Human impact on the hydroenvironment of Lake Parishan, SW Iran, through the late Holocene

Matthew Jones[1*], Morteza Djamali[2], Jonathan Holmes[3], Lloyd Weeks[4], Melanie J. Leng[5, 1], Arash Lashkari[6], Kourosh Alamdari[7], Dariush Noorollahi[8], Louise Thomas[9] and Sarah E. Metcalfe[1]

1. School of Geography, University of Nottingham, University Park, Nottingham. NG7 2RD. UK
2. Institut Méditerranéen de Biodiversité et d'Ecologie (IMBE) – UMR CNRS 7263 / IRD 237, Aix-Marseille Université, Technopôle de l'Environnement Arbois-Méditerranée, BP 80, F-13545 Aix-en-Provence cedex 04, France
3. Environmental Change Research Centre, Department of Geography, University College London, Pearson Building, Gower Street, London WC1E 6BT. UK
4. School of Humanities, University of New England, Armidale, NSW 2351. Australia
5. NERC Isotope Geosciences Facilities, British Geological Survey, Nottingham NG12 5GG. UK
6. Iranian Center for Archaeological Research, Islamic Researches Group, Tehran, Iran.
7. Heritage & Tourism Organization, Fars Province, Iran.
8. Faculty of Geography, University of Tehran, Corner of Vesal St. and Azin Vally, Enghelab Ave., Tehran, Iran
9. Faculty of Science, The Open University, Milton Keynes, MK7 6AA. UK

*corresponding author
matthew.jones@nottingham.ac.uk Tel: +44(0)115 8468406

Abstract

A multiproxy record from Lake Parishan, SW Iran, shows human impact on the lake and its catchment over the last 4000 years. The Parishan record provides evidence of changes in lake hydrology, from ostracod, diatom and isotope analyses, that are directly linked to human activity in the catchment; recorded by pollen and charcoal and supported by regional archaeological and historical data. The lake ostracod fauna is particularly sensitive to human induced catchment alterations and allow us to identify changes in catchment hydrology that are due to more than a simple change in precipitation: evaporation state. Oxygen isotope data from endogenic carbonates follow these faunal changes but also displays a longer trend to more positive values through the period, coincident with regional patterns of water balance for the late Holocene in the eastern Mediterranean.

Keywords

Iran, agriculture, late Holocene, lake, pollen, ostracods

Introduction

There is compelling evidence from many regions on Earth that people have had a substantial impact on the environment for thousands of years (Ruddiman et al., 2015) e.g. via deforestation (Roberts, 2013) or irrigation (Magee, 2005). Less clear, and pertinently for this volume, is determining at which point people made a global impact such that a 'golden spike' marking the beginning of a new Anthropocene era might be identified (e.g. Gale and Hoare, 2012; Smith and Zeder, 2013). Palaeoenvironmental archives such as lake sediments can often only provide a relatively local or regional view of past environmental change. Importantly, however, lacustrine archives can preserve multiple proxies of change, allowing information on climate, environment and their drivers, including human activity, to be compared directly from one sediment record. This avoids the issues of dating error or archival systematics that can complicate human-climate-environment comparisons from multiple sites, environmental and/or archaeological (e.g. Jones, 2013a). Despite clear evidence of past human activity that could alter the environment (e.g. Smith and Zeder, 2013; Ramsey et al., this volume), multiple proxies are needed to establish clear links between this activity and recorded environmental change. Moving past correlation to causation is difficult in the palaeosciences, irrespective of whether the environment is affecting people or the other way round, but is important for a robustly defined Anthropocene.

Here we present a new record of environmental change from Lake Parishan in the Fars Province of South West Iran through the last 4,000 years. We use multiproxy data from a single core to establish the dominant forcing factors of the environment in and around the lake. South West Iran has a long history of human occupation with cereal agriculture and animal domestication dating back to around 10,000 years BP (Weeks, 2013a; Riehl et al., 2013). The Zagros, and their 'Hilly Flanks' have long been of interest to debates about the origins of agriculture (Braidwood and Braidwood, 1949) and people's interaction with their environment in general (e.g. Miller, 2013). Despite this, continuous palaeoenvironmental records from Iran, and especially from the south and east, are scarce. Current palaeoenvironmental and palaeoclimatic understanding for the Holocene of Iran is drawn largely from the records of Lakes Urmia, Zeribar and Mirabad (e.g. Djamali et al., 2008; Stevens et al., 2006), hundreds of kilometres to the north of Parishan (Fig. 1). These sites sit in a different climate regime to Parishan today (Jones, 2013b) and therefore may not reflect past change further south. Our new data provide a more local reconstruction of environmental change to compare directly with local archaeological investigations (e.g. Potts et al., 2009). A pollen record of the past 5000 years does exist from Fars, from Lake Maharlou (Fig. 1) (Djamali et al., 2009), but largely provides information on human-induced landscape change in the catchment, and not hydroclimatic changes of the lake itself.

The Lake Parishan multiproxy data set allows us to narrow down the possible explanations for the changes seen in the Parishan record, with data describing environmental changes within the lake (ostracods, isotopes, diatoms, pollen) and within the catchment (pollen, charcoal, in-wash proxies such as magnetic susceptibility). The record provides new palaeoenvironmental information from the region as a whole, and shows that people have had a significant impact on lake hydrology at various times during the last 4000 years.

Site Description

Lake Parishan (29.5°N 51.8°E, 820 masl) lies in a fault-bounded basin 15km southeast of Kazerun, in the Fars region of SW Iran (Fig. 1). As one of only a few recently extant lakes in the region Lake Parishan is an important freshwater site and is Ramsar listed (No. 37; 23/06/1975). Over the last 25 years, lake area has fluctuated between 0 – 52 km^2, with a corresponding maximum depth of 0 to 5m (UNDP/GEF, 2010). The surface catchment is 270 km^2. The lake has no surface outflow and given local average annual precipitation (450 mm) and evaporation (2400 to 3100 mm/yr) regimes (Lotfi and Moser, 2010) the lake is liable to drying. The lake dried out completely in 1987 (UNDP/GEF, 2010) and again since our fieldwork of 2007. Lake waters had a pH of between 8.5 and 9 in 2001/2002 with variable conductivity values between 3500 and 8900 µS/cm (Lotfi and Moser, 2010). Na or Mg and Cl are the dominant ions in the lake. Spring samples show more variability, with water more likely to be Ca – HCO_3 dominated (Shirini Feshan, 2000).

The lake and its catchment are an important agricultural centre with over 800 wells (UNDP/GEF, 2010) exploiting its important groundwater resource. Given recent drops in lake level there is significant local effort being put into understanding the lake system (e.g. Lotfi and Moser, 2010; UNDP/GEF, 2010). Lake Parishan's clear sensitivity to changes in the catchment water balance in recent years makes it a potentially useful site for observing past changes in environment.

Methods

Fieldwork

Core LPIII was taken in February 2007 using a Livingstone corer (Livingstone, 1955) from the south-central part of the lake (29.514°N, 51.800°E) in 2.1m water depth. Four drives retrieved a ~2.5m core sequence with some small gaps between drives (Fig. 2). In addition, water samples were taken in leak-proof plastic bottles, at arm's length below the surface, for the analysis of the oxygen and hydrogen isotope composition of lake water to help constrain the interpretation of the palaeo-isotope data recorded in core carbonates.

Sedimentology and Geochemical proxies

Before the cores were sampled magnetic susceptibility was measured every 2cm on a Bartington MS2C Core Logging Sensor with a 60 cm loop, with data corrected for core diameter and drift using the accompanying Multisus software. Loss on Ignition (LOI) at 550°C and 925°C (e.g. Hieri et al., 2001) was undertaken at a 4cm resolution, providing data on changes in organic and inorganic carbon content in the core.

1cm (sediment length) samples from every 4cm down the core were prepared for isotope analysis of sedimentary, endogenic, carbonates at the NERC Isotope Geosciences Facility (NIGF) following standard laboratory protocols (e.g. Leng, 2005). Samples were left in 5% sodium hypochlorite overnight and then sieved at 90μm in deionised water to remove shell carbonates i.e. from ostracods (see below) and snails. Dried samples were reacted in acid at 25^{o}C under vacuum and the resulting CO_2 collected for analysis of oxygen and carbon isotope ratios ($^{18}O/^{16}O$, $^{13}C/^{12}C$) on an Optima dual-inlet mass spectrometer. $\delta^{18}O$ and $\delta^{13}C$ values, reported in standard delta units as part per thousand deviations from the VPDB standard, have analytical reproducibility of 0.1‰.

Following preparation for isotope analysis, selected carbonate samples were analysed by XRD in the Faculty of Engineering, University of Nottingham to record the carbonate mineralogy. Finely ground samples were analysed in cavity mounts (Hardy and Tucker, 1988) on a Siemens D500 X-Ray diffractometer. The scanning range was 5-65° 2θ and the scan rate was 2° 2θ per minute with a step size of 0.05.

Bulk organic components of the sediment were analysed for %C, %N and $\delta^{13}C_{organic}$ at the same resolution as the LOI and carbonate isotope data, by combustion in a Costech ECS4010 on-line to a VG TripleTrap and Optima dual-inlet mass spectrometer at the NIGF. Samples were first reacted in 5% HCl overnight and then thoroughly washed, to disaggregate the sediment and remove carbonates. The isotope data are reported in the standard delta units ($\delta^{13}C$) as parts per thousand deviations from the VPDB standard. Analytical reproducibility is <0.1‰ for $\delta^{13}C$ and 0.2 for C/N for the standard and sample material.

Pollen

Twenty six samples were treated for pollen analysis following the classical extraction technique described in Moore et al. (1991). An outline diagram at 8cm resolution was first produced, with additional samples then counted between 104 and 132 cm to increase this section to 4cm resolution. Pollen grains were identified using the pollen reference collection developed for Iranian flora at the Institut Méditerranéen de Biodiversité et d'Ecologie (Aix-en-Provence, France) but also the available pollen bibliography on the Mediterranean region, Europe and the Middle East (e.g. van Zeist and Bottema, 1977; Reille, 1992, 1995, 1998; Beug 2004). Pollen typification followed Beug (2004). About 300 pollen grains excluding the pollen of aquatic plants were counted from each sample layer and the percentage values were calculated and plotted using Tilia and TGView software (Grimm, 2004/2005).

The full pollen record from core LPIII will be discussed elsewhere (Djamali et al., in press) and here we present selected taxa in order to reconstruct the environment in and around the lake through the time period of study, in particular the extent of human impact on the catchment and the hydrological variations of the lake. We use the presence of *Olea* (olive) and *Platanus* (plane tree) pollen as indicators of agricultural practice (following Djamali et al., 2009, 2011). We also present the *Quercus* (oak) pollen curve as a measure of the natural vegetation regime. In addition, *Sporormiella* (fungi associated with animal dung (van Geel, 2001)) is used as evidence of pastoral activities. *Sparganium*-type pollen and *Riella* spores provide information on lake level changes (Djamali et al., 2008), while charcoal is a measure of burning in the region, often associated with agricultural practices in the later Holocene (e.g. England et al., 2008), but also potentially of natural origin (e.g. Turner et al., 2007).

Ostracods

Ostracod faunal assemblages were determined from 40 levels within the core (at a 4cm resolution) in order to characterize the hydrological and hydrochemical evolution of the lake, following methods in Griffiths and Holmes (2000). At each level, ostracod valves were picked from the weighed coarse (>90µm) fraction of samples that had been processed for endogenic carbonate isotope analyses. Ostracod specimens were picked under a low-power binocular microscope and stored in micropalaeontological slides. All of the adult and later-moult-stage valves were recovered from each sample: although the occurrence and preservation of the smallest instars were noted, these moult stages were neither picked nor counted owing to difficulty in identification. Identifications followed Meisch (2000). Valves that were insufficiently complete to allow identification were not picked although the approximate abundance of broken valves in each sample was noted. Ostracod species occurrences were expressed as number of valves per gram of dry sediment, and as percentages.

Diatoms

A preliminary set of samples for diatom analysis were prepared from 15 levels; approximately every 16cm through the core sequence. These were treated to remove organic matter and carbonates, using standard procedures. The weight of the dried sample was recorded to allow for an estimation of valves per gram. The prepared samples were mounted onto coverslips using Naphrax resin and studied at 1000 x magnification using either an Olympus CX41 or a Zeiss Axioskop2 Plus microscope. Selected levels were examined using a JEOL 6400 Scanning Electron Microscope in the Faculty of Engineering, University of Nottingham. Identifications were made using standard diatom floras including Krammer and Lange-Bertalot (1986 and 1988a and b), Patrick and Reimer (1966 and 1975), and the regional study of Witowski et al. (2008). Ecological interpretations were based mainly on Gasse (1986); Reed (1998); Reed et al., (2012) and information in the European Diatom Database (http://craticula.ncl.ac.uk/Eddi/jsp/index.jsp).

Chronology

Four age estimates, 3 from radiocarbon analysis of bulk organic material (Table 1) and one from U-Th analysis (Table 2), have been carried out on the 250cm core. Radiocarbon analyses were undertaken at the Poznan Radiocarbon Laboratory. The U-Th analysis was undertaken at the Open University, UK. Following acid digestion of bulk sediment samples U and Th were purified using ion exchange chromatography before being run on a Nu Instruments Multi-collector ICP-MS in a solution of 3% HNO3, using a sample - standard bracketing technique. Based on these age estimates, the core spans from present day (the lake was extant at the time of coring) to around 4,000 cal BP.

The paired set of radiocarbon and U-series age estimates from 225cm were analysed to help establish if there was a significant old carbon effect on the radiocarbon ages, because Lake Parishan is in a carbonate catchment. Although there were also issues of contamination with the U-Series age estimate (Table 2), the use of a standard Open University laboratory correction for lake sediments of this type allowed the calculation of an old carbon error of approximately 360 years for the sequence.

The clear shift in the pollen diagram at 125cm, with the establishment of olive (*Olea*) and deforestation of oak (*Quercus*), likely marks the start of the Achaemenid Persian Empire 2500 cal BP (e.g. Djamali, 2009), which had a significant centre at Persepolis, only 110 km from Parishan (see further detail in the Discussion below). This pollen stratigraphic marker confirms the estimate of old carbon error for core LPIII (Fig. 2).

Our final age model (Fig. 2) is therefore based on the radiocarbon age estimates and a 360 year old carbon correction. The dating control on this record from Parishan is important when comparing the data with other sites, and the old carbon issues identified here may have implications for the age models for other sites in the Zagros such as Zeribar and Mirabad (Stevens et al., 2001, 2006; Wasylikowa et al., 2008). However, for this paper it is the relationship between proxies from the same core that is vital to the discussion, and the temporal relationships between them are internally robust.

Results

Sedimentology and Geochemical proxies

The data show a number of trends and events through the core (Fig. 3). There is a peak in magnetic susceptibility between 200 and 170cm, also marked by an increase in non-combusted, residual material from the LOI analyses. The amount of this residual material generally decreases up through the core, with a particular step change to lower values between 130 and 110cm. This depth interval is also marked by a reduction in magnetic susceptibility, to negligible values, and an increase in both organic and inorganic carbon. This step change is part of a long term trend to higher values, from 200cm towards the top of the core, in the amount of organic carbon. C/N ratios show a marked shift from values around 14 to lower values, of around 10, at 110cm. These data all suggest a general trend to reduced amounts of catchment material, both in terms of inorganic in-wash (reduction in residual LOI material and magnetic susceptibility) and non-aquatic organic matter, C/N values of 10 are typical of aquatic algae (e.g. Leng et al., 2010), through the core.

Carbonate mineralogy is variable down core with samples at 128 and 224cm dominated by calcite, samples at 80 and 112cm having a mixture of calcite and aragonite, and samples from 16 and 64cm dominated by aragonite. The carbonate isotope values also show an up core trend to more positive values with a particularly marked step in δ^{13}C values at 125cm from ~ –3‰ to ~ +2‰, in part explained by the shift in mineralogy; aragonite is 1.9‰ (0.6‰) more positive in δ^{13}C (δ^{18}O) compared to calcite precipitated in waters with the same temperature and isotopic composition (Grossman, 1984; Grossman and Ku, 1986). Oxygen and hydrogen isotope ratios of the lake waters collected in 2007 show a clear evaporative signal (Supplementary Figure 1), and δ^{18}O trends to more positive values likely represents a shift to more evaporative dominant conditions given the associated change from calcite to aragonite (e.g. Jones et al., 2006). However, there is no co-variation between δ^{18}O and δ^{13}C from the carbonates in LPIII (Supplementary Table 1) that is typically seen in evaporative lake systems (e.g. Li and Ku, 1997) suggesting an alternative control, other than evaporation, on the δ^{13}C system. The isotope value of bulk organic matter is similar (between –21 and –23‰) until the top 20cm of the core, where it shifts to lower values, and it remains unclear what would cause the changes in $\delta^{13}C_{carbonate}$, other than changes in carbonate mineralogy as discussed above, without impacting on the total dissolved inorganic carbon pool also used by the organic material.

Pollen

Variations of oak (*Quercus*) and pistachio (*Pistacia*) pollen indicate that the regional forest vegetation did not significantly change from the beginning of the sequence (pollen zones LPIII-A and LPIII-B) up to about 120cm (pollen zone LPIII-C) where oak pollen decreases while there is a significant increase (from 0-1% to 6% of the terrestrial pollen sum) in pollen of cultivated trees (*Olea* and *Platanus*) and steppe plants (upland herbs) (Fig. 4). The increasing percentages of the pollen of upland herbs in LPIII-C is matched by increasing values of the Cerealia-type and *Plantago lanceolata*-type pollen (anthropogenic herbs in Fig. 4) as well as dung-associated *Sporormiella* (Non-Pollen Palynomorphs). The pollen zone of LPIII-C, which represents intensified agro-sylvo-pastoral activities in the catchment, is also coincident with a sudden increase of pollen of aquatic plants such as *Sparganium*-type. Later, in LPIII-D, pastoral activities likely reach their maximum, between approximately 70cm to 40cm depth, as this is the period of highest values of *Plantago lanceolata*-type pollen and *Sporormiella* spores. Microcharcoal also increases from around 120cm depth, peaking at 60 and 30cm, with occasional peaks lower in the sequence e.g. at 212cm. Pollen is not well preserved in the uppermost 30cm of the core.

Ostracods

Ostracod shells are found in all of the samples examined, although abundance varies markedly from15 valves (244cm) to 746 valves (228cm). All samples contain adults and a range of juvenile instars: adults and juvenile moults are generally very well preserved, even the earliest instars. Most of the adult specimens and the vast majority of the juvenile instars are present as disarticulated valves, with only a small proportion of carapaces preserved. In total eight ostracod taxa were recovered from LPIII (Fig. 5). The presence of adults and a range of juvenile moult stages suggest that the assemblages are largely *in situ* with signs of minimal *post mortem* transport.

In general, the lower part of the core, below about 100cm, is characterised by a higher abundance of shells than above. Overall, the ostracod assemblages are consistent with a slightly saline lake. *Cyprideis torosa* is the most common species, followed by *Limnocythere inopinata*, indeterminate species 1, *Darwinula stevensoni*, *Candona* sp. juveniles and *Heterocypris salina*. The remaining two taxa, indeterminate species 2 and 3, occur sporadically. Based on the stratigraphical distribution of taxa, the most striking difference is between the lower part of the core, below ~132cm, which is dominated by *C. torosa*, and the upper part dominated by *L. inopinata*. In the lowest parts of LPIII, significant numbers of *L. inopinata*, *H. salina* and indeterminate species 1 and lesser numbers of *Candona* sp. (probably *Candona* cf. *neglecta*) accompany *C. torosa*. An exception to this pattern is at 244 cm, where *L. inopinata* dominates, although total specimen numbers are small. In the upper part of the core, *C. torosa* is absent from most levels, although *H. salina*, *D. stevensoni* and indeterminate species 1 occur in many levels. At 104 to 108cm, a reversal to this pattern is found, with *C. torosa* dominant much like in the lower part of the core.

Diatoms

Diatoms are only preserved in some sections of the Parishan core (Fig. 6), with most taxa indicative of brackish and often shallow water conditions. Counts are low (ca. 100 valves) in spite of counting multiple slides. Results from only 8 of the 15 samples were considered adequate to interpret and the impact of differential preservation must be taken into account. The sequence can be divided into roughly four sections: from the base to 144-145cm; the sample from 128-129cm; a section of core where preservation was too poor to allow for counting (112-113 to 32-33cm) and the top two samples (9-10 and 16-17cm). The lower part of the core was dominated by *Amphora* spp. which appeared to be wrapped in silica (confirmed under the SEM). Some valves could be identified as *A. coffeaeformis* (*Halamphora coffeaformis)*, a benthic, high salinity alkalibiont found in both saline lakes and marine environments. Other diatoms present included benthic species indicative of high salinity/brackish conditions such as *Campylodiscus clypeus*, *Mastogloia braunii* and *Anomoeoneis sphaerophora*. *Nitzschia granulata,* more usually a marine diatom, but also occasionally recorded in salt lakes (Gasse, 1986) was noted. Resting spores of *Chaetoceros amanita* were recorded in transect counts. These taxa are generally epipelic or benthic and occur predominantly in Na-Cl dominated waters of moderate to high conductivity (3000 - >30,000 µS cm^{-1} in different data sets). The low diatom numbers and rather poor preservation indicate a highly evaporated water body, inimical to good diatom preservation. A stress response of accreting silica around valves has been recorded in a highly evaporated crater lake in Mexico (Metcalfe, 1990). This accretion of silica probably accounts for their numerical abundance in the fossil material and may not reflect the importance of *Amphora* in the life assemblage. Overall, the conditions indicated at the bottom of the core are consistent with recent water samples (see Site Description).

The sample from 128-129cm was distinctive because of its high diversity and more abundant diatoms. *Nitzschia* cf *gracilis*, *Brachysira apopina* and *Cymbella (Navicymbula) pusilla* were the most abundant taxa (although silica 'wrapped' Amphora spp. were still present). The increased abundance of diatoms and their better preservation indicate that the lake may have become less saline/alkaline, at least intermittently. *N. gracilis* may be planktonic and has a lower reconstructed EC optimum than the other taxa found here (around 3000 µS cm-1 according to Reed et al., 2012). It may also indicate higher nutrient levels (Patrick and Reimer, 1975). High variability in salinity may be indicated by the presence of *B. apopina* which has very high reconstructed EC optima (> 50,000 µS cm-1) based on work in Spanish and Turkish lakes (Reed, 1998, Reed et al., 2012). An increasing proportion of epiphytic taxa at this depth may indicate more aquatic vegetation near the coring site. It is interesting to note that this sample has high percentages of both *B. apopina* and *C. pusilla* which are both the only species in their genus that are halophilous.

The next five samples in the core preserved very few valves, although the sample from 80-81cm was again dominated by the 'wrapped' *Amphora* spp, so it appears that conditions again became unfavourable for diatom preservation. Preservation is much better in the top sample (9-10 cm) than in the one below, which is again dominated by 'wrapped' *Amphora* spp. with C*. clypeus*. *C. amanita* resting spores again noted. Both these samples show a significant presence of *Epithemia smithii* (ca. 20%) which may indicate the availability of more aquatic vegetation. Unfortunately, this taxon is not recorded in available salinity reconstruction databases. Overall the diatom assemblage indicates shallow, high conductivity water.

Discussion

There are strong and significant correlations between the different variables analysed for this study (Supplementary Table 1). Based on these correlations, two end-member environmental states are interpreted for the last 4,000 years in and around Lake Parishan and its catchment. These two lake states are marked most clearly in the stratigraphic record by the shift between the two dominant ostracod taxa (Figs. 5 and 7) and the interpretation of the changes seen between these two taxa, and associated shifts in other proxies, are key to our overall interpretation of the data set.

Although *C. torosa* has a higher salinity tolerance than *L. inopinata* (e.g. Holmes, 1992), a decrease in salinity midway through the sequence is not consistent with other proxies including the positive $\delta^{18}O$ trend (more evaporation), change in carbonate mineralogy from calcite to aragonite (more evaporation) and the disappearance of diatoms from the record. Collectively these latter three proxies suggest an increase in evaporative enrichment above about 120cm. *Cyprideis torosa* and *L. inopinata* also have differing preferences on a water composition (alkalinity: Ca) gradient with *C. torosa* preferring Ca-enriched and alkalinity-deplete waters (alkalinity: Ca <1), and *L. inopinata* preferring Ca-deplete and alkalinity-enriched conditions (alkalinity: Ca >1) (Forester, 1983; 1986). These two contrasting water types fall on separate evaporative pathways (e.g. Hardie and Eugster, 1970) and so cannot be explained by differences in the degree of evaporative evolution.

Lake conditions supportive of *L. inopinata* occur in the latter half on the record from LPIII but also occur in three distinct phases between ~4,000 and 3,000 cal BP (Fig. 7), with the event at ~3200 cal BP being marked more noticeably by a decrease in *C. torosa* rather than an increase in *L. inopinata.* Of note is that the substantial shifts in other proxies for in-lake and catchment conditions c. 2,200 cal BP and in the latter half on the record, e.g. reduced oak pollen, increasing aquatic macrophyte vegetation (*Sparganium*-type pollen), increased charcoal and increased *Sporomiella,* also occur in these three events during the 4th Millennium BP.

Without the addition of human activity it is difficult to develop a scenario that would lead to the combination of changes in the environmental proxies observed. Tectonic activity may impact upon groundwater flow, potentially changing both the amount and source of surface- and/or ground-water to the lake. However, the Parishan system seems to shift, relatively frequently, between two clear states. It seems unlikely that successive tectonic events would firstly change water flow conditions and then reset to the original condition at the next tectonic event, and for this to happen repeatedly. We have discussed above why a change in evaporation amount, as part of a climatic precipitation – evaporation lake level control, cannot fully explain the shifts in all variables recorded.

Combined, these multi-proxy data therefore suggest that during periods of increased catchment agriculture (increased burning, increased deforestation, increased animal dung), surface (reduced in-wash) and groundwater flow were reduced to the lake. With an increase in precipitation relative to surface and groundwater inflow from the carbonate catchment the amount of Ca in lake waters was relatively reduced, leading to an increase in the alkalinity/Ca ratio and a shift in the ostracod assemblage. As relatively less water entered the lake, lake levels fell and the waters become more evaporatively enriched (as the ratio of evaporation to total input to the lake, precipitation plus surface-and ground-water inflow, increased) leading to higher $\delta^{18}O$ values and aragonite deposition (rather than calcite). This fall in lake levels also led to more shallow water areas suitable for *Sparganium* type reeds to grow. Increased lake productivity, as marked by increased organic material in the sediments fits a hypothesis of increased nutrient in-wash into the lake during periods of increased agriculture. The data therefore suggest that increased agriculture in the catchment had a significant impact on lake hydrology and biogeochemistry. *Limnocythere inopinata* and associated end members of other proxy ranges therefore mark periods when the lake was impacted by human activity whereas *C. torosa* marks a more natural lake and catchment scenario (Table 3).

The impacted period immediately after 2400 cal BP, most likely associated with the beginning of the Achaemenid Empire (see below), is very marked in the record and shows a different set of inter-proxy relationships compared to the full record. The diatom flora at this point in the core suggest a freshening of the system, as do lower $\delta^{18}O$ data. Other proxies do not show anything in particular of note here that is not consistent with the overall patterns described above. This level in the core (~ 130 cm) represents the onset of the most intensive agricultural phase in the LPIII proxy record, marked especially by the rise in olive pollen. Given that diatoms disappear almost entirely from the core in the levels above this it appears there may have been a very short freshening of the system, perhaps associated with the initial catchment deforestation, at the onset of the Achaemenid Empire. This increase in water flow into the lake during anthropogenic catchment disturbance may, arguably, be a more typical response to human activity in a lake catchment (e.g. Rosenmeier et al. 2002) but is only short-lived at Parishan, with longer term proxy shifts suggesting the long term impact of agriculture is reduced amounts of water entering the lake. Conditions through this phase are marked by the lowest oak pollen percentages in the record, suggesting a possible threshold in catchment vegetation below which runoff is increased.

Lake Parishan and regional archaeological evidence

Given the apparent impact of people on Lake Parishan and its catchment we review these new palaeoenvironmental results against the regional archaeological framework.

Northern Fars has a long history of agro-pastoral production, stretching back to the early Holocene (Weeks, 2013b). The earliest pollen samples from the LPIII core, which cover the period from c. 4000 cal BP, include peaks in micro-charcoal at c. 3800 and 3500 cal BP (Fig. 7) and correlate with increasing human activities in the landscape. These peaks equate to the archaeological periods known as the Middle and Late Kaftari, which witnessed a dramatic increase in known human settlement in Fars (Potts et al. 2009). However, the LPIII core does not show the evidence for the early adoption of arboriculture in the Kaftari period that was seen clearly in the Maharlou core (Djamali et al. 2009, 2011). Following the Kaftari period, between c. 3500-2500 years BP, archaeological surveys in Fars indicate a relatively widespread and significant reduction in the number of known settlements (Potts et al. 2009). Although the site of Tall-e Jidun in the Kazerun plain close to Lake Parishan appears from surface collection survey to have been occupied from c. 3500 years BP (Nobari et al. 2009), the corresponding section of the LPIII core shows few indicators of human agro-pastoral activities or landscape modification, especially in the micro-charcoal record.

The spike in pollen from cultivated trees (primarily *Olea* and *Platanus*) in the LPIII core at 120cm provides informative parallels and contrasts with existing archaeological and historical information. This period coincides with the rise of the Achaemenid empire and a "massive investment of energy and organizational power to bring the Persian heartland under cultivation" (Henkelman 2013: 528). This includes archaeological evidence for the construction of various water control mechanisms in the vicinity of the Persian capitals Pasargadae and Persepolis, including dams, barrages, and irrigation canals, that significantly expanded the area that could be reached by irrigation (Boucharlat 2013; Boucharlat et al. 2012; Sumner 1986). Texts from Persepolis attest to large-scale agricultural and pastoral production supported by the availability of large numbers of dependent labourers to harvest crops and maintain canals, as well as the efforts of local independent farmers and herders. In particular, there is historical evidence for extensive cultivation of fruit trees during the Achaemenid period and for the foundation of estates that had variable functions, including orchards, parks, gardens, and hunting preserves (Boucharlat 2013: 513; Uchitel 1997). One single administrative text from Persepolis lists more than 6000 fruit tree seedlings to be planted in five estates, including apple, mulberry, pear, quince, date, pomegranate, and olive (Henkelman 2013: 528). Interestingly, although historical sources from the Classical period describe Fars as a fertile and well-watered region with many farms and gardens with fruit trees, heavily wooded hills and river banks densely covered with plane trees and poplars (Sumner 1986: 17-18), they commonly note the absence or poor quality of olives and olive trees in the general region of southern Iran (Djamali et al., in press). The pollen evidence from the LPIII core, in particular the evidence for olive cultivation, thus provides a significant new strand of evidence for the discussion of arboriculture in Achaemenid and post-Achaemenid Iran.

The Kazerun region falls broadly within the area of the Achaemenid heartland (Henkelman 2008) and it is likely to have witnessed significant occupation at this time, as can be documented not only in the immediate hinterlands of Persepolis and Pasargadae, but also c. 50 km to the north of Kazerun in the Mamasani District (Askari Chaverdi et al. 2010; Potts et al. 2009). Unfortunately, Achaemenid settlement in the immediate vicinity of Lake Parishan remains poorly understood. Achaemenid occupation has been recorded at a number of sites in the Kazerun plain, and there is a large Achaemenid settlement recorded at the mound of Tall-e Jidun (Nobari et al. 2009, 2012).

However, the region is more famous as the location of the important Sasanian city of Bishapur, and increasing human use of the landscape in the Sasanian and early Islamic periods (c. 1700 years BP onwards) (Keall 1989; Calmard 2013) is supported by the increasing micro-charcoal and *plantago lanceolata*-type pollen counts in the upper sections of LPIII, if not by significant evidence of tree cultivation (Djamali et al., in press).

Summary

The multi-proxy sequence from Lake Parishan provides a case study of clear human impact on a lake environment, marked in the stratigraphic record. It is not uncommon for lake records from the later Holocene to show such impact, especially in the pollen data (e.g. England et al., 2008; Djamali et al., 2009). The Parishan record is rare in that changes in lake hydrology can be linked to these human impacts over much of the last 4000 years. The ostracod fauna of Parishan seem particularly sensitive to these catchment alterations by people, and due to the particular characteristics of the two dominant species allow us to differentiate change in catchment hydrology with a more complex model than a simple change in evaporative state.

The $\delta^{18}O$ record also follows these changes, but superimposed on a longer trend to more positive values through the core that matches regional patterns of lake change for the late Holocene in the eastern Mediterranean (e.g. Roberts et al., 2008). We cannot discount some climate control on the proxy data from Parishan. However, given the sensitivity of the lake today, and our own observations of its desiccation, it is apparent that peoples' exploitation of groundwater and surface waters, and management of catchment vegetation do significantly impact lake levels at Parishan. Our record of the last 4000 years shows this is not a new problem; further investigation of the archaeological record would now be of interest in terms of the potential impact of these proposed human-induced hydrological changes on the populations that caused them.

As ever, the discussion of the Parishan record highlights the need for caution in the interpretation of any late Holocene palaeoenvironmental record from substantially inhabited parts of the world solely in terms of climate. Human impact on the proxy record is clear. However we define and discuss the Anthropocene (c.f. Ruddiman et al., 2015) these data provide evidence of human impact on the local environment including the lake, an important natural resource, in direct (agriculture) and, arguably, indirect (catchment disturbance and hydrology) ways at various points through the last 4,000 years. Via our multi proxy approach we present one case study where uncertainty in the link between environmental correlation and human causation is greatly reduced.

Acknowledgements

We thank the directors of the Mamasani Archaeological Project, especially Dan Potts, Alireza Askari, Alireza Sardori and Cameron Petrie for their invitation to carry out this work. We thank the

University of Nottingham, the Iranian Centre for Archaeological Research and the British Institute for Persian Studies for financial and logistical support that made this work possible. The isotope work was funded via grant IP-1051-0508 from the NERC Isotope Geoscience Facilities Steering Committee to MJ. We also thank Hajar Askari for assistance in the field. Thanks to two anonymous reviewers for their comments which improved the manuscript. This manuscript was completed whilst MJ was a Visiting Fellow in the School of Geography, Planning and Environmental Management at the University of Queensland.

References

Askari Chaverdi A, Khosrowzadeh A, McCall B et al. (2010) Archaeological Evidence for Achaemenid Settlement within the Mamasani Valleys, Western Fars, Iran. In Curtis J and Simpson St J (eds), *The World of Achaemenid Persia*. London: I.B. Tauris, pp. 287-297.

Beug H-J, (2004) Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Pfeil, München.

Boucharlat R (2013) Southwestern Iran in the Achaemenid period. In Potts DT (ed.) *The Oxford Handbook of Ancient Iran*. Oxford: Oxford University Press, pp. 503-527.

Boucharlat R, De Schacht T and Gondet S (2012) Surface Reconnaissance in the Persepolis Plain (2005-2008). New data on the city organisation and landscape management. In Basello GP and Rossi AV (eds) *Dariosh Studies II. Persepolis and its Settlements: Territorial System and Ideology in the Achaemenid State.* Naples: Università degli Studi di Napoli “L’Orientale”.

Calmard J (2013) Kazerun ii. History. *Encyclopaedia Iranica* XVI, Fasc. 2: 212-216.

Djamali M., Jones MD, Migliore J et al. (in press) Olive cultivation in the heart of the Persian Achaemenid Empire: new insights to agricultural practices and environmental changes reflected in a late Holocene pollen record from Lake Parishan, SW Iran. *Vegetation History and Archaeobotany*

Djamali M, de Beaulieu J-L, Miller NF, et al. (2009) Vegetation history of the SE section of Zagros Mountains during the last five millennia; a pollen record from the Maharlou Lake, Fars Province, Iran. *Vegetation History and Archaeobotany* 18: 123-136.

Djamali M, de Beaulieu J-L, Shah-Hosseini M et al. (2008) A late Pleistocene long pollen record from Lake Urmia, NW Iran. *Quaternary Research* 69: 413-420.

Djamali M, Miller NF, Ramezani E et al. (2011) Notes on the arboricultural and agricultural practices in ancient Iran based on new pollen evidence. *Paléorient* 36: 175-188.

England A, Eastwood WJ, Roberts CN et al. (2008) Historical landscape change in Cappadocia (central Turkey): a palaeoecological investigation of annually laminated sediments from Nar lake.*The Holocene* 18:1229-1245.

Forester RM (1983) Relationship of two lacustrine ostracode species to solute composition and salinity: Implications for palaeohydrochemistry. *Geology* 11: 435-438.

Forester RM (1986) Determination of the dissolved anion composition of ancient lakes from fossil ostracodes. *Geology* 14: 796-798.

Gale SJ and Hoare PG (2012) The stratigraphic status of the Anthropocene. *The Holocene* 22: 1491-1494.

Gasse F (1986) *East African diatoms*. J. Cramer.

Griffiths HI and Holmes JA (2000) *Non-marine ostracods and Quaternary palaeoenvironments*. Quaternary Research Association Technical Guide, 8: 179pp.

Grimm EC 2004, 2005. TILIA and TGView software. Ver 2.0.2. Illinois State University, Springfield.

Grossmam EL (1984) Carbon isotopic fractionation in live benthic foraminifera – comparison with inorganic precipitate studies. *Geochimica and Cosmochimica Acta* 48: 1505-1512.

Grossman EL and Ku TL (1986) Oxygen and carbon isotope fractionation in biogenic aragonite – temperature effects. *Chemical Geology* 59: 59-74.

Hardie LA and Eugster HP (1970) The evolution of closed-basin brines. *Mineralogical Society of America Special Paper 3*: 273-290.

Hardy R and Tucker M (1988) X-ray powder diffraction of sediments. In: Tucker M (ed.) *Techniques in Sedimentology*. Blackwell: Oxford, pp. 191–228.

Henkelman WFM (2008) From Gabae to Taoce: The geography of the central administrative province. In Briant P, Henkelman WFM and Stolper MW (eds), *L'archive des Fortifications de Persépolis: État des questions et perspectives de recherches*. Paris: Éditions de Boccard, pp. 303-316.

Henkelman WFM (2013) Administrative realities: The Persepolis Archives and the archaeology of the Achaemenid heartland. In Potts DT (ed.), *The Oxford Handbook of Ancient Iran*: Oxford: Oxford University Press, pp. 528-546.

Heiri O, Lotter AF, and Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25: 101-110.

Holmes J. (1992) Nonmarine ostracods as Quaternary palaeoenvironmental indicators. *Progress in Physical Geography* 16: 405-431**.**

Jones MD (2013a) What do we mean by wet? Geoarchaeology and the reconstruction of water availability. *Quaternary International* 308–309: 76-79.

Jones MD (2013b) Key questions regarding the palaeoenvironment of Iran. In: Potts D (Ed.) *The Oxford Handbook of Ancient Iran*. New York: Oxford University Press.

Jones MD, Roberts CN et al. (2006) A high-resolution late Holocene lake isotope record from Turkey and links to North Atlantic and monsoon climate. *Geology* 34: 361-364.

Keall EJ (1989) Bišapūr. *Encyclopaedia Iranica* V, Fasc. 3: 287-289

Krammer K and Lange-Bertalot H (1986) Susswasserflora von Mitteleuropa, Band 2/1. Bacillariophyeae. 1. Teil: Naviculaceae. Gustav Fischer Verlag, Jena.

Krammer K and Lange-Bertalot H (1988a) Susswasserflora von Mitteleuropa, Band 2/2. Bacillariophyeae. 2. Teil: Bacillariaceae, Epithemiacieae, Surirellaceae. Gustav Fischer Verlag, Stuttgart/New York.

Krammer K and Lange-Bertalot H (1988b) Susswasserflora von Mitteleuropa, Band 2/3. Bacillariophyeae. 3. Teil: Centrales, Fragilariaceae, Eunotiaceae . Gustav Fischer Verlag, Stuttgart/Jena.

Leng MJ, Lamb AL, Heaton THE et al. (2005) Isotopes in lake sediments. In Leng MJ (ed.) *Isotopes in Palaeoenvironmental Research.* Dordrecht: Springer, pp. 147-184.

Leng MJ, Baneschi I, Zanchetta G et al. (2010) Late Quaternary palaeoenvironmental reconstruction from Lakes Ohrid and Prespa (Macedonia/Albania border) using stable isotopes. *Biogeosciences* 7: 3109-3122.

Li HC and Ku TL (1997) delta C-13-delta O-18 covariance as a paleohydrological indicator for closed-basin lakes. *Palaeogeography, Palaeoclimatoogy,. Palaeoecology* 133: 69-80.

Livingstone DA (1955) A lightweight piston sampler for lake deposits. *Ecology* 36: 137-139.

Lofti A and Moser M (2010) Lake Parishan: A Concise Baseline Report. Available from http://wetlandsproject.ir/english/enshowfiles.aspx?attachid=1524 Accessed 11/02/15

Magee P (2005). The chronology and environmental background of Iron Age settlement in Southeastern Iran and the question of the origin of the Qanat irrigation system. *Iranica Antiqua 40*: 217-231.

Meisch C (2000) *Freshwater Ostracoda of western and central Europe*. Süßwasserfauna von Mitteleuropa 8/3. Gustav Fischer, Stuttgart.

Metcalfe SE (1990) *Navicula elkab* – a species in need of redefinition? *Diatom Research* 5: 419-423.

Miller NF (2013) Agropastoralism and archaeobiology: Connecting plants, animals and people in west and central Asia. *Environmental Archaeology 18*: 247-256.

Moore PD, Webb JA and Collinson ME (1991) *Pollen analysis* 2nd edn. Oxford: Blackwell.

Nobari AH, Shahidi HK et al. (2009) Survey of a multiperiod mound at Tall-e Jidun in Kazerun, southern Iran. *Antiquity* 83/320: Project Gallery.

Nobari AH, Rezaei MHH et al. (2012) Results from a survey of Chalcolithic settlements in the plain of Kazeroun, Iran. *Antiquity* 86/331: Project Gallery.

Patrick R and Reimer CW (1966) *The Diatoms of the United States exclusive of Alaska and Hawaii. Vol. 1*. Monographs of the Academy of Natural Sciences of Philadelphia. No. 13.

Patrick R and Reimer CW (1975) *The Diatoms of the United States exclusive of Alaska and Hawaii. Vol. 2, Part 1*. Monographs of the Academy of Natural Sciences of Philadelphia. No. 13.

Potts DT, Roustaei K et al. 2009. The Mamasani district and the archaeology of southwestern Iran. In Potts DT, Roustaei K et al. (eds.) *The Mamasani Archaeological Project Stage 1: The ICHTO/Sydney University Archaeological Research Project in the Mamasani Region, Fars Province, Iran*:. Oxford: Archaeopress, pp.1-16.

Ramsey M, Jones M et al. (in press) Modifying the marsh: Evaluating Early Epipaleolithic hunter-gatherer impacts in the Azraq wetland, Jordan. *The Holocene*.

Reed JM (1998) A diatom-conductivity transfer function for Spanish salt lakes. *Journal of Paleolimnology* 19: 399-416.

Reed JM, Mesquita-Jones F and Griffiths HI (2012) Multi-indicator conductivity transfer functions for Quaternary palaeoclimate reconstructions. *Journal of Paleolimnology* 47: 251-275.

Reille M (1992) *Pollen et spores d'Europe et d'Afrique du Nord*. Laboratoire de botanique historique et de palynologie, Marseille.

Reille M (1995) *Pollen et spores d'Europe et d'Afrique du Nord*. Laboratoire de botanique historique et de palynologie-Supplément 1, Marseille.

Reille M (1998) *Pollen et spores d'Europe et d'Afrique du Nord*. Laboratoire de botanique historique et de palynologie-Supplément 2, Marseille.

Riehl S, Zeidi M and Conard NJ (2013) Emergence of agriculture in the foothills of the Zagros Mountains of Iran. *Science* 341: 65-67.

Roberts N (2013). *The Holocene: an environmental history*. John Wiley & Sons.

Roberts N, Jones MD, Benkaddour A et al. (2008). Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis. *Quaternary Science Reviews* 27: 2426-2441.

Rosenmeier MF, Hodell DA, Brenner M et al. (2002) Influence of vegetation change on watershed hydrology: Implications for paleoclimatic interpretation of lacustrine δ18O records. *Journal of Paleolimnology* 27: 117-131.

Ruddiman WF, Ellis EC et al. (2015) Defining the epoch we live in. *Science* 348: 38-39.

Shirini Feshan Z (2000) *Hydrogeomorphology of the Lake Parishan (Famour) basin: with an emphasis on Karst landforms*. Unpublished Masters Dissertation, University of Tehran

Smith BD and Zeder MA (2013) The onset of the Anthropocene. *Anthropocene 4*: 8-13.

Stevens LR, Ito E. et al. 2006. Timing of atmospheric precipitation in the Zagros Mountains inferred from a multi-proxy record from Lake Mirabad, Iran. *Quaternary Research* 66: 494–500.

Stevens LR, Wright HE and Ito E (2001) Proposed changes in seasonality of climate during the Lateglacial and Holocene at Lake Zeribar, Iran. *The Holocene* 11: 747–755.

Sumner W (1986) Achaemenid settlement in the Persepolis plain. *American Journal of Archaeology* 90/1: 3-31.

Turner R, Roberts N. and Jones MD (2008) Climatic pacing of Mediterranean fire histories from lake sedimentary microcharcoal. *Global and Planetary Change 63*: 317-324.

Uchitel A (1997) Persian paradise: Agricultural texts in the Fortification Archive. *Iranica Antiqua* 32: 137-144.

UNDD/GEF (2010) Lake Parishan Integrated Management Plan. Available from http://wetlandsproject.ir/WetlandFile/4454b30b-bc62-47b4-a2da-da4bfda5fdb7LP%20Management%20Plan_English.pdf Accessed 11/02/15

Van Geel B (2001) Non-Pollen Palynomorphs. In: Smol JP, Birks HJB and Last WM (Eds.) *Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, algal, and siliceous indicators.* Dordrecht: Kluwer Academic Publishers,

van Zeist W and Bottema S (1977) Palynological investigations in western Iran. *Palaeohistoria* 19:19-85.

Wasylikowa K and Witkowski A (Eds) (2008) *The Palaeoecology of Lake Zeribar and surrounding areas, Western Iran, during the last 48,000 years*. Diatom Monographs Vol. 8, Koeltz Scientific Books, Konigstein. pp. 376

Weeks L (2013a) In Matthews and Fazeli Nashli (eds.) *The Neolithisation of Iran: the Formation of New Societies* Oxford: BANEA and Oxbow Books, pp. 86-96.

Weeks L. (2013b) The development and expansion of a Neolithic way of life. In Potts DT (ed.), *The Oxford Handbook of Ancient Iran*: Oxford: Oxford University Press, pp. 49-75

Witowski A, Wasylik K, Lange-Bertalot H, et al. (2008) Diatom palaeolimnology of Lake Zeribar, Iran, in the Late Pleistocene and Holocene. In: Diatom Monographs Vol. 8, pp. 159-235

Figures

Figure 1 Location map for Lake Parishan (P) in Iran, compared to location of lakes Urmia (U), Zeribar (Z), Mirabad (Mi) and Maharlou (Ma). Topographic background is from the GTOPO30 digital elevation model (Data available from the U.S. Geological Survey).

Figure 2 Age Depth model for core LPIII. The final age model (solid line) is produced from the radiocarbon age estimates (diamonds; 2σ ranges) corrected by a 360 year old carbon effect (crosses) based on the U-Series age estimate (squares). The triangle marks the pollen stratigraphic marker for the beginning of the Achaemenid empire, used as a check on the old carbon estimate.

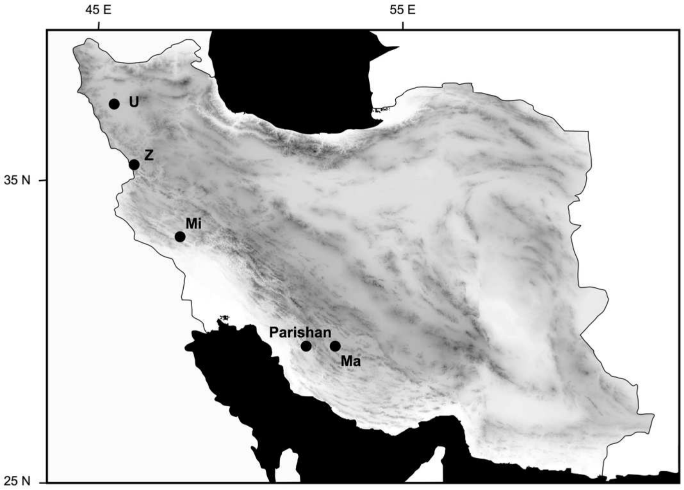
Figure 3 Sedimentary and geochemical data from core LPIII plotted against depth. Organic C data here are from the Costech analyses and show the same trends as the LOI data (not shown).The location of carbonate samples analysed for mineralogy are shown (A=Aragonite; C=Calcite).

Figure 4 Selected pollen data for the LPIII sequence (from the full sequence from Djamali et al, in press) grouped into pollen of trees and shrubs (Trees), herbaceous plants growing on well-drained soils outside the wetland (Upland Herbs), aquatic and subaquatic plants growing inside and around the wetland (Aquatics/Subaquatics), biological remains of animal and fungal origin (Non-Pollen Palynomorphs; NPPs) and the dinoflagellates (Algae). AP/NAP: Arboreal/Non-Arboreal Pollen; LPAZ: Local Pollen Assemblage Zones.

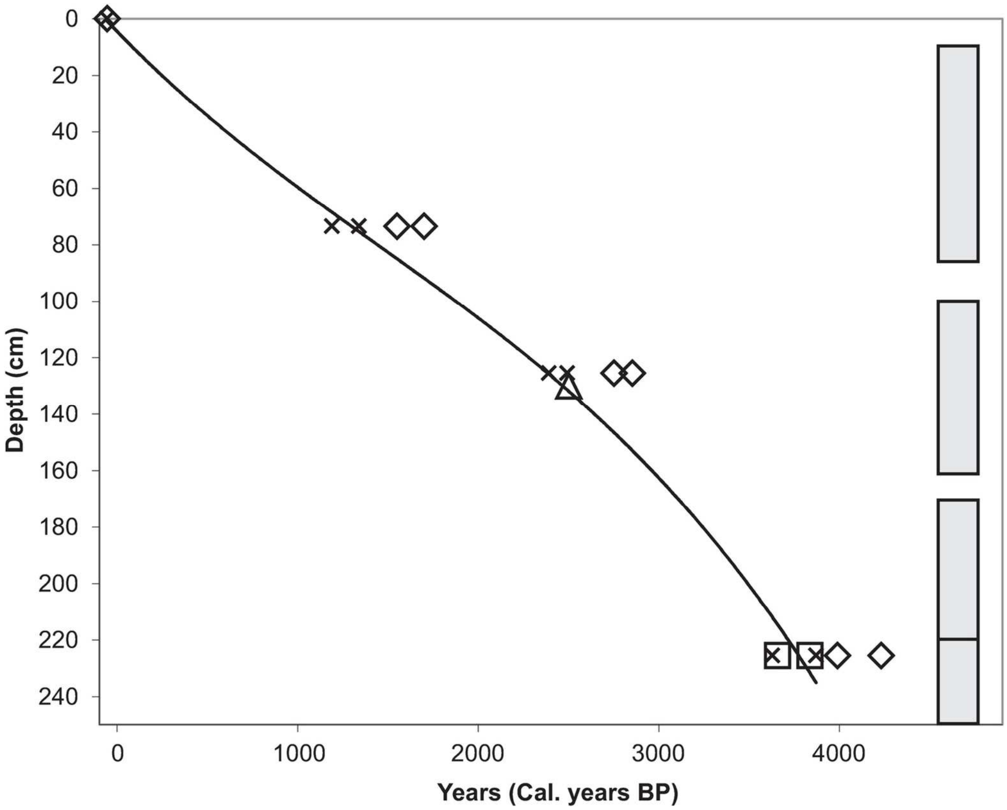
Figure 5 Ostracod fauna from the LPIII core plotted against depth.

Figure 6 Diatom flora (% count) from core LPIII plotted against depth.

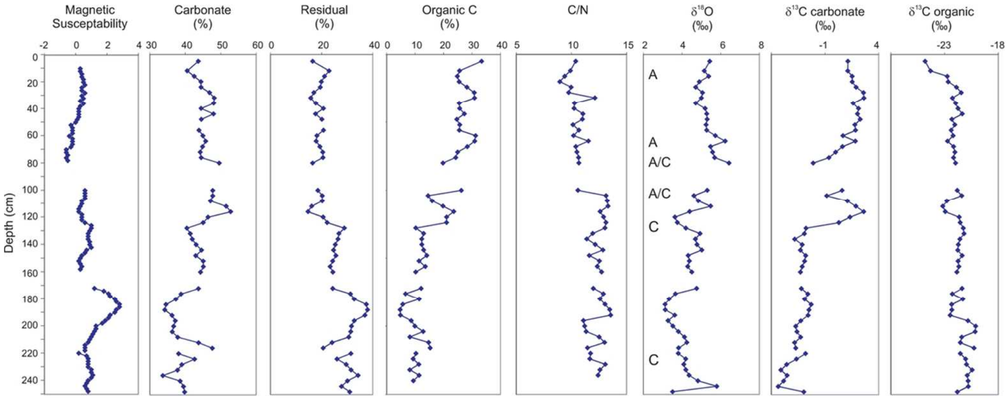
Figure 7 Summary figure showing the key variables highlighting lake water and catchment change in and around Lake Parishan. Periods of human impact, as defined by *L. inopinata* (Table 3), are highlighted.



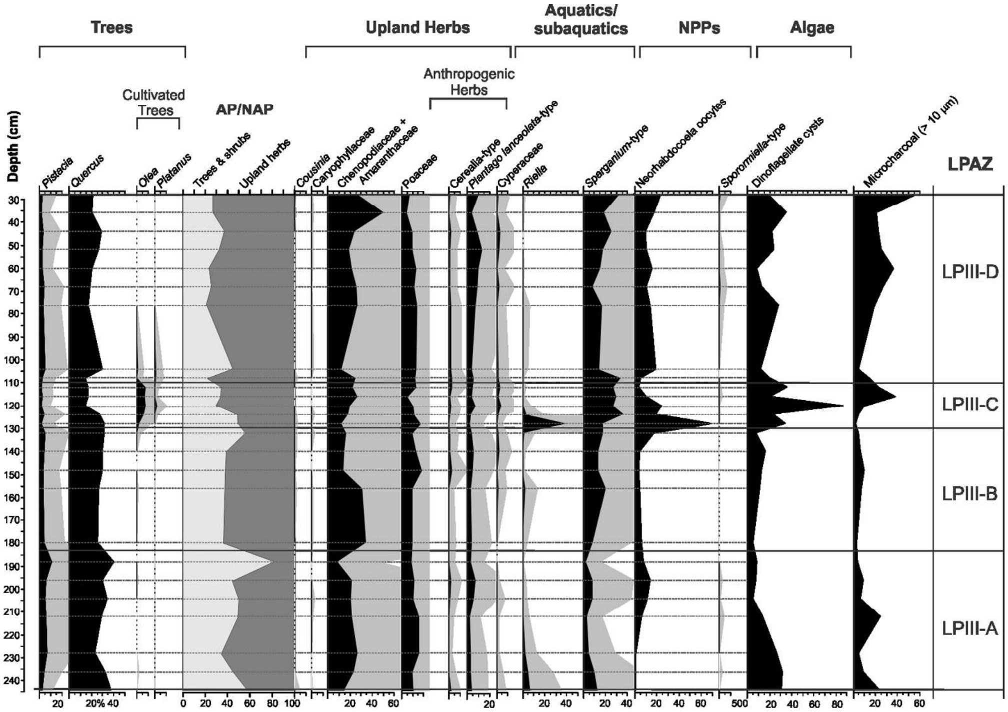
179x129mm (300 x 300 DPI)



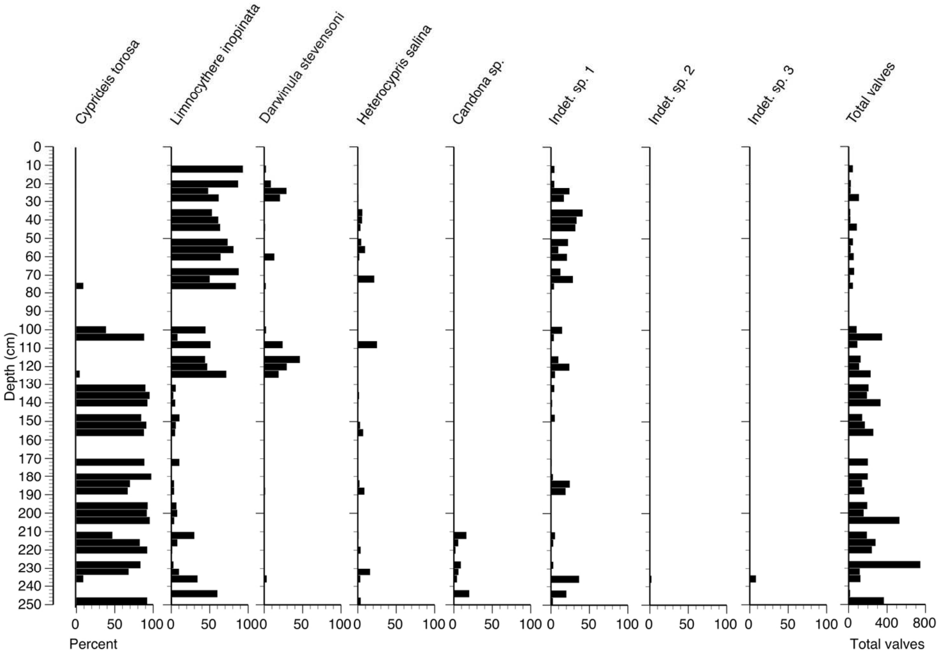
140x112mm (300 x 300 DPI)



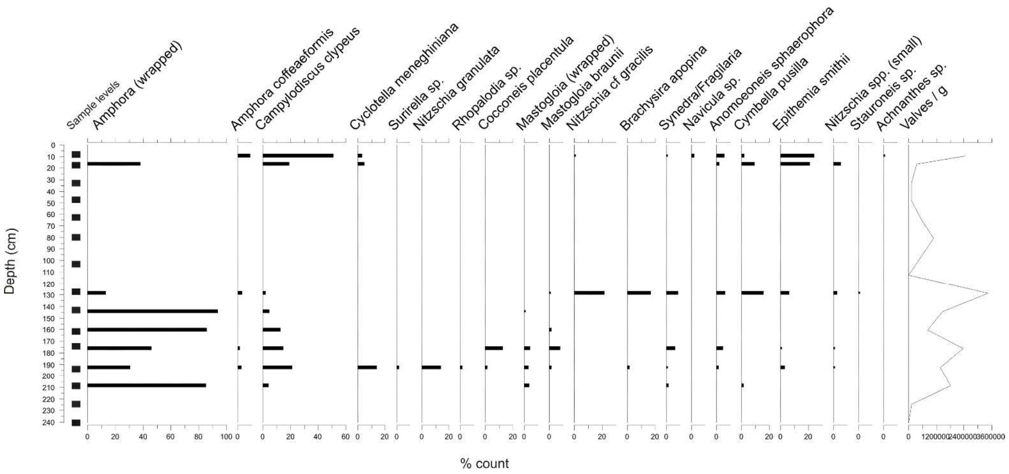
112x44mm (300 x 300 DPI)



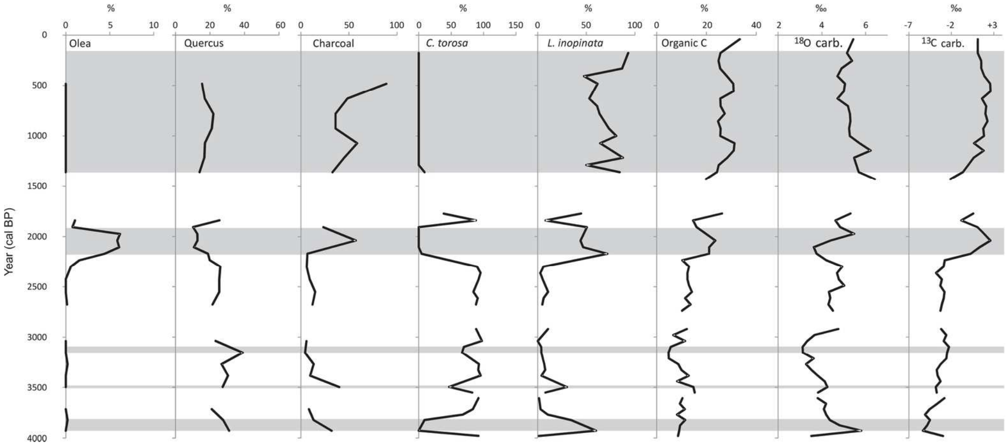
152x107mm (300 x 300 DPI)



167x112mm (300 x 300 DPI)



260x119mm (300 x 300 DPI)



158x69mm (300 x 300 DPI)

Table 1 Radiocarbon age estimates from core LPIII. Calibration undertaken using Calib 7.0 and IntCal13; 2 sigma ranges are reported.

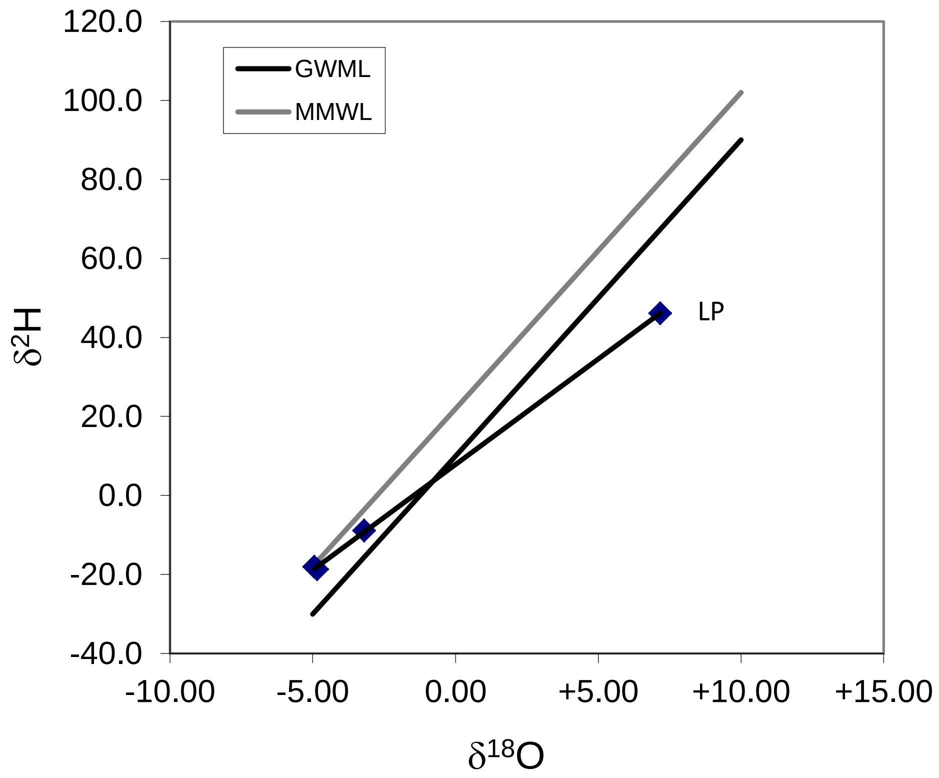
Sample name	Laboratory code	Radiocarbon age (years BP)	Calibrated age (years BP)	
LP III 73-74	Poz-21263	1705 ± 30	1549	1698
LP III 125-126	Poz-45410	2685 ± 35	2750	2851
LP III 225-226	Poz-21264	3750 ± 30	3987	4229

Table 2 U-Series age estimate from core LPIII. Age Corrected using ^{232}Th/^{238}U Detrital Molecular Ratio of 3.12.

	^{238}U (ppm)	^{234}U (ppm)	^{230}Th (ppb)	^{232}Th (ppb)	^{230}Th/^{232}Th	^{230}Th/^{234}U	^{234}U/^{238}U	Age (years BP)	^{230}Th/^{234}U corr	^{234}U/^{238}U corr	Corrected Age (years BP)
	8.63390	0.00076	0.01427	1254.72	2.12425	0.06226	1.62174	6992	0.03379	1.65294	3745
Uncertainty	0.06816	0.00000	0.00012	226.81	0.08675	0.00051	0.01318	117	0.0004	0.01946	90

Table 3 The two end member environmental states for Lake Parishan through the last 4000 years based on relationships defined in Supplementary Table 1

Impacted lake state	**Natural lake state**
High *L. inopinata*	High *C. torosa*
Alk/Ca > 1	Alk/Ca < 1
Low oak	High oak
High charcoal	Low charcoal
High Sporormiella	Low Sporormilella
High Sparganium	Low Sparganium
High carbonate	Low carbonate
High organic carbon	Low organic carbon
Low $\delta^{13}C_{org}$	High $\delta^{13}C_{org}$
High $\delta^{18}O$	Low $\delta^{18}O$
High $\delta^{13}C_{carb}$	Low $\delta^{13}C_{carb}$
Low magnetic susceptibility	High magnetic susceptibility



Supplementary Figure Isotopic values of lake waters from Lake Parishan (LP) collected in February 2007 compared to nearby waters from the Bishapur River and local springs. The lake water describes a clear Local Evaporation Line from the Global and Mediterranean Meteoric Water Lines.

Supplementary Table Correlation analysis (r^2 and p values shown) between selected variables from core LPIII. Significant relationships are shaded.

	Olea	Quercus	Charcoal	Sporormiella	Sparganium	C_torosa	L_inopinata	Carb	C_org	d13C_org	C:N	d18O_carb	d13C_carb	Mag_susc
Olea	1	-0.464	0.085	-0.179	0.554	-0.308	0.165	0.436	0.157	-0.241	0.392	-0.286	0.410	-0.134
		0.022	0.705	0.401	0.005	0.144	0.440	0.033	0.465	0.256	0.058	0.175	0.046	0.532
Quercus		1	-0.543	-0.259	-0.712	0.567	-0.570	-0.740	-0.691	0.534	0.212	-0.317	-0.735	0.637
			0.009	0.222	0.000	0.004	0.004	0.000	0.000	0.007	0.319	0.131	0.000	0.001
Charcoal			1	0.683	0.374	-0.684	0.639	0.646	0.774	-0.400	-0.624	0.579	0.698	-0.532
				0.000	0.086	0.000	0.001	0.001	0.000	0.065	0.002	0.005	0.000	0.011
Sporormiella				1	-0.053	-0.443	0.595	0.181	0.610	-0.214	-0.578	0.423	0.334	-0.404
					0.807	0.030	0.002	0.398	0.002	0.315	0.003	0.039	0.110	0.050
Sparganium					1	-0.532	0.473	0.709	0.529	-0.356	-0.098	0.230	0.709	-0.459
						0.007	0.020	0.000	0.008	0.088	0.649	0.280	0.000	0.024
C_torosa						1	-0.916	-0.488	-0.704	0.479	0.351	-0.536	-0.659	0.593
							0.000	0.016	0.000	0.018	0.092	0.007	0.000	0.002
L_inopinata							1	0.497	0.792	-0.440	-0.519	0.656	0.637	-0.711
								0.014	0.000	0.031	0.009	0.000	0.001	0.000
Carb								1	0.704	-0.586	-0.193	0.436	0.787	-0.697
									0.000	0.003	0.366	0.033	0.000	0.000
C_org									1	-0.480	-0.662	0.621	0.844	-0.747
										0.018	0.000	0.001	0.000	0.000
d13C_org										1	0.036	-0.337	-0.644	0.415
											0.869	0.107	0.001	0.044
C:N											1	-0.630	-0.363	0.466
												0.001	0.081	0.022
d18O_carb												1	0.334	-0.793
													0.111	0.000
d13C_carb													1	-0.512
														0.011

Light grey shading: Correlation is significant at the 0.05 level.

Dark grey shading: Correlation is significant at the 0.01 level.