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Vegetation, fire and climate history of the Lesser Caucasus: a new Holocene record from Zarishat fen (Armenia)

SÉBASTIEN JOANNIN,[1,2]* ADAM A. ALI,[3] VINCENT OLLIVIER,[4] PAUL ROIRON,[3] ODILE PEYRON,[3] SAMY CHEVAUX,[2] SAMUEL NAHAPETYAN,[5] PETROS TOZALAKYAN,[6] ARKADI KARAKHANYAN[6] and CHRISTINE CHATAIGNER[7]
[1]Geography, School of Environment, Education and Development, University of Manchester, Manchester, UK
[2]CNRS UMR 5276 LGL TPE, Université Lyon 1, Villeurbanne, France
[3]CNRS UMR 5059, CBAE, Montpellier, France
[4]CNRS UMR 7192, PrOCauLAC, Paris, France
[5]Department of Cartography and Geomorphology, Yerevan State University, Armenia
[6]Institute of Geological Sciences, National Academy of Sciences of Armenia, Armenia
[7]Maison de l'Orient, UMR 5133, Lyon, France

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ABSTRACT: Vegetation, fire and climate history are investigated in the 10 000-year record of Zarishat fen located today in the steppe grasslands of Armenia (Near East). Pollen-based climate quantification provides a reconstruction of seasonal parameters. The development of *in-situ* water-dependant plants and of forests at lower altitude at 8200 cal a BP echoes the shift from an arid and cold [annual precipitation (P_{ann}) = 452 mm; mean temperature of the coldest month (MTCO) = −11.1 °C)] Early Holocene to a more humid and warmer (P_{ann} = 721 mm; MTCO = −6.8 °C) Mid–Late Holocene. This marks the onset of lower seasonality, in particular more effective precipitation brought during late spring by the Westerlies. Paralleling the Mediterranean precipitation pattern, precipitation in the Near East and Central Asia decreased during the Mid–Late Holocene in favour of higher seasonality controlled in winter/spring by the Siberian High. Fire history and sedge-based fen development record drier phases at approximately 6400, 5300–4900, 3000, 2200–1500 and 400 cal a BP, which resemble the precipitation pattern of the South-Western Mediterranean and contrast with the Holocene pattern in the South-Central and South-Eastern Mediterranean regions. Arid phases in Armenia are believed to be related to multi-centennial-scale variation of Westerly activity (North Atlantic Oscillation-like).

KEYWORDS: climate and human impacts; fire; Holocene; Near East; vegetation.

Introduction

The impact of the modern global warming is under intense debated as it is regionally modulated due to the complexity and interactions of the underlying climate mechanisms. To better constrain regional specificities in response to climate change, it is therefore crucial to study past local- to regional-scale climate changes. Lake and marine sediments are good climate archives, but the studied sites must be found at the edge of the zone affected by the investigated climate mechanism [i.e. in Europe, the most important climatic mechanisms are the North Atlantic Oscillation (NAO), Westerly winds and anticyclones]. The need for climate archives from regions affected is shared by palaeoclimatologists and palaeoecologists, as well as by climate modellers to validate their models (e.g. Kleinen *et al.*, 2011) and by archaeologists to better constrain relationships between environment, climate and humans (e.g. Montoya *et al.*, 2013).

Separating Euro-Mediterranean and Asian areas, the Near East is a region of a particular interest. The climate is dominated by the influence of cold and dry air masses from the Siberian anticyclone, which, when occasionally weakening, allows the Westerlies to penetrate from the Eastern Mediterranean and Black Sea and to provide snowfall in winter and rainfall in spring (e.g. Berg, 1950; Lydolph, 1977; Fig. 1). In summer, the climate becomes warmer and drier southward. Such seasonal contrast strongly influences the development of steppe-forest on the Anatolian and Armenian Plateaus. Past drivers for Holocene vegetation change remain unclear in the Near East [i.e. authors have hypothesized the impact of the Indian summer monsoon (Djamali *et al.*, 2010) or of the westerlies (Roberts *et al.*, 2011)]. One of the main questions is to explain the delay of forest development in the Near East until ca. 9000–8000 cal a BP (e.g. Lake Van: Wick *et al.*, 2003; Georgia: Connor and Kvavadze, 2008; Lake Paravani: Messager *et al.*, 2013) compared with Europe where it follows the onset of the Holocene (ca. 11 700 cal a BP). According to Turner *et al.* (2010), upland grasslands were maintained by dry-season burning that helped to delay the spread of woodland by up to 3 ka. Messager *et al.* (2013) also questioned the possible role of distance to glacial tree refugia, topography and/or orography, and therefore the location of the studied site above or below the treeline. Other explanations raise a climatically controlled shift from an arid Early Holocene towards a more humid Mid Holocene which followed the high-latitude air temperature and sea surface temperature in the North Atlantic (Chen *et al.*, 2008) or the opening of the Mediterranean corridor into the Black Sea (Shumilovskikh *et al.*, 2012). The second problem is to determine the impact of short-term (i.e. centennial-scale) climate changes, which is even less clear in this region, given the record of phases with opposite palaeohydrological signal (i.e. humid and arid phases) throughout the mid and late Holocene (e.g. Roberts *et al.*, 2011).

The Near East is also of importance when considering the long history of animal domestication and agriculture (e.g. Zohary and Hopf, 1993; Zeder, 2008; Vigne, 2011) and its impact on the environment. The Early Holocene delayed afforestation is hypothesized by Turner *et al.* (2010) to have resulted from fire activity being controlled by climate and amplified by human actions during the Neolithic agricultural

*Correspondence: S. Joannin, [1]Geography, School of Environment, as above.
E-mail: sebastien.joannin@manchester.ac.uk

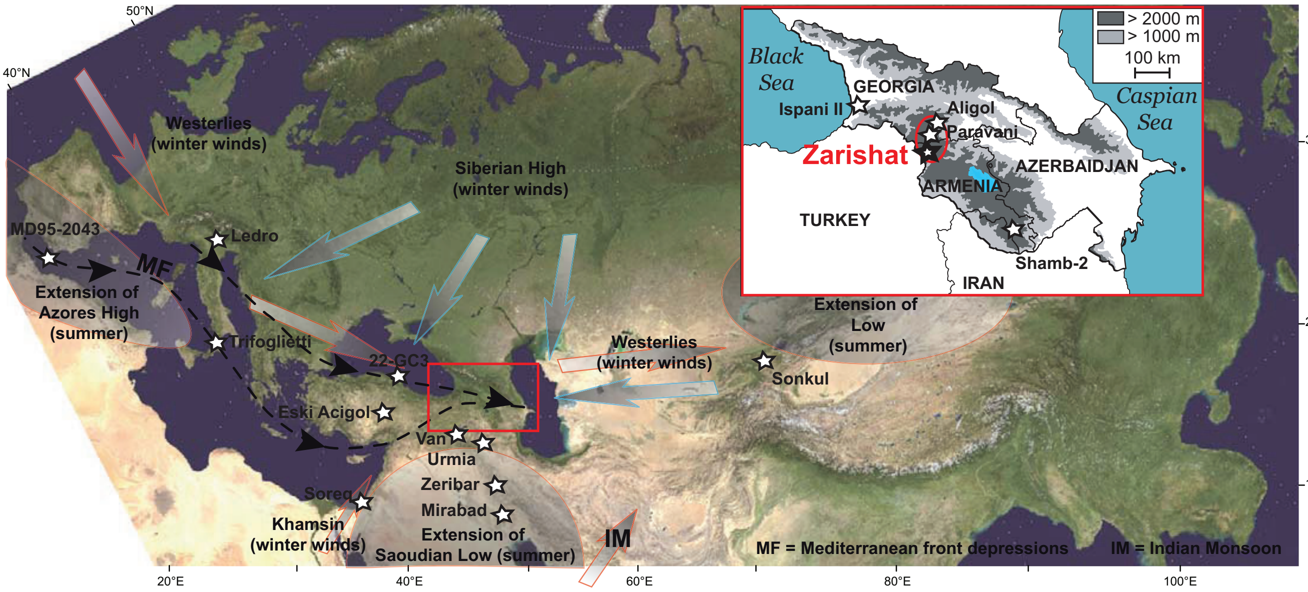

Figure 1. Map of Eurasia showing prevailing wind directions as well as modern cyclone and anticyclone action centres that joined over the Caucasus. Stars show a selection of palaeoenvironmental studies from Eurasia and Armenia/Georgia. The Zarishat fen is located in the southern part of the Djavakheti Plateau (see oval outline in the inset). Dashed lines show cyclone trajectories in winter. This figure is available in colour online at wileyonlinelibrary.com.

expansion. In the Lesser Caucasus, the southern part of the Djavakheti Plateau (in northern Armenia, often named Javakheti or Dzhavakheti) has been used as a source of obsidian (i.e. a volcanic glass for tool manufacture; Chataigner and Gratuze, 2013) since the Pleistocene (Early–Middle Palaeolithic) and the Holocene (i.e. Bronze Age and Iron Age). To reconstruct past environmental changes and their possible relationship to climate and human impacts, we have investigated the sediment archive of Zarishat fen (Fig. 1). Compared with other palaeoenvironmental studies in Armenia (Saiadian, 1985), the Zarishat small drainage system (i.e. fen), located today above the treeline, provides a continuous and high temporal resolution Holocene record of vegetation and fire history from Armenia, as well as the first pollen-based climate quantification.

Study area

Geological setting

The Zarishat fen (40°59.254′N, 43°40.309′E, 2116 m a.s.l.) is located in the Armenian part of the Djavakheti Plateau, which extends across north-western Armenia, southern Georgia and north-eastern Turkey. At a larger scale, this plateau is part of the Armenian Plateau. At a smaller scale, Zarishat is situated within the Ashotsk Depression on the Aghvorik Plateau (Neill *et al.*, 2013), close to the artificial Arpi Lake and the Arpi Lake Natural Park. Zarishat village is situated north of the fen.

The main volcanic activity during the Quaternary ended in the Late Pleistocene (e.g. Lebedev *et al.*, 2008; Ollivier *et al.*, 2010; Messager *et al.*, 2013). This activity led to effusions of basalt and obsidian, favouring small depressions that collect deluvial waters and where local wetlands, such as the Zarishat fen (Jenderedjian, 2005) can develop (Fig. 2).

Present climate and phytogeography

The Armenian Plateau induces a local high-pressure system in winter and a low-pressure system in summer due to thermal effects (Lydolph, 1977). In winter, the Armenian Plateau is more affected by easterly flow, resulting in cold dry conditions, than by westerly flow which occasionally penetrates the area (when the Siberian anticyclone and subtropical anticyclones in southern Iran weaken) to produce snow cover. Mountain-valley circulation, due to differential heating, can produce thunderstorms (particularly in late spring, i.e. May–June), while snow retards a rise in air temperature. The Zarishat area is characterized by a mountain climate. The meteorological station of Ashocq is the closest station to Zarishat. It is expected to document similar climatic conditions to those at the site (Fig. 3), i.e. a low annual temperature (1 °C on average), with a minimum in January (−13 °C on average) and a maximum in July (13 °C on average). Annual insolation and precipitation are about 100 days and 550 mm, respectively. A subalpine to mountain semi-arid bioclimatic zone characterizes the Djavakheti Plateau (Connor and Kvavadze, 2008). The major vegetation types are steppe and pine woods. Grasslands are expected to result from over-grazing in recent times (e.g. Badenkov *et al.*, 1990; Messager *et al.*, 2013). Trees are absent from the Djavakheti Plateau, but coniferous and mixed forests grow at lower altitude north-westward (Walter, 1974; Connor, 2011). Pines have been planted over wide areas since Soviet times. The modern phytogeography of Zarishat is mountain steppe, dominated by grasses. Grazing and haymaking are practised around the Zarishat fen. The upper line of crop cultivation is about 2000–2400 cal a BP (Badenkov *et al.*, 1990) and crops are observed in the Ashotsk Depression. Pine plantations are present at lower altitude, south of Zarishat. The vegetation of the fen is dominated by sedge taxa, such as Cyperaceae.

Materials and methods

Core sampling and sedimentology

Coring of the Zarishat fen, which is almost dry at the end of summer, was performed using a Russian corer at two locations. A 128-cm-long core was drilled at site A and recovered in three sections (A1, A2 and A3; Fig. 4). From base to top, this core contained laminated and silty clays

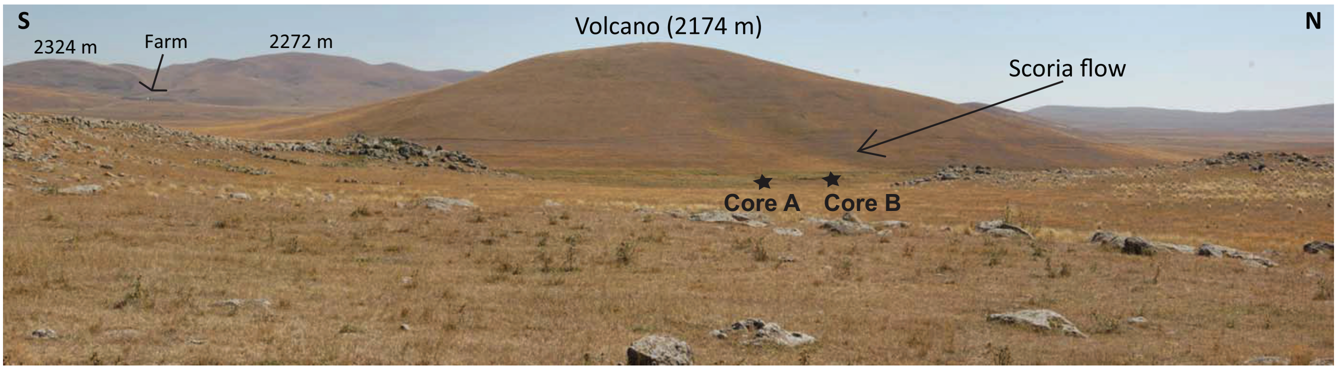

Figure 2. Zarishat fen and core locations. This figure is available in colour online at wileyonlinelibrary.com.

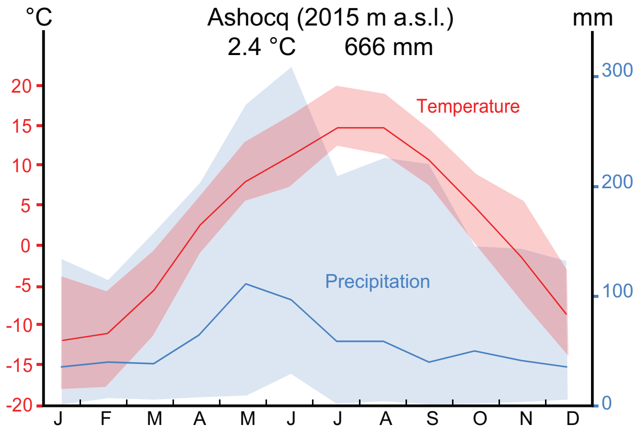

Figure 3. Ombrothermic diagram of the meteorological station of Ashocq, ca. 17 km from Zarishat fen. The temperature and precipitation records span 49 and 70 years, respectively. This figure is available in colour online at wileyonlinelibrary.com.

(from 128 to 103 cm), more organic clays (from 103 to 80 cm) and then peaty sediment. A second core site (Core B) provided one section which contained 40 cm of laminated and silty clays below the peat layer. From a geomorphological perspective, the shape of the basin drainage and site location indicate that this section lies stratigraphically below Core A and is presumably older (see 'Pollen and charcoal age and provenance in the Zarishat record').

The cores were logged with a GEOTEK Multi-Sensor Core Logger to obtain geophysical measurements [gamma-ray wet bulk density, magnetic susceptibility (MS)] at 5-mm intervals. The master core (MC), i.e. the ideal and complete lithological sequence using both parallel cores, was established based on lithological changes in combination with MS and gamma-density profiles (Fig. 4).

Radiocarbon dating

Eight accelerator mass spectrometry (AMS) ^{14}C ages were measured on terrestrial organic material from Core A (Table 1). Macrofossils and charcoals were collected from sediment samples sieved with a 100-μm mesh screen. Unfortunately, no datable macrofossils were found at the base of Section A3 and in Core B. Radiocarbon ages were calibrated in years cal BP via the Calib 6.0 software using the calibration curve IntCal09 (Reimer *et al.*, 2009). Dates are expressed as intercepts with 2σ ranges. The age–depth model is interpolated by a smooth, cubic spline curve (Fig. 4) using the 'Clam' model developed by Blaauw (2010).

Pollen analysis

Pollen samples

Samples of 1 cm^3 of sediment were treated chemically (HCl, KOH, HF, acetolysis) and physically (sieving) following standard procedures (Moore *et al.*, 1991). Samples were taken at 2-cm resolution across the 128 cm of Core A; only five samples were studied in Core B. A total of 59 pollen samples (including seven samples studied by Chevaux, 2012) were analysed under a light microscope at a standard magnification of 400×. Ten pollen samples were sterile. Eighty-five pollen types were identified using photo atlases (Reille, 1992–1998; Beug, 2004) and the reference collection at University of Franche-Comté.

A minimum of 300 or 100 terrestrial pollen grains (excluding wetland plants, i.e. mainly Cyperaceae) was counted for the richest and the poorest samples, respectively. The average sum is 308 pollen grains. Percentages were calculated based on the total pollen sum without Cyperaceae. Using the Psimpoll program (K. D. Bennett, freely available at chrono.qub.ac.uk/psimpolle/psimpoll.html), percentages of the major pollen types are represented in Fig. 5. Local pollen assemblage zones were defined using the CONISS function of Psimpoll. Figure 6 presents a pollen diagram in percentage and in age for selected major arboreal and non-arboreal taxa.

Pollen-based climate reconstruction

Quantitative estimates of temperature/precipitation are inferred from Zarishat pollen data with the Modern Analogue Technique 'MAT' (Fig. 7). In the MAT (Guiot, 1990), the similarity between each fossil sample and modern pollen assemblage is evaluated by a chord distance: if the chord distance is above a threshold defined by a Monte-Carlo method, the modern samples are rejected. Estimates of past climatic parameters are obtained by taking a weighted average of the values for all selected best modern analogues, where the weights used are the inverse of the chord distance. To reduce uncertainties, we have applied to the analogue selection a constraint by biomes. A biome is assigned to each modern and fossil pollen sample following the procedure defined by Peyron *et al.* (1998) based on a plant functional type–pollen data attribution. The biomes assigned to the selected modern analogues (e.g. cold steppes) are compared with that assigned to the fossil assemblage (e.g. cold steppes), and only the analogues with consistent biomes (cold steppes/cold steppes) are retained for the analogue matching step. Winter and late spring precipitation (P_{win}, $P_{May–Jun}$) are the hydrological parameters that are assumed to have the strongest relationship with pollen data in Armenia. In

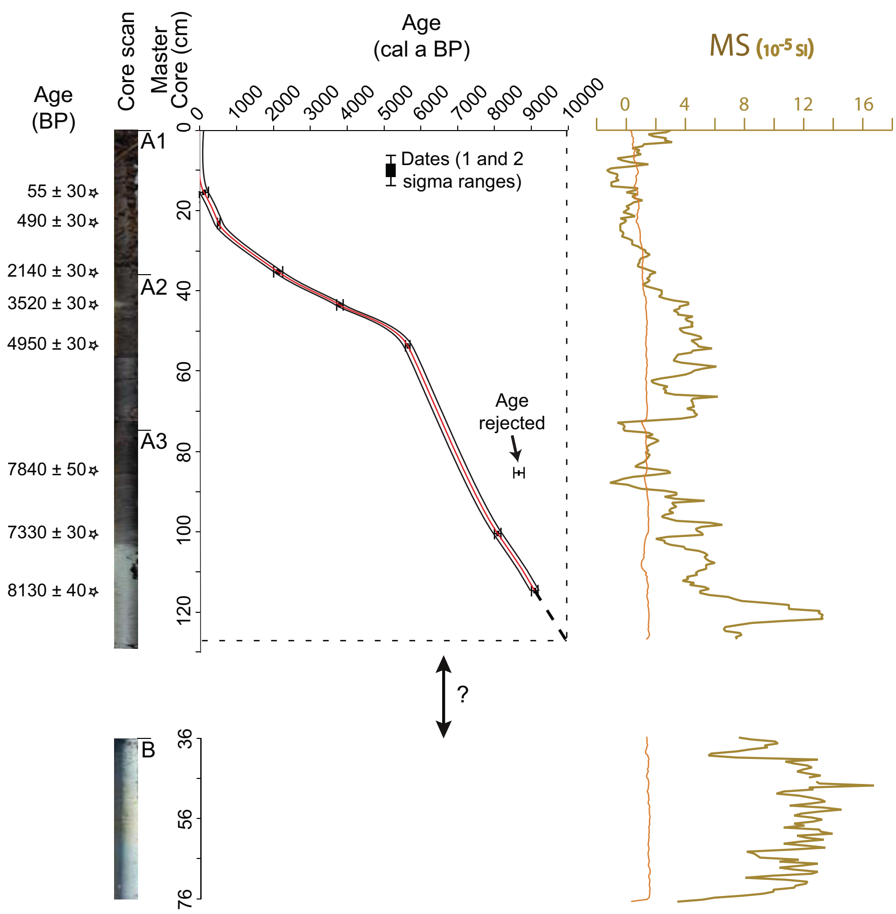

Figure 4. Lithology, gamma-ray wet bulk density and magnetic susceptibility (MS) of cores A and B and age–depth model based on calibrated radiocarbon ages (black dots with 2σ errors) (AMS, see Table 1) from Zarishat. This figure is available in colour online at wileyonlinelibrary.com.

Table 1. AMS–radiocarbon dates with 2σ range of calibration from cores of Zarishat fen.

Sample ID	Laboratory code	AMS ^{14}C age (BP)	Depth MC (cm)	Age (cal a BP) (2σ)
C1-1-16.5	Lyon-8487	55 ± 30	16.5	0–256
C1-1-23.5	Lyon-8488	490 ± 30	23.5	501–545
C1-1-34.5	POZ-46335	2140 ± 30	35	2004–2302
C1-1-43.5	Lyon-8489	3520 ± 30	43.5	3701–3875
C1-1-52.5	Lyon-8490	4950 ± 30	53	5606–5734
C1-1-76.5*	POZ-46336	7840 ± 50	86.5	8462–8967
C1-3-93.5	Lyon-8491	7330 ± 30	101	8033–8190
C1-3-104	POZ-46334	8130 ± 40	114	8996–9246

*Age rejected. MC = master core. All material was terrestrial organic.

southern Georgia also, statistical analysis showed that rainfall was the parameter most strongly correlated with pollen composition (Connor and Kvavadze, 2008). The temperature of the coldest month (MTCO) is also reconstructed because this variable imposes a limit on the growth of plants, and is a principal variable determining the composition and structure of the vegetation (Huntley, 2012).

To improve the climate reconstruction, in particular to reduce the potential effect of spatial autocorrelation (Telford and Birks, 2005), we have updated the modern pollen dataset by adding 45 surface samples from southern Georgia (Connor *et al.*, 2004; Connor and Kvavadze, 2008). The updated dataset now contains 3058 surface samples.

Macroscopic charcoal analysis

Macroscopic charcoal samples of 1 cm^3 were taken contiguously for the uppermost 86 cm of masterCore A. Samples were soaked in a 3% $(NaPO_3)_6$ solution for a minimum of 2 days before wet sieving through a 160-μm screen. The remaining particles were bleached in a 10% NaOCl solution to aid in distinguishing charcoal from dark organic matter. The sieving method is assumed to represent local-scale fires, i.e. 1 km from the fen (e.g. Carcaillet *et al.*, 2001; Higuera *et al.*, 2007). Identification, counting and area measurements of charcoal particles were undertaken using a 20× stereoscope coupled with a digital camera and image-analysis software (Regent Instruments Canada Inc.).

First, peak components of total charcoal influx $CHAR_i$ series were interpolated to constant time steps ($C_{interpolated}$), corresponding to the median temporal resolution of the record. Low-frequency variations in $CHAR_i$, namely $C_{background}$, represent changes in charcoal production, transport, sedimentation, mixing and sampling. We therefore decomposed $CHAR_i$ into background ($C_{background}$) and peak (C_{peak}) components using a locally defined threshold that identified charcoal peaks probably related to the occurrence of one or more local fires (i.e. 'fire events' within ca. 1 km).

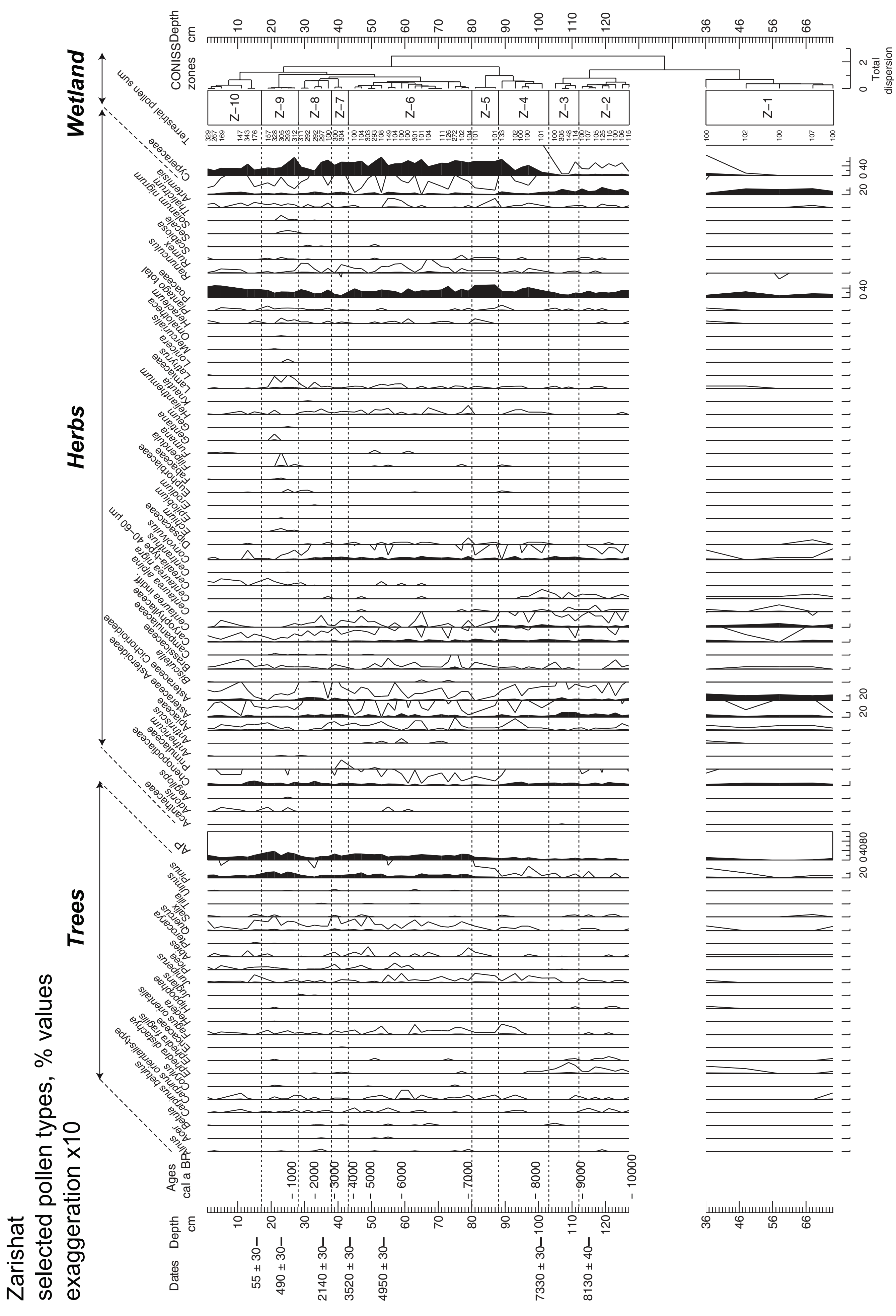

Figure 5. Pollen diagram against depth showing percentages of main pollen taxa. Pollen zones are based on CONISS. 10× exaggerations of the pollen curves are also shown.

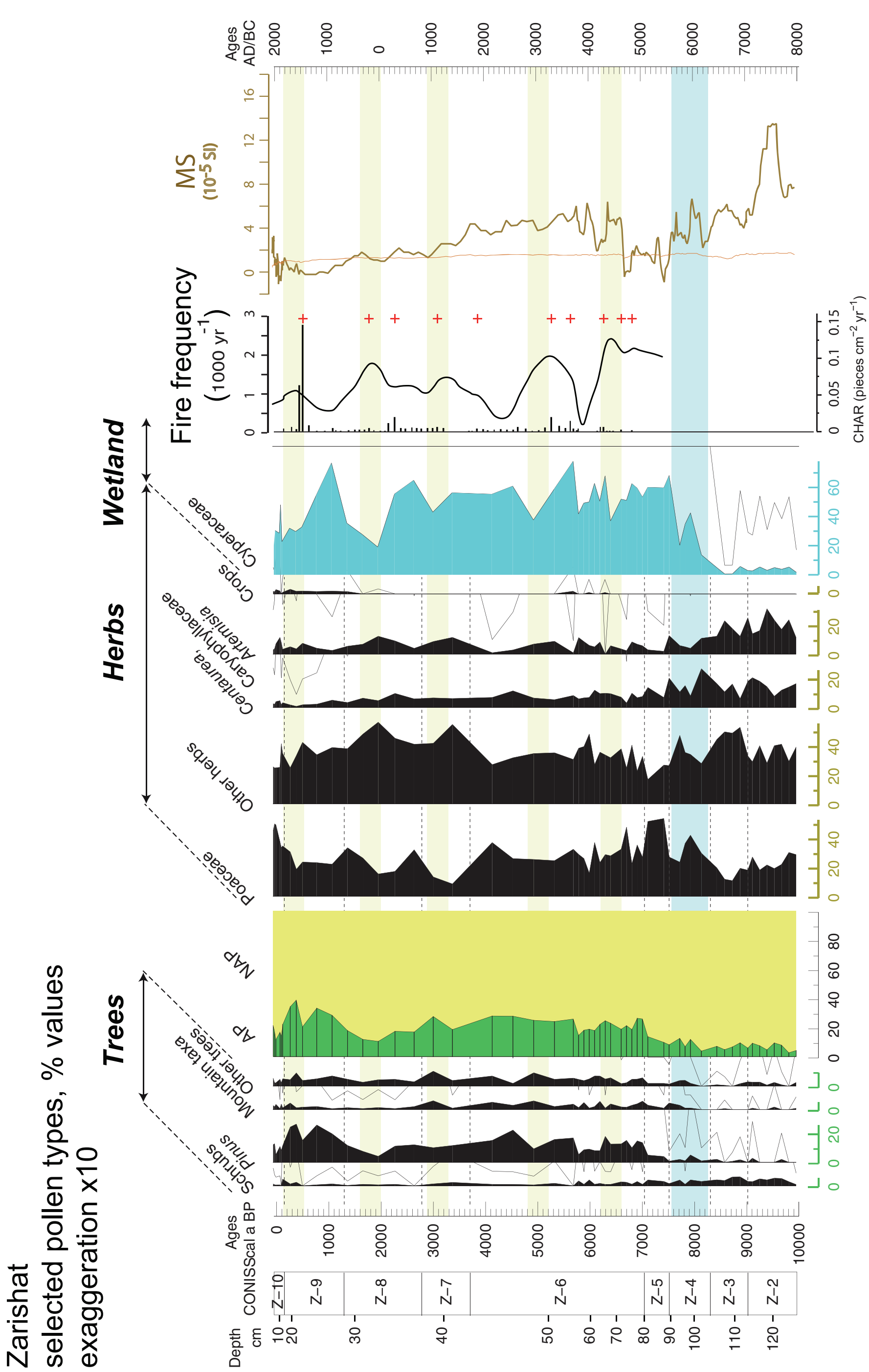

Figure 6. Pollen diagram against age showing percentages of main pollen taxa or groups of taxa. Depth and pollen zones from Fig. 5 are reported. Fire frequency, CHAR (i.e. charcoal accumulation rate), fire events (crosses) and magnetic susceptibility are also shown. Vertical shading is used to represent arid (five narrow strips) and humid (one wider strip at around 8000 a BP) phases. This figure is available in colour online at wileyonlinelibrary.com.

The locally weighted regression was applied with a 500–800-year window that maximized a signal-to-noise (peak-to-background) index and the goodness-of-fit between the empirical and modelled $C_{background}$ distributions (Higuera *et al.*, 2009). The residual series related to peaks were obtained by subtraction (i.e. $C_{peak} = C_{interpolated} - C_{background}$).

Consistent with theoretical evidence (Higuera *et al.*, 2007) and previous work (e.g. Gavin *et al.*, 2006; Higuera *et al.*, 2008), we assumed in a second step that C_{peak} was composed of two subpopulations, namely C_{noise}, representing variability in sediment mixing, sampling, and analytical and naturally occurring noise, and C_{fire}, representing significant peaks of charcoal inputs from local fires. For each peak, we used a Gaussian mixture model to identify the C_{noise} distribution. We considered the 99th percentile of the C_{noise} distribution as a possible threshold separating samples into 'fire' and 'non-fire' events. All statistical treatments were performed using the program CharAnalysis (P. E. Higuera, freely available at charanalysis.googlepages.com).

Results and interpretation

Age model

One ^{14}C age from a depth of 86.5 cm was excluded from the age–depth model, having both low organic content and large error margin (7840 ± 50; Table 1). The age–depth curve (Fig. 4) shows a sedimentation rate (1.7 cm · 100 a^{-1}) which diminishes at ca. 5500 cal a BP (0.6 cm · 100 a^{-1}) and a slight acceleration (4.6 cm · 100 a^{-1}) during the last millennium. The age–depth model is extrapolated to the base of Section A3. The Zarishat record covers 10 000 cal a BP. The Holocene is therefore not entirely recorded. The average temporal resolution for the pollen analysis is estimated to 184 years per sample.

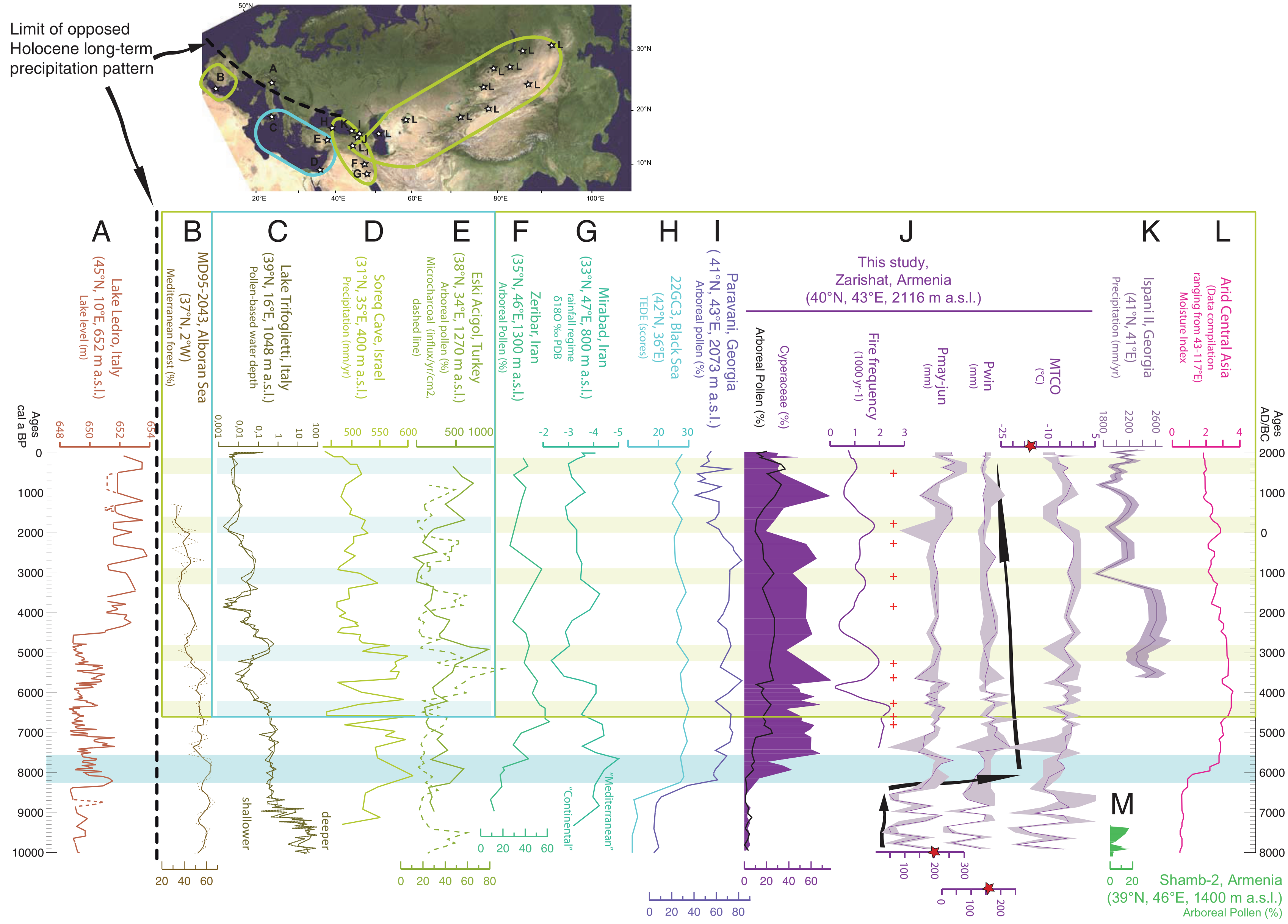

Figure 7. Comparison of palaeorecords from Lake Ledro (A; Magny *et al.*, 2012), Alboran Sea (B; Fletcher *et al.*, 2013), Lake Trifoglietti (C; Joannin *et al.*, 2012), Soreq Cave (D; Bar-Matthews *et al.*, 2003), Eski Acigol (E; Turner *et al.*, 2008; Roberts *et al.*, 2011), Zeribar (F; Stevens *et al.*, 2001), Mirabad (G; Stevens *et al.*, 2006), 22GC3 (H; Shumilovskikh *et al.*, 2012), Paravani (I; Messager *et al.*, 2013), Zarishat (J; this study), Ispani II (K; Connor and Kvavadze, 2008), Central Asia (L; Chen *et al.*, 2008; L_1 corresponds to Lake Van, Wick *et al.*, 2003) and Shamb-2 (M; Ollivier *et al.*, 2011). Shaded strips are used to represent arid and humid phases (as in Fig. 6). The stars indicate present day MTCO, winter and late spring (May–June) precipitation. This figure is available in colour online at wileyonlinelibrary.com.

Table 2. Pollen-based climate parameters reconstructed for the time interval recorded at Zarishat.

Climate parameter	Possible Lateglacial	10–0 ka, Holocene	10–8.2 ka, Early Holocene	8.2–0 ka, Mid–Late Holocene
MTCO (°C)	−13.1	−7.8	−11.1	−6.8 (Δ = +4.3)
P_{ann} (mm)	197	659	452	721 (Δ = +269)
P_{win} (mm)	40	141	92	156 (Δ = +64; +70%)
$P_{May–Jun}$ (mm)	49	192	122	213 (Δ = +91; +75%)

Pollen analysis

Pollen sequence

The vegetation history of Zarishat fen is divided into 10 local pollen assemblage zones (LPAZs) for the Holocene (Z-2 to Z-10) and the possible Lateglacial period (Z-1). Ten samples were sterile (at depths of 7, 9, 17, 43, 69, 83, 85, 91, 99 and 103 cm).

Core B starts with pollen zone Z-1, which is mainly dominated by steppic taxa such as *Artemisia* and taxa from open ground (Asteraceae Cichorioideae, Poaceae, *Centaurea*, Chenopodiaceae and Caryophyllaceae). The upper part of zone Z-1 is characterized by the development of shrubs (mainly *Ephedra* and *Juniperus*) and the delivery of wind-transported *Pinus* pollen grains.

Core A starts with pollen zone Z-2 (ca. 9950 to ca. 8950 cal a BP) in which open-ground and steppic vegetation are dominant. Other taxa such as *Centaurea* and Poaceae developed, while Asteraceae Cichorioideae is very low compared with zone Z-1. Zone Z-3 (ca. 8950 to ca. 8250 cal a BP) is also characterized by a steppic vegetation, and includes more shrubs, such as *Ephedra*.

A major change then occurs in zone Z-4, as attested to by the development of Cyperaceae, which is a water-dependant taxon, suggesting the development of the fen. This change continues upwards. Zone Z-4 (ca. 8250 to ca. 7500 cal a BP) is also characterized by the development of more thermophillous taxa, such as deciduous *Quercus*, *Fagus orientalis* and *Carpinus orientalis*. However, percentages of woody taxa [Arboreal Pollen (AP)] remain relatively low and therefore question the presence of deciduous trees near Zarishat fen.

Cyperaceae fully develops during zones Z-5 (ca. 7500 to ca. 7050 cal a BP) and Z-6 (ca. 7050 to ca. 3700 cal a BP). The first zone is also characterized by tree development, such as deciduous *Quercus*, *Pinus* and *Juniperus*. A more diverse assemblage of trees developed in Zone Z-6. *Abies*, *Ulmus*, *Tilia*, *Acer*, *Betula*, *Alnus* and *Carpinus betulus* are recorded. The first record of *Picea* is dated to ca. 6200 cal a BP.

In zone Z-7 (ca. 3700 to ca. 2800 cal a BP), the amount of Poaceae reaches its minimum. In zone Z-8 (ca. 2800 to ca. 1200 cal a BP), Cyperaceae and AP decrease concomitantly and attain a minimum at about 2000 cal a BP. They increase again in zone Z-9 (ca. 1200 to ca. 150 cal a BP) with a maximum of *Pinus*, while zone Z-10 is characterized by more open-ground taxa, such as Poaceae. Pollen grains of the relict tree taxon *Pterocarya* are found in zones Z-9 and Z-10. This taxon, which was present in Armenia during the Early Pleistocene (Joannin *et al.*, 2010; Ollivier *et al.*, 2010), has very high pollen production (Stuchlik and Kvavadze, 1998; Filipova-Marinova *et al.*, 2010) and occurs regularly in Holocene pollen records from the Tsalka Plateau in Georgia (Connor, 2011), which is just as far away from *Pterocarya* populations as Zarishat. The low percentages of *Pterocarya* in the Zarishat record suggest long-distance transport.

Pollen-based climate reconstruction

Only two samples of the possible Lateglacial period show too few modern analogues to be selected (one and five, respectively): they have been removed from this study. For all other samples, eight modern analogues have been selected for climate reconstruction. The climate reconstruction appears robust for the entire Holocene: the adopted threshold is 66.17, and the Chord distance, which measures the quality of the modern analogues, is low, especially after 8200 cal a BP (Fig. 7). The modern analogues selected (biome: cold steppe) are mainly located in southern Georgia, in Armenia and in the former Soviet Union.

Average MTCO, winter and late spring (May–June) precipitation (P_{ann}, P_{win} and $P_{May–Jun}$) are shown in Table 2. In Core B (possible Lateglacial period), they illustrate cold and very dry conditions. During the 10 000-year- Holocene record, the mountain climate of Zarishat is well reconstructed and matches that of the present. The first part of the record (ca. 10 000 and ca. 8200 cal a BP) shows lower and more variable climate parameter values than the second part (from ca. 8200 cal a BP onwards). Note that the shift that took place at ca. 8.2 ka resulted in a considerable change in climatic conditions, in terms of both precipitation (ΔPann = +269 mm) and temperature (ΔMTCO = +4.3 °C). When considering the seasonal parameters for precipitation, it appears that winter and late spring precipitation increase by about +70 and 75%, respectively. A progressive decreasing trend is observable in winter precipitation during the Mid–Late Holocene.

Macroscopic charcoal analysis

The use of local thresholds resulted in good separation of C_{fire} and C_{noise}, with median SNI (local noise index) >9.5 (Kelly *et al.*, 2011).

Charcoal particles were elongated in shape, with mean length/width ratio of ca. 2.40. This suggests that fires mostly burned sedge and grassland vegetation. As there is no charcoal at the base of the sequence, the fire activity provides a 7200-year record, which leads us to identify long intervals between fires. Along the studied interval, a general decreasing trend is observed and five peaks of fire frequency are identified at ca. 6400, ca. 5300–4900, ca. 3000, ca. 2200–1500 and ca. 400 cal a BP.

Discussion

Age and provenance of pollen and charcoal in the Zarishat record

Core B is expected to be older than Core A. This cannot be validated by radiocarbon dating but can be argued based on the location of the Core B site at the margin of the wetland system, upstream from a soft slope break which has slowed the transfer of fine sediment (rock flour) provided by glaciers on the surrounding reliefs, which persisted until the beginning of the Holocene. At a wider regional scale, several studies have demonstrated the presence of glacial morphologies and formations at low altitudes (around 1600–2000 m a.s.l.) in Turkey (Taurus, Anatolia, Pontides: Erinç, 1952; Kuzucuoglu and Roberts, 1998; Çiner, 2003), Caucasus (Milanovsky, 2008), Lesser Caucasus (Ollivier *et al.*, 2010; Messager *et al.*, 2013) and south-eastern Iran (Kuhle, 2007) with a general glacier retreat starting during the interval 12 000–8500 cal a BP (Sevastianov *et al.*, 1990; Messager *et al.*, 2013). Subsequently, in this physiographic context, with weak supply of water (small thalweg of a wet meadow), only the centre of the depression (Core A) was eroded and filled with the more humid Holocene sedimentation, causing a tearing of deposits and leaving a chronostratigraphic gap between the two cores. When comparing the pollen content of Z-1 with the Early Holocene Z-2, it appears that they are largely dominated by steppic and open-ground taxa and thus included in the same first-order cluster of the CONISS function. However, they show a strong difference in the percentages of Asteraceae Cichorioideae pollen grains, which are very resistant to oxidation. Therefore, high values of this grain in zone Z-1 combined with high MS values may attest to very dry sedimentation and oxidation conditions. With the present data, Core B can certainly be considered older than the Core A basement, i.e. 10 000 cal a BP, with an unknown long-gap separating them.

The major insight from comparison of pollen and macroscopic charcoal analysis (Fig. 6) is that the tree limit never reached Zarishat fen (i.e. 2116 m a.s.l.). Charcoal particles are indeed from non-ligneous plants and tree pollen grains are weakly recorded, although being highly diverse. This latter feature suggests pollen transport from forested areas, probably located at lower altitude in the valleys. Based on the high tree pollen percentages (up to 80%), in particular those of *Abies* (<10%) and *Fagus* (<12%), recorded at Lake Paravani (2073 m a.s.l.), Messager *et al.* (2013) concluded that the highest belts (coniferous and mixed forest) may have reached the watershed during the most favourable climatic periods (i.e. Mid Holocene), while forest communities were located at lower altitude. Although being in a different climate context (Badenkov *et al.*, 1990), comparable pollen-based treelines from Abkhazia (western Georgia; Connor and Kvavadze, 2008) record a maximum altitude of approximately 2050 m a.s.l.

Vegetation and fire history of the Lesser Caucasus

Possible Lateglacial period and Early Holocene

Steppic vegetation developed under arid and cold climate conditions possibly during the Lateglacial. The Holocene, beginning at 11 700 cal a BP, is not entirely recorded at Zarishat. Starting from ca. 10 000 cal a BP up to ca. 8250 cal a BP (Z-2 and Z-3; Fig. 6) steppic and shrubby vegetation developed. According to the low abundances of Cyperaceae, we expect low water supply during the possible Lateglacial and Early Holocene. Zarishat must have been an ephemeral wetland allowing the deposition of coarse and silty clays over several thousand years. A similar deposit is observed at numerous sites in southern Georgia (Margalitadze, 1995; Connor, 2011; Messager *et al.*, 2013).

Mid and Late Holocene

The strong development of water-dependent Cyperaceae (i.e. sedge) at ca. 8250 cal a BP indicates more effective precipitation delivered into Zarishat fen. The full development lasts 900 years with a short stop at ca. 7800 cal a BP, perhaps due to a brief return to dryer conditions, although this is not corroborated by changes in tree percentages. During this period, steppic taxa decrease while tree pollen increases. This change results in a sedimentary change to organic silts, characterized by lower MS values. These observations suggest more humid conditions for the Mid and Late Holocene than for the Early Holocene. The presence of *Picea* starts at ca. 6200 cal a BP, when this taxon become more developed in the pollen diagram from Lake Paravani (Messager *et al.*, 2013). However, note that a progressive drying and a possible cooling along the Mid–Late Holocene is shown by long-term decreasing trends of Cyperaceae as well as mountain taxa (*Abies* and *Fagus orientalis*) and temperate taxa (e.g. *Carpinus betulus*, *Carpinus orientalis* and deciduous *Quercus*).

Short-term variations are observed. From ca. 7500 to ca. 7050 cal a BP (Z-5), the surroundings of the fen are mainly composed of Poaceae, while trees develop from 7050 cal a BP onwards. It is noteworthy that a first decrease in Cyperaceae occurred in phase with a fire frequency peak. This may suggest that fire burned the Cyperaceae growing in the Zarishat fen. Such a relationship is observed at ca. 6400, ca. 5300–4900, ca. 3000, ca. 2200–1500 and ca. 400 cal a BP, where decreases in the amount of Cyperaceae match increases in fire frequency. During the last three phases, Poaceae, which is the main constituent of the herbaceous landscape, is also decreasing.

The observed reverse correlation between fire frequency and Cyperaceae–Poaceae development may be driven by climate. It is indeed possible that climate conditions such as aridity can, at the same time and at a local-scale, (1) decrease the development of grass in the surroundings and of sedge in the fen by lowering the amount of water availability in the drainage basin, and (2) enable local fire to invade the dry Cyperaceae. Such phases of aridity would also have impacted the forest patches located at lower altitude, resulting in reduced tree pollen grains in the pollen record. This is the case for *Pinus* pollen grains at ca. 5000 cal a BP, and for tree pollen grains (mainly *Pinus* and mountain taxa) between 2200 and 1500 cal a BP. The possible human role in shaping Cyperaceae-dominated mires with fire cannot be excluded as it is current practice in Djavakheti (Fig. 4.22 in Connor, 2011).

Human impact

Archaeological remains, cultivated taxa (i.e. *Cerealia*-type) in the pollen record and fire history can be used to depict human presence and influence. Obsidian from the Aghvorik source close to Zarishat (i.e. 15 km; Chataigner and Gratuze, 2013) were used during the archaeological periods of the Early-Mid Palaeolithic, the Neolithic, the Early Bronze Age (ca. 5500–4200 cal a BP/3500–2200 BC), the Late Bronze Age and Iron Age (ca. 3400–2700 cal a BP/1400–700 BC) (MAE, 2010). Remains dated to other periods do not indicate permanent settlement by humans before the Late Bronze Age and Iron Age when a fortress was established at Aghvorik (MAE, 2010, 2011). The palaeoenvironmental record from Zarishat did not allow documentation of the Palaeolithic.

The pollen record offers the possibility to detect human presence using cultivated taxa, such as Cerealia-type pollen grains (Beug, 2004; Tweddle *et al.*, 2005; Joannin *et al.*, 2013). In the record from Zarishat fen (Fig. 6), the curve of cultivated taxa suggests two phases of local-scale farming from 6300 to 5700 cal a BP (4300–3700 BC) and since ca. 1500 cal a BP (AD 500). A Holocene fire history of southern Georgia based on microcharcoals (i.e. regional-scale fires), published by Connor (2011), reports increases during the Chalcolithic period (up to 5000 BP/3000 BC) and Classical–Medieval times (2500–600 BP/500 BC to AD 1400), and therefore suggests a minor role of humans during these periods. Turner *et al.* (2008) emphasize a low role for societies in Central Anatolia from a regional record of fire activity at Eski Acigol (Fig. 7). According to these authors, only the two last millennia (i.e. from 3000 to 1000 cal a BP/1000 BC to AD 1000) record climate-decoupled fire cycles, and therefore argue for human-induced management on the landscape. At Zarishat (Fig. 6), Chalcolithic local-scale agriculture attested to by the presence of crop pollen is not practised along with sedge clearance by fire, given that a low fire frequency is recorded at ca. 6200–5800 cal a BP.

Past and modern climate factors for the Lesser Caucasus

Long-term Holocene climate change

The Zarishat pollen record (Fig. 7) is dominated by steppic vegetation during the Early Holocene, followed during the Mid Holocene by an increased tree cover combined with the local development of Cyperaceae starting at 8200 cal a BP. Then, a progressive decreasing trend is observed in AP as well as in sedge vegetation.

The steppe meadow developed under dry climatic conditions during the Early Holocene. Similar open-land vegetation and climate conditions are confirmed in pollen records in a synthesis from the Balkan peninsula to southern Siberia (Wright *et al.*, 2003), in lowland Bulgaria (Connor *et al.*, 2013; Filipova-Marinova *et al.*, 2013), in Turkey at lakes Van (1648 m a.s.l.; Wick *et al.*, 2003) and Eski Acigol (Roberts *et al.*, 2011) and in the marine record from 22GC3 (Shumilovskikh *et al.*, 2012), on the Djavakheti Plateau in Georgia (Messager *et al.*, 2013), in Iran at lakes Zeribar (Stevens *et al.*, 2001), Mirabad (Stevens *et al.*, 2006) and Urmia (Djamali *et al.*, 2010), in Armenia at the Shamb-2 travertine (Ollivier *et al.*, 2011), in Central Asia at lake Sonkul (Mathis *et al.*, 2012) and in the synthesis including different biotic (e.g. pollen and diatoms) and abiotic proxies (e.g. $\delta^{18}O$ and lake-level) developed by Chen *et al.* (2008).

Compared with the onset of humid conditions favourable to the forest development as early as 11.7 ka in Europe (e.g. Joannin *et al.*, 2013), Wick *et al.* (2003) hypothesize an influence of the Siberian Highs during the plants' growing season (i.e. spring), which could have maintained arid conditions during the first three millennia of the Holocene in the Near East. According to Turner *et al.* (2010), regional-scale fire activity was controlled by climate and amplified by human actions during the Neolithic agricultural expansion, so that upland grasslands were maintained by dry-season burning that helped to delay the spread of woodland by up to 3 ka. According to Djamali *et al.* (2010), a delay of up to 6.3 ka cal BP in the Near East was due to a typical Mediterranean continental climate (mainly winter-dominated precipitation) in which spring precipitation was reduced or eliminated by northward shifts of the inter-tropical convergence zone (ITCZ) and subtropical anticyclonic belt that prevented the eastward penetration of the North Atlantic and Black Sea lows. An arid early Holocene with a delay in forest development are also reported in the West, Central and East Mediterranean areas (see, for example, the synthesis of Magny *et al.*, 2011 and Roberts *et al.*, 2011) and is probably due to strong seasonal contrast with high winter precipitation and low summer precipitation (e.g. Desprat *et al.*, 2013). At Zarishat, dry-season burning is not recorded during the Early Holocene. Strong Siberian Highs most probably blocked westerly winds (and precipitation) and caused dry late springs. Then, a more humid Mid Holocene developed in the Mediterranean and in the Near East. However, this onset is surprisingly rapid in the Near East, as documented by palaeoenvironmental records presented in Fig. 7. There, temperate trees developed at 8.3 ka cal BP at 22GC3, at 8.2 ka cal BP at Lake Van (varve chronology) and Eski Acigol, at 8.3 ka cal BP at Lake Paravani (Messager *et al.*, 2013), and at 7.8 ka cal BP in Iran (Zeribar and Mirabad lakes). An abrupt onset at approximately 8.0 ka cal BP is also recorded in a compilation of Eurasian data ranging from Lake Van (i.e. 43°E) towards eastern China (Chen *et al.*, 2008). The Zarishat depression itself shifted from an ephemeral wetland to fen as documented by the development of water-dependant plants (i.e. sedge) at 8.2 ka cal BP. This marked the change from an arid and cold Early Holocene ($P_{ann} = 452$ mm and MTCO = –11.1 °C) to a more humid and warmer Mid–Late Holocene ($P_{ann} = 721$ mm and MTCO = –6.8 °C), which is due to the onset of less strongly contrasting seasonal parameters as well as reduced variability in pollen-based climate parameters, such as May–June precipitation and MTCO. More effective precipitation develops during spring (May to June) by the Westerlies. This shift marks the installation of present-day climate over East Anatolia and North Iran, where late spring is the period with most rainfall, while summer is cool/warm and dry. Today, precipitation results from depressions preferentially following the Black Sea (Fig. 1). Southward, precipitation is supplied by moisture advected from the Persian Gulf (Stevens *et al.*, 2001), although this is a relatively minor contribution (Djamali *et al.*, 2010),

Although highly debated, the opening of the Black Sea corridor led to the conversion of lacustrine waters to marine waters in the Black Sea at around 8.3–8.0 ka cal BP (e.g. Filipova-Marinova *et al.*, 2013), coinciding with the Near East precipitation regime change. Orographic rainfall in northern Anatolia originates mainly from the Black Sea, and therefore, high evaporation rates from airstreams passing over the Black Sea surface and increasing westerly winds are likely to influence the precipitation regime and vegetation in the northern Near East (Shumilovskikh *et al.*, 2012).

The palaeoenvironmental records from the Mediterranean, Near East and Central Asian illustrated in Fig. 7 show a similar aridification trend, which opposed the wetness trend observed in general in Europe (e.g. Magny *et al.*, 2013) illustrated by a lake-level reconstruction of Lake Ledro (Magny *et al.*, 2012). This allows us to extend eastward the approximate limit (dashed line in Fig. 7) discussed by Magny *et al.* (2007, 2013) for the opposition between northern Europe and Mediterranean–Near East–Central Asia climate patterns. The observed progressive aridification may be due to decreasing precipitation during the Mid–Late Holocene favoured by higher seasonality, controlled in winter/spring by the Siberian highs which block the westerlies due to decreasing summer insolation. According to Messager *et al.* (2013), deforestation on the Djavakheti Plateau started at 2000–3000 cal a BP, driven by deterioration of the climate and human impact.

Centennial-scale climate changes

At Zarishat, fire frequency history and sedge-based transgressions and regressions of the fen provide a record of drier phases at ca. 6400, ca. 5300–4900, ca. 3000, ca. 2200–1500 and ca. 400 cal a BP. While excluding the human impact depicted through cereal pollen grains, these drier phases are recorded at Ispani II, a pollen-based precipitation record from coastal Georgia (Connor and Kvavadze, 2008), and observed in the estimated rainfall regime recorded through $\delta^{18}O$ measurements at Mirabad (Stevens *et al.*, 2006) and other lakes (e.g. Van, Zeribar) synthesized by Turner *et al.* (2008). Similar internal variations are observed at MD95-2043 based on declining Mediterranean forests, and extended to the South-West Mediterranean in a recent data compilation by Fletcher *et al.* (2013). There, the limiting factor for vegetation development is the winter precipitation stored as soil moisture and used during the growing season. Therefore, arid phases can be caused by weak westerlies (i.e. dry winters) causing by an NAO-like cyclicity of Westerly activity on a multi-centennial scale during the Mid and Late Holocene (Fletcher *et al.*, 2013). Such a scenario is inversely recorded in South-Central and South-Eastern Mediterranean areas. Recorded are high water-depth from the Trifoglietti lake in southern Italy (Joannin *et al.*, 2012) as well as peaks in the geochemically based precipitation reconstructed in the speleothem at Soreq Cave (Bar-Matthews *et al.*, 2003) and in the low microcharcoal influx and AP recorded at Eski Acigol in Turkey (Turner *et al.*, 2008). In the Eski Acigol record, regional fire activity recorded in Central Anatolia therefore appears to be controlled by spring precipitation.

The record of wet phases in southern Italy, Israel and central Turkey suggests a climatically decoupled South-Central and South-East Mediterranean compared with South-West Mediterranean and the Near East. Regardless of whether they express arid or wet phases, their pacing resembles the centennial-scale variability linked to Westerly activity, which is itself the result of teleconnection with North Atlantic climate variability.

During the Late Holocene, two AP increases, although dominated by the development of pine forest, underlined the Medieval Warm period (1100–700 cal a BP/AD 900–1300) and the Little Ice Age (400–200 cal a BP/AD 1600–1850). The Little Ice Age differs from the Medieval Warm period with the spread of mountain taxa coinciding with the growth of Caucasian glaciers (Solomina, 2000).

Conclusions

Although relatively shallow (128 cm), the sediment infill of the small drainage basin of Zarishat fen offers a rare chance to discuss long- and short-term environmental changes occurring during the last 10 000 years in the Lesser Caucasus. Sediment deposition, vegetation and fire history have been investigated as well as pollen-based climate quantification to provide a reconstruction of seasonal climate parameters in the Near East. The results have been compared with similar records from Mediterranean and Asian areas.

Thanks to a robust chronology (i.e. seven AMS radiocarbon dates), we confirm that local-scale records of pollen and macrocharcoal are prone to regional-scale climate changes. Therefore, our study of the Zarishat fen deposits shows the usefulness of working with a well-constrained, relatively small system located higher than past and modern treelines.

The Zarishat basin shifted from an ephemeral wetland to fen, as documented by the development of water-dependant plants (i.e. sedge) at 8200 cal a BP. This marked the change from an arid and cold Early Holocene ($P_{ann} = 452$ mm and MTCO = –11.1 °C) to a more humid and warmer Mid–Late Holocene ($P_{ann} = 721$ mm and MTCO = –6.8 °C), which is due to the onset of less strongly contrasting seasonal parameters, in particular more effective precipitation brought in the spring by the Westerlies. Paralleling the Mediterranean Holocene precipitation trend, Near East and Central Asia precipitation decreased progressively during the Mid–Late Holocene in association with higher seasonality controlled in winter/spring by the Siberian High. These patterns can be related with the decrease of northern hemisphere summer insolation.

Fire history and sedge-based transgressions and regressions of the fen are coeval in phase and provide a record of drier phases at ca. 6400, ca. 5300–4900, ca. 3000, ca. 2200–1500 and ca. 400 cal a BP. While excluding human impact recorded through cereal pollen grains, these arid phases, also recorded in southern Georgia, resemble the precipitation pattern of the South-Western Mediterranean and contrast with the South-Central and South-Eastern Mediterranean regions. Arid phases in northern Armenia are therefore believed to be related to centennial-scale variation of Westerly activity (NAO-like).

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Abbreviations. AMS, accelerator mass spectrometry; AP, arboreal pollen; LPAZ, local pollen assemblage zone; MS, magnetic susceptibility; MTCO, mean temperature of the coldest month; NAO, North Atlantic Oscillation.

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