atlantica* (c. 3 %) at the beginning of the sub-zone; high tree concentration (>3,000 grains cm^{-3}) **NAP:** Moderate percentages of steppic herbs (*Artemisia* 13-29 % and Chenopodiaceae 11-33 %) with significant peak of NAP (85 %) near the base **GA:** Low **DC:** Low **CC:** Low to moderate with one single high peak at 201.3 ka BP (>5,000 particles cm^{-3})	Expansion of oak steppe-forest along with Mediterranean taxa (*Pistacia*), short-term influence of steppe vegetation	7a
	2	99.88 - 101.30	203.11 - 207.56	AP <40 %; decrease *Quercus*	**AP:** Reduction of tree & shrubs (AP 17-50 %) mainly by deciduous *Quercus* (10-30 %) and *Pinus* (1-8 %) but still above 15 %; increase of *Ephedra distachya*-type (1-3 %) and *Betula* (0-2 %) **NAP:** Rapid expansion of Chenopodiaceae (15-47 %), peak values for *Artemisia* (9-32 %) at the beginning; moderate Poaceae (5-19 %) values **GA:** Low **DC:** Low to high **CC:** Low to moderate	More open (steppe) landscape with still patchy pioneer & temperate tree	7b
	3	101.30 - 104.19	207.56 - 216.28	Chenopodiaceae <40 %; increase *Quercus*	**AP:** Predominance of deciduous *Quercus* (2-56 %) with significant peak at 102.8 mcblf (212.6 ka BP) followed by a decreasing trend; high values of *Pinus* (0-19 %); *Betula* (0-4 %) and *Juniperus* (0-2 %) are abundant; *Pistacia* cf. *atlantica* and *Ulmus* pollen occur sporadically; high tree concentration (>3,000 grains cm^{-3}) **NAP:** Peak of *Artemisia* (6-38 %), Poaceae (5-21 %), and Tubuliflorae (2-13 %) percentages at the beginning of the sub-zone; very low Chenopodiaceae values (4-48 %)	Expansion of oak-pine steppe-forest	7c

PAS	PAZ	Composite depth (mcblf)	Age (ka BP)	Criteria for lower boundary	Main palynological characteristics (minimum – maximum in %)	Dominant vegetation type	MIS
					GA: Low **DC:** No occurrence **CC:** High		
Vb		104.19 - 109.05	216.28 - 227.42	Chenopodiaceae >40 %	**AP:** Very low tree percentages (1-12 %) and tree concentration (<2,000 grains cm^{-3}); decrease of deciduous *Quercus* (0-9 %), *Pinus* (0-3 %), and *Juniperus* (<1 %) **NAP:** Predominance of Chenopodiaceae (37-76 %); Poaceae (4-15 %), and *Artemisia* (6-26 %) are abundant **GA:** Low **DC:** Low **CC:** Low with moderate values at the end of this zone	Extensive desert steppe vegetation	7d
Vc	1	109.05 - 109.94	227.42 - 230.71	Disappearance *Pistacia*; decrease AP, increase Chenopodiaceae	**AP:** Continuous decrease in AP (14-19 %), mainly deciduous *Quercus* (2-5 %), *Pinus* (2-10 %); *Pistacia* cf. *atlantica* disappears **NAP:** Strong increase in Chenopodiaceae (23-32 %) abundances, moderate reduction of *Artemisia* (19-27 %) and Poaceae (18-26 %) **GA:** Low **DC:** Low **CC:** Low	Increasing influence of steppe taxa, expansion of open vegetation	7e
	2	109.94 - 111.73	230.71 - 236.95	Decrease *Quercus* and *Pistacia*; increase *Pinus*	**AP:** Percentages of deciduous *Quercus* (6-21 %), *Betula* (0-1 % and *Pistacia* cf. *atlantica* decline while those of *Pinus* (4-26 %) and *Juniperus* (2-5 %) rise **NAP:** Steppe taxa expand, mainly *Artemisia* (5-26 %) and Poaceae (21-36 %), still low Chenopodiaceae (3-13 %) percentages **GA:** High **DC:** Low **CC:** Low with one peak at the end of the sub-zone.	All temperate tree taxa declined gradually, while *Pinus* and grassland expanded (Pinus-dominated steppe-forest)	
	3	111.73 - 112.64	236.95 - 240.31	*Quercus* >10 %; Chenopodiaceae <40 %	**AP:** Peak values for *Betula* (4-8 %) and *Pistacia* cf. *atlantica* (1-2 %), rapid expansion of deciduous *Quercus* (10-40 %); *Pinus* (0-3 %), *Juniperus* (0-1 %), and *Ulmus* are abundant; highest tree concentration (c. 5,300-15,300 grains cm^{-3}) during that PAZ **NAP:** Retreat in steppe percentages mainly *Artemisia* (13-37 %) Chenopodiaceae (3-6 %); moderate Poaceae values (12-20 %) **GA:** Low **DC:** No occurrence **CC:** Moderate to high	Expansion of oak steppe-forest along with Mediterranean sclerophylls (*Pistacia*)	
	4	112.64 - 113.70	240.31- 242.48	Occurrence *Pistacia*	**AP:** Increase in temperate trees & shrubs, in particular deciduous *Quercus* (1-10 %) and *Betula* (1-5 %); occurrence of *Pistacia* cf. *atlantica* (~1 %), *Juniperus* (~1 %), and *Ulmus* (sporadic) **NAP:** Herbaceous taxa continue, mainly Poaceae (7-20 %) and *Artemisia* (37-56 %); pronounced decrease in Chenopodiaceae (6-59 %) **GA:** Low **DC:** No occurrence **CC:**	Steppe taxa become less widespread, giving way to open grassland	

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PAS	PAZ	Composite depth (mcblf)	Age (ka BP)	Criteria for lower boundary	Main palynological characteristics (minimum – maximum in %)	Dominant vegetation type	MIS
					Moderate to high		
VI		113.70 - 118.18	242.48 - 250.14	Not defined	**AP:** Very low abundances of arboreal pollen percentages (*Betula* 0-1 % and deciduous *Quercus* 0-1 %), very low tree concentration (c. 570-1,320 grains cm^{-3}) **NAP:** Predominance of steppe taxa, mainly Chenopodiaceae (52-66 %) and *Artemisia* (18-33 %) **GA:** Low **DC:** Low **CC:** Moderate	Extensive open desert-steppe vegetation	8