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

23
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49

50 **Abstract**

51

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

62

63

64 **Keywords**

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

66

67 **Introduction**

68 There is compelling evidence from many regions on Earth that people have had a substantial
69 impact on the environment for thousands of years (Ruddiman et al., 2015) e.g. via deforestation
70 (Roberts, 2013) or irrigation (Magee, 2005). Less clear, and pertinently for this volume, is
71 determining at which point people made a global impact such that a 'golden spike' marking the
72 beginning of a new Anthropocene era might be identified (e.g. Gale and Hoare, 2012; Smith and
73 Zeder, 2013). Palaeoenvironmental archives such as lake sediments can often only provide a
74 relatively local or regional view of past environmental change. Importantly, however, lacustrine
75 archives can preserve multiple proxies of change, allowing information on climate, environment
76 and their drivers, including human activity, to be compared directly from one sediment record. This
77 avoids the issues of dating error or archival systematics that can complicate human-climate-
78 environment comparisons from multiple sites, environmental and/or archaeological (e.g. Jones,
79 2013a). Despite clear evidence of past human activity that could alter the environment (e.g. Smith
80 and Zeder, 2013; Ramsey et al., this volume), multiple proxies are needed to establish clear links
81 between this activity and recorded environmental change. Moving past correlation to causation is
82 difficult in the palaeosciences, irrespective of whether the environment is affecting people or the
83 other way round, but is important for a robustly defined Anthropocene.

84
85 Here we present a new record of environmental change from Lake Parishan in the Fars Province
86 of South West Iran through the last 4,000 years. We use multiproxy data from a single core to
87 establish the dominant forcing factors of the environment in and around the lake. South West Iran
88 has a long history of human occupation with cereal agriculture and animal domestication dating
89 back to around 10,000 years BP (Weeks, 2013a; Riehl et al., 2013). The Zagros, and their 'Hilly
90 Flanks' have long been of interest to debates about the origins of agriculture (Braidwood and
91 Braidwood, 1949) and people's interaction with their environment in general (e.g. Miller, 2013).
92 Despite this, continuous palaeoenvironmental records from Iran, and especially from the south and
93 east, are scarce. Current palaeoenvironmental and palaeoclimatic understanding for the Holocene
94 of Iran is drawn largely from the records of Lakes Urmia, Zeribar and Mirabad (e.g. Djamali et al.,
95 2008; Stevens et al., 2006), hundreds of kilometres to the north of Parishan (Fig. 1). These sites sit
96 in a different climate regime to Parishan today (Jones, 2013b) and therefore may not reflect past
97 change further south. Our new data provide a more local reconstruction of environmental change
98 to compare directly with local archaeological investigations (e.g. Potts et al., 2009). A pollen record
99 of the past 5000 years does exist from Fars, from Lake Maharlou (Fig. 1) (Djamali et al., 2009), but
100 largely provides information on human-induced landscape change in the catchment, and not
101 hydroclimatic changes of the lake itself.

102
103 The Lake Parishan multiproxy data set allows us to narrow down the possible explanations for the
104 changes seen in the Parishan record, with data describing environmental changes within the lake

105 (ostracods, isotopes, diatoms, pollen) and within the catchment (pollen, charcoal, in-wash proxies
106 such as magnetic susceptibility). The record provides new palaeoenvironmental information from
107 the region as a whole, and shows that people have had a significant impact on lake hydrology at
108 various times during the last 4000 years.

109

110 **Site Description**

111 Lake Parishan (29.5°N 51.8°E, 820 masl) lies in a fault-bounded basin 15km southeast of Kazerun,
112 in the Fars region of SW Iran (Fig. 1). As one of only a few recently extant lakes in the region Lake
113 Parishan is an important freshwater site and is Ramsar listed (No. 37; 23/06/1975). Over the last
114 25 years, lake area has fluctuated between 0 – 52 km², with a corresponding maximum depth of 0
115 to 5m (UNDP/GEF, 2010). The surface catchment is 270 km². The lake has no surface outflow and
116 given local average annual precipitation (450 mm) and evaporation (2400 to 3100 mm/yr) regimes
117 (Lotfi and Moser, 2010) the lake is liable to drying. The lake dried out completely in 1987
118 (UNDP/GEF, 2010) and again since our fieldwork of 2007. Lake waters had a pH of between 8.5
119 and 9 in 2001/2002 with variable conductivity values between 3500 and 8900 μS/cm (Lotfi and
120 Moser, 2010). Na or Mg and Cl are the dominant ions in the lake. Spring samples show more
121 variability, with water more likely to be Ca – HCO₃ dominated (Shirini Feshan, 2000).

122

123 The lake and its catchment are an important agricultural centre with over 800 wells (UNDP/GEF,
124 2010) exploiting its important groundwater resource. Given recent drops in lake level there is
125 significant local effort being put into understanding the lake system (e.g. Lotfi and Moser, 2010;
126 UNDP/GEF, 2010). Lake Parishan's clear sensitivity to changes in the catchment water balance in
127 recent years makes it a potentially useful site for observing past changes in environment.

128

129 **Methods**

130 *Fieldwork*

131 Core LP111 was taken in February 2007 using a Livingstone corer (Livingstone, 1955) from the
132 south-central part of the lake (29.514°N, 51.800°E) in 2.1m water depth. Four drives retrieved a
133 ~2.5m core sequence with some small gaps between drives (Fig. 2). In addition, water samples
134 were taken in leak-proof plastic bottles, at arm's length below the surface, for the analysis of the
135 oxygen and hydrogen isotope composition of lake water to help constrain the interpretation of the
136 palaeo-isotope data recorded in core carbonates.

137

138 *Sedimentology and Geochemical proxies*

139 Before the cores were sampled magnetic susceptibility was measured every 2cm on a Bartington
140 MS2C Core Logging Sensor with a 60 cm loop, with data corrected for core diameter and drift
141 using the accompanying Multisus software. Loss on Ignition (LOI) at 550°C and 925°C (e.g. Hierl

142 et al., 2001) was undertaken at a 4cm resolution, providing data on changes in organic and
143 inorganic carbon content in the core.
144 1cm (sediment length) samples from every 4cm down the core were prepared for isotope analysis
145 of sedimentary, endogenic, carbonates at the NERC Isotope Geosciences Facility (NIGF) following
146 standard laboratory protocols (e.g. Leng, 2005). Samples were left in 5% sodium hypochlorite
147 overnight and then sieved at 90µm in deionised water to remove shell carbonates i.e. from
148 ostracods (see below) and snails. Dried samples were reacted in acid at 25°C under vacuum and
149 the resulting CO₂ collected for analysis of oxygen and carbon isotope ratios (¹⁸O/¹⁶O, ¹³C/¹²C) on
150 an Optima dual-inlet mass spectrometer. δ¹⁸O and δ¹³C values, reported in standard delta units as
151 part per thousand deviations from the VPDB standard, have analytical reproducibility of 0.1‰.
152 Following preparation for isotope analysis, selected carbonate samples were analysed by XRD in
153 the Faculty of Engineering, University of Nottingham to record the carbonate mineralogy. Finely
154 ground samples were analysed in cavity mounts (Hardy and Tucker, 1988) on a Siemens D500 X-
155 Ray diffractometer. The scanning range was 5-65° 2θ and the scan rate was 2° 2θ per minute with
156 a step size of 0.05.
157 Bulk organic components of the sediment were analysed for %C, %N and δ¹³C_{organic} at the same
158 resolution as the LOI and carbonate isotope data, by combustion in a Costech ECS4010 on-line to
159 a VG TripleTrap and Optima dual-inlet mass spectrometer at the NIGF. Samples were first reacted
160 in 5% HCl overnight and then thoroughly washed, to disaggregate the sediment and remove
161 carbonates. The isotope data are reported in the standard delta units (δ¹³C) as parts per thousand
162 deviations from the VPDB standard. Analytical reproducibility is <0.1‰ for δ¹³C and 0.2 for C/N for
163 the standard and sample material.

164

165 *Pollen*

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

176

177 The full pollen record from core LPIII will be discussed elsewhere (Djamali et al., in press) and here
178 we present selected taxa in order to reconstruct the environment in and around the lake through
179 the time period of study, in particular the extent of human impact on the catchment and the

180 hydrological variations of the lake. We use the presence of *Olea* (olive) and *Platanus* (plane tree)
181 pollen as indicators of agricultural practice (following Djamali et al., 2009, 2011). We also present
182 the *Quercus* (oak) pollen curve as a measure of the natural vegetation regime. In addition,
183 *Sporormiella* (fungi associated with animal dung (van Geel, 2001)) is used as evidence of pastoral
184 activities. *Sparganium*-type pollen and *Riella* spores provide information on lake level changes
185 (Djamali et al., 2008), while charcoal is a measure of burning in the region, often associated with
186 agricultural practices in the later Holocene (e.g. England et al., 2008), but also potentially of natural
187 origin (e.g. Turner et al., 2007).

188

189 *Ostracods*

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

202

203 *Diatoms*

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

215

216 **Chronology**

217 Four age estimates, 3 from radiocarbon analysis of bulk organic material (Table 1) and one from U-
218 Th analysis (Table 2), have been carried out on the 250cm core. Radiocarbon analyses were
219 undertaken at the Poznan Radiocarbon Laboratory. The U-Th analysis was undertaken at the
220 Open University, UK. Following acid digestion of bulk sediment samples U and Th were purified
221 using ion exchange chromatography before being run on a Nu Instruments Multi-collector ICP-MS
222 in a solution of 3% HNO₃, using a sample - standard bracketing technique. Based on these age
223 estimates, the core spans from present day (the lake was extant at the time of coring) to around
224 4,000 cal BP.

225

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

232

233 The clear shift in the pollen diagram at 125cm, with the establishment of olive (*Olea*) and
234 deforestation of oak (*Quercus*), likely marks the start of the Achaemenid Persian Empire 2500 cal
235 BP (e.g. Djamali, 2009), which had a significant centre at Persepolis, only 110 km from Parishan
236 (see further detail in the Discussion below). This pollen stratigraphic marker confirms the estimate
237 of old carbon error for core LP111 (Fig. 2).

238

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

246

247 **Results**

248 *Sedimentology and Geochemical proxies*

249 The data show a number of trends and events through the core (Fig. 3). There is a peak in
250 magnetic susceptibility between 200 and 170cm, also marked by an increase in non-combusted,
251 residual material from the LOI analyses. The amount of this residual material generally decreases
252 up through the core, with a particular step change to lower values between 130 and 110cm. This
253 depth interval is also marked by a reduction in magnetic susceptibility, to negligible values, and an
254 increase in both organic and inorganic carbon. This step change is part of a long term trend to

255 higher values, from 200cm towards the top of the core, in the amount of organic carbon. C/N ratios
256 show a marked shift from values around 14 to lower values, of around 10, at 110cm. These data all
257 suggest a general trend to reduced amounts of catchment material, both in terms of inorganic in-
258 wash (reduction in residual LOI material and magnetic susceptibility) and non-aquatic organic
259 matter, C/N values of 10 are typical of aquatic algae (e.g. Leng et al., 2010), through the core.

260

261 Carbonate mineralogy is variable down core with samples at 128 and 224cm dominated by calcite,
262 samples at 80 and 112cm having a mixture of calcite and aragonite, and samples from 16 and
263 64cm dominated by aragonite. The carbonate isotope values also show an up core trend to more
264 positive values with a particularly marked step in $\delta^{13}\text{C}$ values at 125cm from $\sim -3\text{‰}$ to $\sim +2\text{‰}$, in
265 part explained by the shift in mineralogy; aragonite is 1.9‰ (0.6‰) more positive in $\delta^{13}\text{C}$ ($\delta^{18}\text{O}$)
266 compared to calcite precipitated in waters with the same temperature and isotopic composition
267 (Grossman, 1984; Grossman and Ku, 1986). Oxygen and hydrogen isotope ratios of the lake
268 waters collected in 2007 show a clear evaporative signal (Supplementary Figure 1), and $\delta^{18}\text{O}$
269 trends to more positive values likely represents a shift to more evaporative dominant conditions
270 given the associated change from calcite to aragonite (e.g. Jones et al., 2006). However, there is
271 no co-variation between $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ from the carbonates in LPIII (Supplementary Table 1) that
272 is typically seen in evaporative lake systems (e.g. Li and Ku, 1997) suggesting an alternative
273 control, other than evaporation, on the $\delta^{13}\text{C}$ system. The isotope value of bulk organic matter is
274 similar (between -21 and -23‰) until the top 20cm of the core, where it shifts to lower values, and
275 it remains unclear what would cause the changes in $\delta^{13}\text{C}_{\text{carbonate}}$, other than changes in carbonate
276 mineralogy as discussed above, without impacting on the total dissolved inorganic carbon pool
277 also used by the organic material.

278

279 *Pollen*

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

292 around 120cm depth, peaking at 60 and 30cm, with occasional peaks lower in the sequence e.g. at
293 212cm. Pollen is not well preserved in the uppermost 30cm of the core.

294

295 *Ostracods*

296 Ostracod shells are found in all of the samples examined, although abundance varies markedly
297 from 15 valves (244cm) to 746 valves (228cm). All samples contain adults and a range of juvenile
298 instars: adults and juvenile moults are generally very well preserved, even the earliest instars. Most
299 of the adult specimens and the vast majority of the juvenile instars are present as disarticulated
300 valves, with only a small proportion of carapaces preserved. In total eight ostracod taxa were
301 recovered from LP III (Fig. 5). The presence of adults and a range of juvenile moult stages suggest
302 that the assemblages are largely *in situ* with signs of minimal *post mortem* transport.

303

304 In general, the lower part of the core, below about 100cm, is characterised by a higher abundance
305 of shells than above. Overall, the ostracod assemblages are consistent with a slightly saline lake.
306 *Cyprideis torosa* is the most common species, followed by *Limnocythere inopinata*, indeterminate
307 species 1, *Darwinula stevensoni*, *Candona* sp. juveniles and *Heterocypris salina*. The remaining
308 two taxa, indeterminate species 2 and 3, occur sporadically. Based on the stratigraphical
309 distribution of taxa, the most striking difference is between the lower part of the core, below
310 ~132cm, which is dominated by *C. torosa*, and the upper part dominated by *L. inopinata*. In the
311 lowest parts of LP III, significant numbers of *L. inopinata*, *H. salina* and indeterminate species 1 and
312 lesser numbers of *Candona* sp. (probably *Candona* cf. *neglecta*) accompany *C. torosa*. An
313 exception to this pattern is at 244 cm, where *L. inopinata* dominates, although total specimen
314 numbers are small. In the upper part of the core, *C. torosa* is absent from most levels, although *H.*
315 *salina*, *D. stevensoni* and indeterminate species 1 occur in many levels. At 104 to 108cm, a
316 reversal to this pattern is found, with *C. torosa* dominant much like in the lower part of the core.

317

318 *Diatoms*

319 Diatoms are only preserved in some sections of the Parishan core (Fig. 6), with most taxa
320 indicative of brackish and often shallow water conditions. Counts are low (ca. 100 valves) in spite
321 of counting multiple slides. Results from only 8 of the 15 samples were considered adequate to
322 interpret and the impact of differential preservation must be taken into account. The sequence can
323 be divided into roughly four sections: from the base to 144-145cm; the sample from 128-129cm; a
324 section of core where preservation was too poor to allow for counting (112-113 to 32-33cm) and
325 the top two samples (9-10 and 16-17cm). The lower part of the core was dominated by *Amphora*
326 spp. which appeared to be wrapped in silica (confirmed under the SEM). Some valves could be
327 identified as *A. coffeaeformis* (*Halamphora coffeaeformis*), a benthic, high salinity alkaliphile found
328 in both saline lakes and marine environments. Other diatoms present included benthic species
329 indicative of high salinity/brackish conditions such as *Campylodiscus clypeus*, *Mastogloia braunii*

330 and *Anomoeoneis sphaerophora*. *Nitzschia granulata*, more usually a marine diatom, but also
331 occasionally recorded in salt lakes (Gasse, 1986) was noted. Resting spores of *Chaetoceros*
332 *amanita* were recorded in transect counts. These taxa are generally epipelagic or benthic and occur
333 predominantly in Na-Cl dominated waters of moderate to high conductivity (3000 - >30,000 $\mu\text{S cm}^{-1}$
334 in different data sets). The low diatom numbers and rather poor preservation indicate a highly
335 evaporated water body, inimical to good diatom preservation. A stress response of accreting silica
336 around valves has been recorded in a highly evaporated crater lake in Mexico (Metcalf, 1990).
337 This accretion of silica probably accounts for their numerical abundance in the fossil material and
338 may not reflect the importance of *Amphora* in the life assemblage. Overall, the conditions
339 indicated at the bottom of the core are consistent with recent water samples (see Site Description).

340
341 The sample from 128-129cm was distinctive because of its high diversity and more abundant
342 diatoms. *Nitzschia cf gracilis*, *Brachysira apopina* and *Cymbella (Navicymbula) pusilla* were the
343 most abundant taxa (although silica 'wrapped' *Amphora* spp. were still present). The increased
344 abundance of diatoms and their better preservation indicate that the lake may have become less
345 saline/alkaline, at least intermittently. *N. gracilis* may be planktonic and has a lower reconstructed
346 EC optimum than the other taxa found here (around 3000 $\mu\text{S cm}^{-1}$ according to Reed et al., 2012).
347 It may also indicate higher nutrient levels (Patrick and Reimer, 1975). High variability in salinity
348 may be indicated by the presence of *B. apopina* which has very high reconstructed EC optima (>
349 50,000 $\mu\text{S cm}^{-1}$) based on work in Spanish and Turkish lakes (Reed, 1998, Reed et al., 2012). An
350 increasing proportion of epiphytic taxa at this depth may indicate more aquatic vegetation near the
351 coring site. It is interesting to note that this sample has high percentages of both *B. apopina* and *C.*
352 *pusilla* which are both the only species in their genus that are halophilous.

353
354 The next five samples in the core preserved very few valves, although the sample from 80-81cm
355 was again dominated by the 'wrapped' *Amphora* spp, so it appears that conditions again became
356 unfavourable for diatom preservation. Preservation is much better in the top sample (9-10 cm) than
357 in the one below, which is again dominated by 'wrapped' *Amphora* spp. with *C. clypeus*. *C.*
358 *amanita* resting spores again noted. Both these samples show a significant presence of *Epithemia*
359 *smithii* (ca. 20%) which may indicate the availability of more aquatic vegetation. Unfortunately, this
360 taxon is not recorded in available salinity reconstruction databases. Overall the diatom
361 assemblage indicates shallow, high conductivity water.

362

363 Discussion

364 There are strong and significant correlations between the different variables analysed for this study
365 (Supplementary Table 1). Based on these correlations, two end-member environmental states are
366 interpreted for the last 4,000 years in and around Lake Parishan and its catchment. These two lake
367 states are marked most clearly in the stratigraphic record by the shift between the two dominant

368 ostracod taxa (Figs. 5 and 7) and the interpretation of the changes seen between these two taxa,
369 and associated shifts in other proxies, are key to our overall interpretation of the data set.

370

371 Although *C. torosa* has a higher salinity tolerance than *L. inopinata* (e.g. Holmes, 1992), a
372 decrease in salinity midway through the sequence is not consistent with other proxies including the
373 positive $\delta^{18}\text{O}$ trend (more evaporation), change in carbonate mineralogy from calcite to aragonite
374 (more evaporation) and the disappearance of diatoms from the record. Collectively these latter
375 three proxies suggest an increase in evaporative enrichment above about 120cm. *Cyprideis torosa*
376 and *L. inopinata* also have differing preferences on a water composition (alkalinity: Ca) gradient
377 with *C. torosa* preferring Ca-enriched and alkalinity-deplete waters (alkalinity: Ca <1), and *L.*
378 *inopinata* preferring Ca-deplete and alkalinity-enriched conditions (alkalinity: Ca >1) (Forester,
379 1983; 1986). These two contrasting water types fall on separate evaporative pathways (e.g. Hardie
380 and Eugster, 1970) and so cannot be explained by differences in the degree of evaporative
381 evolution.

382

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

390

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

399

400 Combined, these multi-proxy data therefore suggest that during periods of increased catchment
401 agriculture (increased burning, increased deforestation, increased animal dung), surface (reduced
402 in-wash) and groundwater flow were reduced to the lake. With an increase in precipitation relative
403 to surface and groundwater inflow from the carbonate catchment the amount of Ca in lake waters
404 was relatively reduced, leading to an increase in the alkalinity/Ca ratio and a shift in the ostracod
405 assemblage. As relatively less water entered the lake, lake levels fell and the waters become more

406 evaporatively enriched (as the ratio of evaporation to total input to the lake, precipitation plus
407 surface-and ground-water inflow, increased) leading to higher $\delta^{18}\text{O}$ values and aragonite
408 deposition (rather than calcite). This fall in lake levels also led to more shallow water areas suitable
409 for *Sparganium* type reeds to grow. Increased lake productivity, as marked by increased organic
410 material in the sediments fits a hypothesis of increased nutrient in-wash into the lake during
411 periods of increased agriculture. The data therefore suggest that increased agriculture in the
412 catchment had a significant impact on lake hydrology and biogeochemistry. *Limnocythere*
413 *inopinata* and associated end members of other proxy ranges therefore mark periods when the
414 lake was impacted by human activity whereas *C. torosa* marks a more natural lake and catchment
415 scenario (Table 3).

416
417 The impacted period immediately after 2400 cal BP, most likely associated with the beginning of
418 the Achaemenid Empire (see below), is very marked in the record and shows a different set of
419 inter-proxy relationships compared to the full record. The diatom flora at this point in the core
420 suggest a freshening of the system, as do lower $\delta^{18}\text{O}$ data. Other proxies do not show anything in
421 particular of note here that is not consistent with the overall patterns described above. This level in
422 the core (~ 130 cm) represents the onset of the most intensive agricultural phase in the LPIII proxy
423 record, marked especially by the rise in olive pollen. Given that diatoms disappear almost entirely
424 from the core in the levels above this it appears there may have been a very short freshening of
425 the system, perhaps associated with the initial catchment deforestation, at the onset of the
426 Achaemenid Empire. This increase in water flow into the lake during anthropogenic catchment
427 disturbance may, arguably, be a more typical response to human activity in a lake catchment (e.g.
428 Rosenmeier et al. 2002) but is only short-lived at Parishan, with longer term proxy shifts
429 suggesting the long term impact of agriculture is reduced amounts of water entering the lake.
430 Conditions through this phase are marked by the lowest oak pollen percentages in the record,
431 suggesting a possible threshold in catchment vegetation below which runoff is increased.

432

433 **Lake Parishan and regional archaeological evidence**

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

436

437 Northern Fars has a long history of agro-pastoral production, stretching back to the early Holocene
438 (Weeks, 2013b). The earliest pollen samples from the LPIII core, which cover the period from c.
439 4000 cal BP, include peaks in micro-charcoal at c. 3800 and 3500 cal BP (Fig. 7) and correlate
440 with increasing human activities in the landscape. These peaks equate to the archaeological
441 periods known as the Middle and Late Kaftari, which witnessed a dramatic increase in known
442 human settlement in Fars (Potts et al. 2009). However, the LPIII core does not show the evidence
443 for the early adoption of arboriculture in the Kaftari period that was seen clearly in the Maharlou

444 core (Djamali et al. 2009, 2011). Following the Kaftari period, between c. 3500-2500 years BP,
445 archaeological surveys in Fars indicate a relatively widespread and significant reduction in the
446 number of known settlements (Potts et al. 2009). Although the site of Tall-e Jidun in the Kazerun
447 plain close to Lake Parishan appears from surface collection survey to have been occupied from c.
448 3500 years BP (Nobari et al. 2009), the corresponding section of the LPIII core shows few
449 indicators of human agro-pastoral activities or landscape modification, especially in the micro-
450 charcoal record.

451

452 The spike in pollen from cultivated trees (primarily *Olea* and *Platanus*) in the LPIII core at 120cm
453 provides informative parallels and contrasts with existing archaeological and historical information.
454 This period coincides with the rise of the Achaemenid empire and a “massive investment of energy
455 and organizational power to bring the Persian heartland under cultivation” (Henkelman 2013: 528).
456 This includes archaeological evidence for the construction of various water control mechanisms in
457 the vicinity of the Persian capitals Pasargadae and Persepolis, including dams, barrages, and
458 irrigation canals, that significantly expanded the area that could be reached by irrigation
459 (Boucharlat 2013; Boucharlat et al. 2012; Sumner 1986). Texts from Persepolis attest to large-
460 scale agricultural and pastoral production supported by the availability of large numbers of
461 dependent labourers to harvest crops and maintain canals, as well as the efforts of local
462 independent farmers and herders. In particular, there is historical evidence for extensive cultivation
463 of fruit trees during the Achaemenid period and for the foundation of estates that had variable
464 functions, including orchards, parks, gardens, and hunting preserves (Boucharlat 2013: 513;
465 Uchitel 1997). One single administrative text from Persepolis lists more than 6000 fruit tree
466 seedlings to be planted in five estates, including apple, mulberry, pear, quince, date, pomegranate,
467 and olive (Henkelman 2013: 528). Interestingly, although historical sources from the Classical
468 period describe Fars as a fertile and well-watered region with many farms and gardens with fruit
469 trees, heavily wooded hills and river banks densely covered with plane trees and poplars (Sumner
470 1986: 17-18), they commonly note the absence or poor quality of olives and olive trees in the
471 general region of southern Iran (Djamali et al., in press). The pollen evidence from the LPIII core, in
472 particular the evidence for olive cultivation, thus provides a significant new strand of evidence for
473 the discussion of arboriculture in Achaemenid and post-Achaemenid Iran.

474

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

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

487

488 **Summary**

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

497

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

507

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

516

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527

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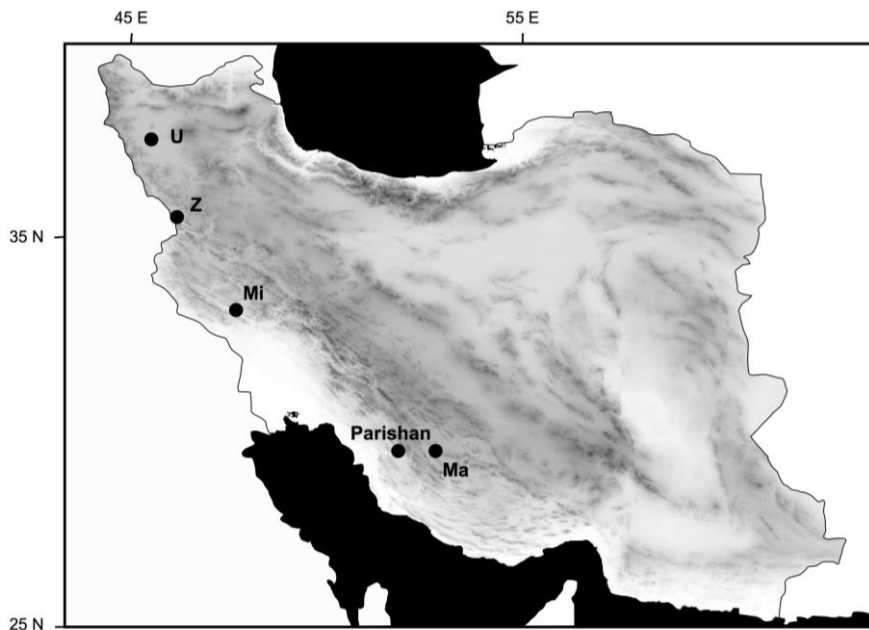
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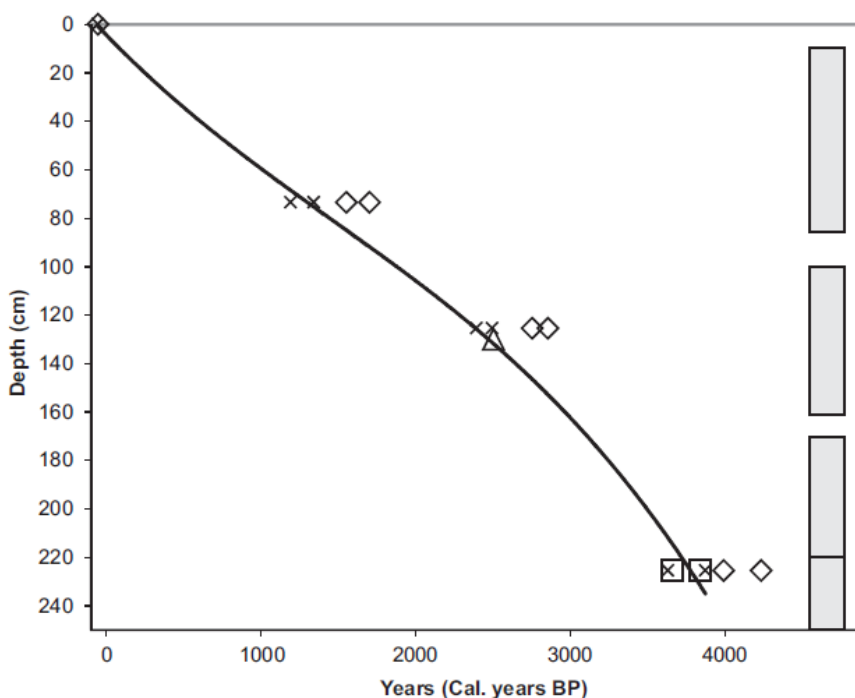
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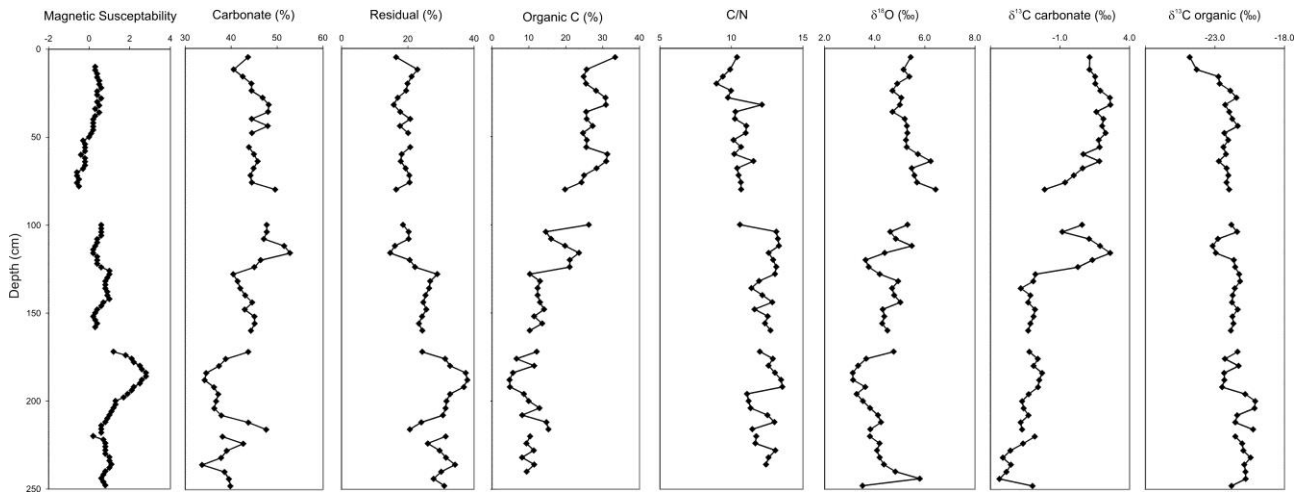
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682



684
 685 **Figure 1** Location map for Lake Parishan (P) in Iran, compared to location of lakes Urmia (U),
 686 Zeribar (Z), Mirabad (Mi) and Maharlou (Ma). Topographic background is from the GTOPO30
 687 digital elevation model (Data available from the U.S. Geological Survey).

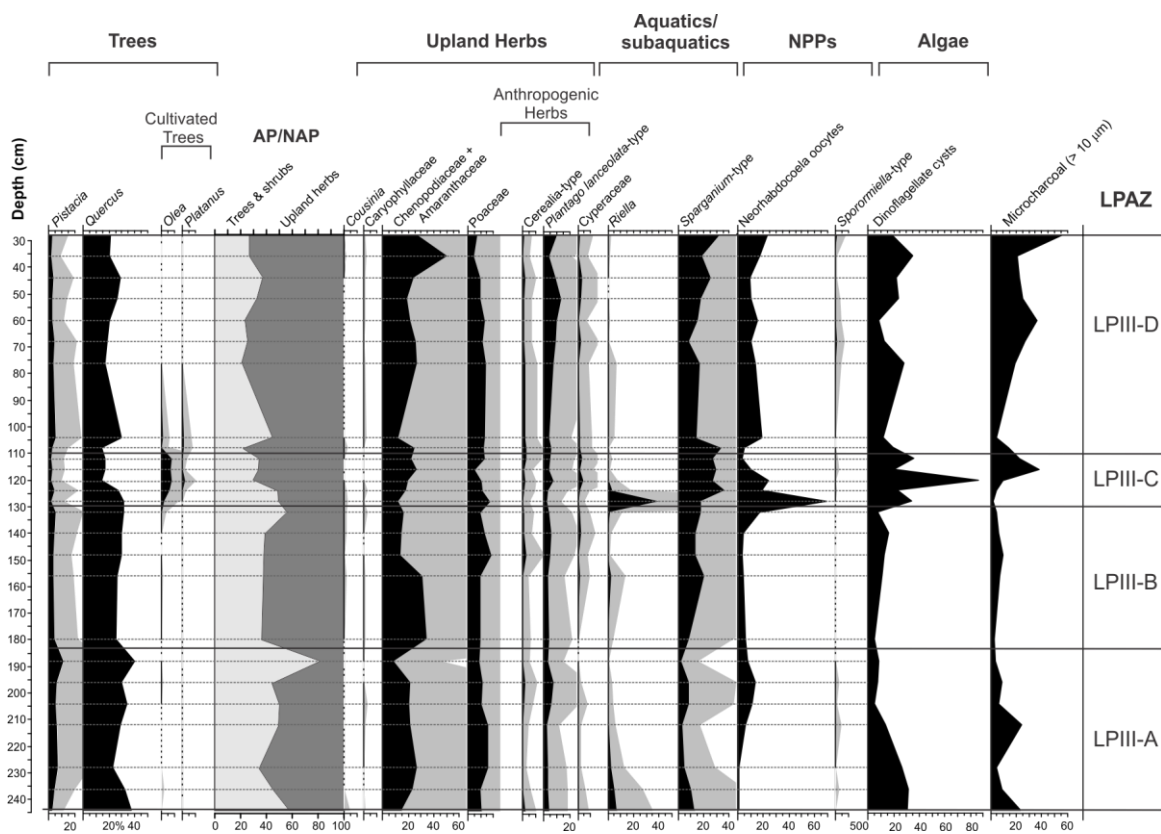


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 689 **Figure 2** Age Depth model for core LPIII. The final age model (solid line) is produced from the
 690 radiocarbon age estimates (diamonds; 2σ ranges) corrected by a 360 year old carbon effect
 691 (crosses) based on the U-Series age estimate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



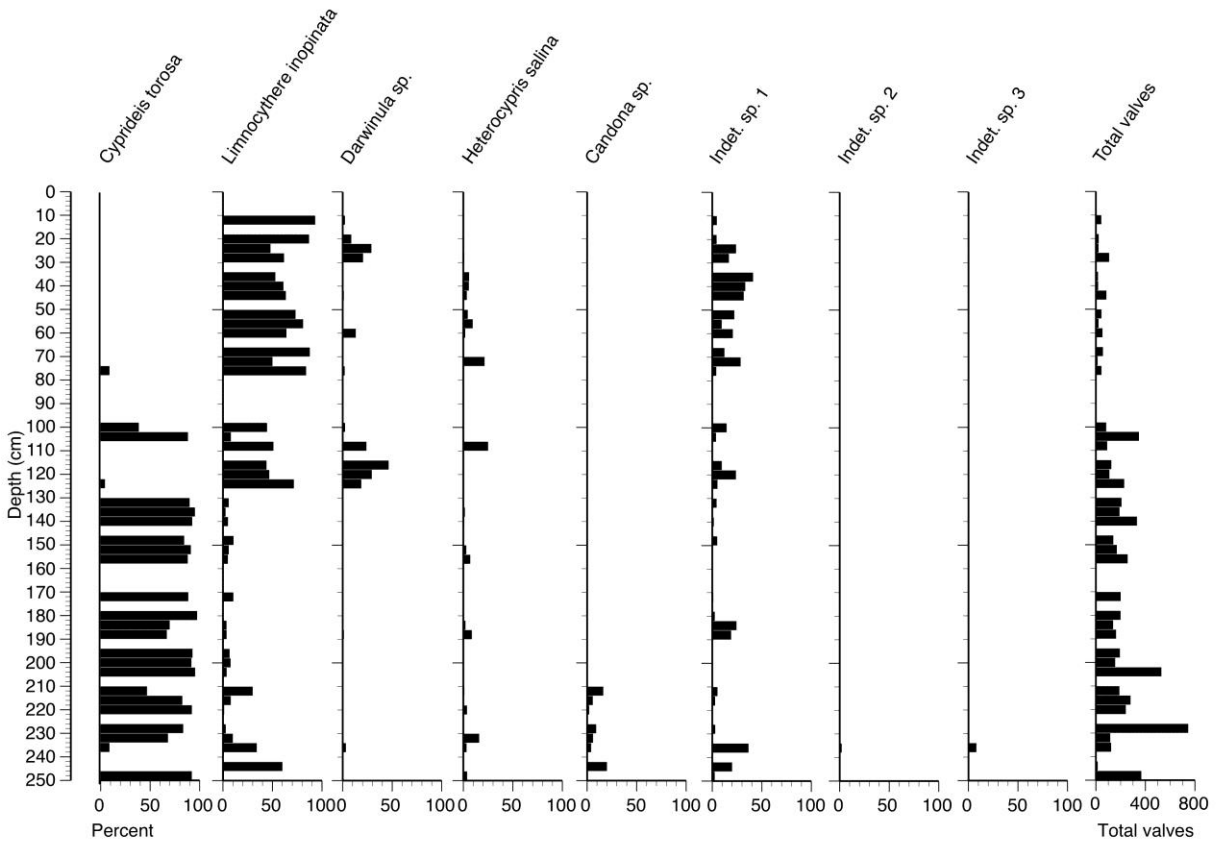
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Figure 3 Sedimentary and geochemical data from core LP III plotted against depth. Organic C data here are from the Costech analyses and show the same trends as the LOI data (not shown). The location of carbonate samples analysed for mineralogy are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



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Figure 4 Selected pollen data for the LP III 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.

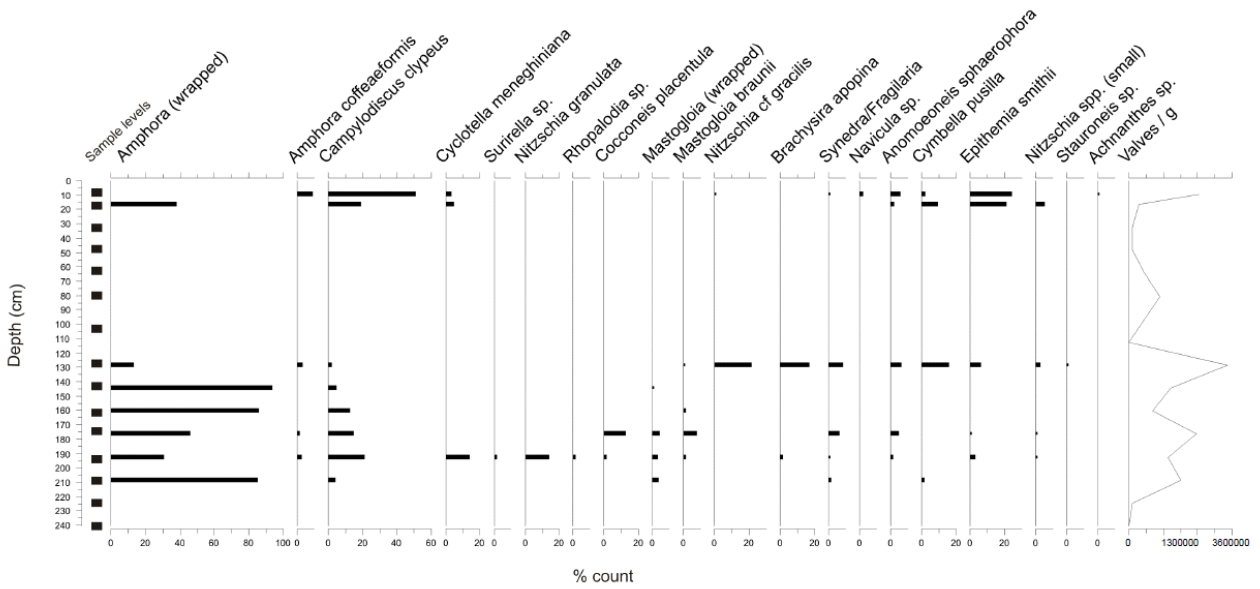


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Figure 5 Ostracod fauna from the LPIII core plotted against depth.

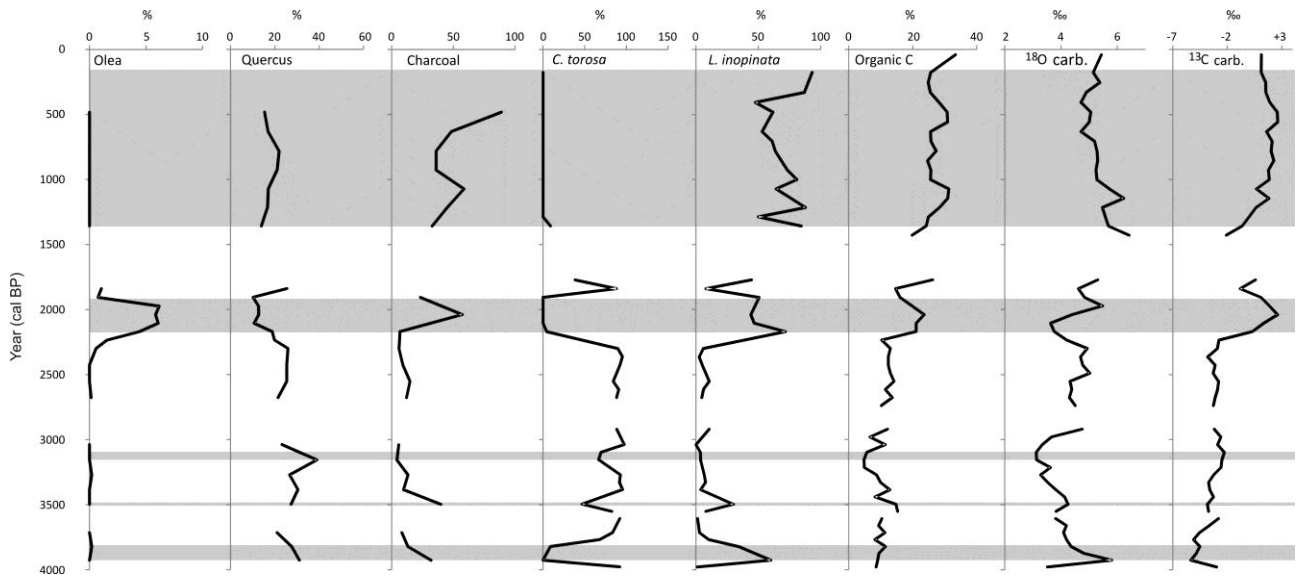
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Figure 6 Diatom flora (% count) from core LPIII plotted against depth.



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

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