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1 **Tracking the hydro-climatic signal from lake to sediment: a field study from central**
2 **Turkey**

3

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23 **Abstract**

24

25 Palaeo-hydrological interpretations of lake sediment proxies can benefit from a robust
26 understanding of the modern lake environment. In this study, we use Nar Gölü, a non-outlet,
27 monomictic maar lake in central Turkey, as a field site for a natural experiment using
28 observations and measurements over a 17-year monitoring period (1997-2014). We compare
29 lake water and sediment trap data to isotopic, chemical and biotic proxies preserved in its
30 varved sediments. Nar Gölü underwent a 3 m lake-level fall between 2000 and 2010.

31 $\delta^{18}\text{O}_{\text{lakewater}}$ is correlated with this lake-level fall, responding to the change in water balance.

32 Endogenic carbonate is shown to precipitate in isotopic equilibrium with lake water and there
33 is a strong relationship between $\delta^{18}\text{O}_{\text{lakewater}}$ and $\delta^{18}\text{O}_{\text{carbonate}}$, which suggests the water balance
34 signal is accurately recorded in the sediment isotope record. Over the same period,

35 sedimentary diatom assemblages also responded, and conductivity inferred from diatoms

36 showed a rise. Shifts in carbonate mineralogy and elemental chemistry in the sediment record

37 through this decade were also recorded. Intra-annual changes in $\delta^{18}\text{O}_{\text{lakewater}}$ and lake water

38 chemistry are used to demonstrate the seasonal variability of the system and the influence this

39 may have on the interpretation of $\delta^{18}\text{O}_{\text{carbonate}}$. We use these relationships to help interpret the

40 sedimentary record of changing lake hydrology over the last 1,725 years. Nar Gölü has

41 provided an opportunity to test critically the chain of connection from present to past, and its

42 sedimentary record offers an archive of decadal- to centennial-scale hydro-climatic change.

43

44 **Keywords:** Oxygen isotopes, Diatom analysis, Lake sediments, Monitoring, Seasonality,

45 Carbonates

46

47

48 **Highlights**

49

- 50 • Study of non-outlet, oligosaline, varve-forming lake in a semi-arid region
- 51 • Water balance signal in oxygen isotopes tracked from lake waters to sediments
- 52 • Strong intra- and inter-annual relationships between isotopes and water balance
- 53 • Diatom-inferred conductivity shows a complex response to change in water balance
- 54 • Implications of monitoring data for interpretation of palaeo-records

55 1. Introduction

56

57 In order to use lake sediments to reconstruct past climate change reliably, it is vital to
58 understand the modern hydrology of the study site (e.g. Hollander and McKenzie, 1991; Leng
59 et al., 1999; Saros, 2009) and to be able to track this signal to the sediments. Lake systems
60 respond to hydro-climatic variations via a number of linked parameters, including lake
61 volume, salinity concentrations and the oxygen isotope ($\delta^{18}\text{O}$) composition of waters. Non-
62 outlet lakes respond particularly dynamically to changes in water balance (Leng and
63 Marshall, 2004 and references therein); with increased evaporation, water volume decreases,
64 salts become concentrated and $\delta^{18}\text{O}_{\text{lakewater}}$ becomes more positive, and vice-versa, although
65 parameters may be subject to hysteretic effects (Langbein, 1961) as well as other factors such
66 as saline groundwater inflows.

67 Limnological parameters such as water balance are registered by proxies preserved in
68 lake sediments, which in turn permit the reconstruction of lake hydrology for pre-
69 instrumental time periods (Fritz, 2008 and references therein). Past water level fluctuations
70 can be reconstructed via dated lake marginal depositional facies, such as shoreline terraces
71 and carbonate platforms (Magny, 2006), and by changes in the species assemblages and life
72 forms of diatoms and other biological indicators (e.g. Barker et al., 1994). Salinity inferred
73 from biological indicators, such as diatom and ostracod assemblages, is sometimes quantified
74 as variability in electrical conductivity (EC) based on transfer function techniques using a
75 modern training set (e.g. Fritz et al., 2010; Reed et al., 2012). Past salinity levels can also be
76 reconstructed semi-quantitatively from elemental chemistry ratios such as Ca/Sr and Mg/Ca
77 (Ito, 2001). In many lakes, the form of carbonate precipitated from lake waters shifts from
78 low-Mg calcite in dilute lake waters to high-Mg calcite or aragonite in more saline lake
79 waters (Kelts and Hsü, 1978) and the Ca/Sr ratio can decrease if there is a shift from calcite

80 to aragonite precipitation (Tesoriero and Pankow, 1996). Stable isotopes can also be used as a
81 palaeo-hydrological proxy: lake water $\delta^{18}\text{O}$ is recorded in carbonates that precipitate in lake
82 water; $\delta^{18}\text{O}_{\text{carbonate}}$ is also modified by temperature and potentially by disequilibrium or
83 diagenetic effects (Leng and Marshall, 2004 and references therein).

84 Limnological sampling, monitoring and observation can provide fundamental insights
85 into all of the processes described above, and therefore strengthen the interpretation of lake
86 sediment records. Monitoring of lake levels leads to an understanding of the sensitivity of a
87 given lake to hydrological and/or climatic change. Recording biological response to measured
88 climate or hydrological change improves the interpretation of downcore species changes.
89 Monitoring data may be especially important when using stable isotopes as a hydro-climatic
90 proxy because it is not possible to apply modern analogue or transfer function techniques,
91 substituting time with space, to these records due to their dependence on multiple climatic
92 and site-specific non-climatic variables (Tian et al., 2011). Monitoring allows the
93 establishment of the key drivers of $\delta^{18}\text{O}_{\text{lakewater}}$ in the lake being studied and a better
94 understanding of how the signal is transferred to carbonates in the sediment record. Such a
95 monitoring approach can provide a basis for judging which proxies provide the most reliable
96 register of environmental changes (such as hydro-climate) and why different proxies can
97 show different trends in the palaeo-limnological record, although the possibility that present
98 lake states are not good analogues for the past should also be considered.

99 There are logistical and financial barriers to collecting modern data and samples over
100 multiple years and different seasons for a length of time suitable to ensure robust proxy
101 interpretation, especially in remote regions. However, in this study, we have been able to
102 collect a substantial number of samples from Nar Gölü (göl = lake in Turkish), a small,
103 hydrologically sensitive maar lake in central Turkey, over a period of 17 years (1997-2014).
104 Although our monitoring and observational data are far from complete, they do allow an

105 assessment to be made of both seasonal variations and multi-year trends. If lake sediments
106 are sufficiently well resolved in time, it is possible to trace changes measured from lake
107 waters collected from certain years to the sediments that correspond to that year. Nar Gölü is
108 particularly useful for such an exercise because the sediment record is annually laminated
109 (varved). We have therefore been able to correlate, with high precision, monitoring and
110 instrumental climate data to palaeo-limnological information from the sediment cores over
111 the same period.

112 The study lake was subject to a progressive water level decrease between 2000 and
113 2010. We examine how this change in lake water balance was registered by different hydro-
114 chemical and biological parameters over time, and how they were subsequently incorporated
115 in the contemporaneous lake sediment record. Some neo-limnological data from Nar Gölü
116 have been previously published: Jones et al. (2005) compared modelled and measured $\delta^{18}\text{O}$
117 results (using water isotope data from 1999-2002) and Woodbridge and Roberts (2010)
118 examined diatom assemblage data (with contemporary samples taken 2002-2007). Here we
119 present new water isotope and chemistry data to extend the record up to 2014 and new
120 sediment isotope and diatom assemblage data to bring the record up to 2010. With this longer
121 time series of monitoring data, we build on these previous studies and aim to: (1) establish
122 the general physical, isotopic and geochemical characteristics of the lake, (2) scrutinise intra-
123 annual trends in lake water chemistry and $\delta^{18}\text{O}_{\text{lakewater}}$ to understand the seasonal variability of
124 the system, (3) compare inter-annual variability in lake water chemistry and $\delta^{18}\text{O}_{\text{lakewater}}$ to
125 physical and climate variables in order to test the drivers of the record, and (4) compare these
126 data to isotopic, biological and geochemical proxies from the sediment record. The analysis
127 of modern limnology and the tracking of signals from the lake water to sediments from the
128 last decade allow us to assess critically individual palaeo-limnological proxies at Nar Gölü,

129 ultimately to better interpret the long-term sediment record of Holocene hydro-climatic
130 change (e.g. Jones et al., 2006; Woodbridge and Roberts, 2011; Yiğitbaşıoğlu et al., in press).

131

132 **2. Site description**

133

134 Nar Gölü (38°20'24"N, 34°27'23"E; 1,363 m.a.s.l.) is a small (~0.7 km²) but relatively deep
135 (>20 m) maar lake in Cappadocia, central Turkey (Figure 1). It is oligosaline, alkaline and
136 predominately groundwater-fed, with a residence time of 8-11 years (Jones et al. 2005;
137 Woodbridge and Roberts, 2010). The crater geology is predominately basalt and ignimbrite
138 (Gevrek and Kazancı, 2000). Nar Gölü lacks any surface outflow. At its southern edge there
139 are a series of small inflowing ephemeral stream channels forming an alluvial fan, and the
140 bathymetric map (Figure 1) shows that this extends into the lake as a fan-delta.

141 The climate of the region is continental Mediterranean (Kutiel and Türkeş, 2005) with
142 annual precipitation at Niğde, 45 km from Nar Gölü and 1,208 m.a.s.l., averaging 339 mm
143 from 1935 to 2010. Mean monthly temperatures 1935-2010 varied from an average of +23°C
144 in July and August to +0.7°C from December to February (see Dean et al., 2013 for more
145 detailed regional climate data).

146 Although the lake watershed contains no permanent dwellings and only a few
147 agricultural fields, Nar Gölü has not entirely escaped human impact. Firstly, groundwater
148 pumping for irrigation in the valley below the lake is likely to have steepened the hydraulic
149 gradient in recent decades, possibly increasing groundwater outflows from the lake.
150 Secondly, in 1990 the Turkish Geological Survey (MTA) drilled boreholes near to the lake to
151 reach artesian geothermal groundwaters (Akbaşlı, 1992). Oral testimony indicates that one of
152 these drill holes significantly disturbed lake hydrology and ecology (potentially including a
153 breakdown in lake stratification and a decrease in the population of aquatic macrophytes),

154 probably for several years, for which there is some evidence in lake sediment cores.
155 Consequently, and given the lake residence time, we restrict our analysis of changing lake
156 conditions to the period since 1997.

157

158 Figure 1

159

160 **3. Materials and methods**

161

162 3.1 Fieldwork

163

164 Water samples were collected from the lake during 22 field visits between 1997 and 2014.

165 When conditions permitted, depth profiles were taken from the deepest part of the lake
166 through the water column using a Van Dorn bottle (Van Dorn, 1956) or a Glew corer (Glew
167 et al., 2001) with temperature, pH and EC measured at the time on a Myron ® meter.

168 Maximum lake depths were estimated using a Garmin Fish Finder ® and a weighted tape and
169 checked against water level stage readings at the lake edge when possible. Bathymetry was
170 measured using a Boomer system coupled with a high precision GPS, based on 53 transect
171 lines north-south and east-west (Smith, 2010), in order to identify a suitable coring site.

172 Samples were taken for isotope and major ion analysis in the UK. Surface water samples
173 were taken in bottles initially washed three times in the sample, at 0.5 m depth to remove any
174 direct effects of exchange with the atmosphere. Where it was not possible to go out on the
175 lake, surface samples were taken from the same spot on the edge of the lake. Edge samples
176 were also taken by members of the local community between February and June 2012, as
177 well as a photo diary that allowed us to establish when snowmelt occurred that year (SI
178 Figure 1). Spring waters from the catchment (Figure 1) were also regularly sampled.

179 Simple sediment traps, consisting of cylindrical plastic tubes under funnels, were
180 attached at a variety of depths onto ropes that were secured with an anchor on the lake bed
181 and a float on the surface and replaced every year. Since 2010, Tinytag ® temperature
182 loggers have been attached to the sediment trap lines at a number of depths through the water
183 column. These provide temperature measurements at 20-minute intervals throughout the year.

184 A 44 cm long sediment core, which covers all but the last few years of the period of
185 lake water monitoring, was taken in 2010 (NAR10) using a weighted stationary piston corer,
186 another having been taken with a Glew corer (36 cm) in 2006 (NAR06). Longer cores
187 spanning 1,720 years were taken in 2001/2 (NAR01/02).

188

189 3.2 Laboratory analyses

190

191 Water samples were analysed for $\delta^{18}\text{O}$ and δD on a VG Isoprime mass spectrometer and a
192 EuroPyrOH analyser. Isotopic ratios are given as ‰ deviations from VSMOW, and analytical
193 reproducibility was 0.05‰ for $\delta^{18}\text{O}$ and 2‰ for δD . Major ion concentrations were measured
194 on water samples as soon as possible after returning from the field on a Metrohm ion
195 chromatography system. Data were converted from milligrams/litre to milliequivalents/litre
196 (meqL^{-1}) (Hem, 1970).

197 Carbonates from sediment traps and core sediments were analysed for $\delta^{18}\text{O}$ using an
198 offline extraction technique and a VG Optima mass spectrometer and data are given as ‰
199 deviations from VPDB, with an analytical reproducibility of 0.1‰. Carbonate mineralogy
200 was investigated by X-ray diffraction. The scanning range used was $5\text{-}65^\circ 2\theta$ and the scan
201 rate was $2^\circ 2\theta$ per minute with a step size of 0.05. The TRACES program by Diffraction
202 Technology was used to identify which minerals were present. Where two or more minerals
203 were present, the proportions of each were determined by calculating the area under the peaks

204 and the percentage of aragonite compared to calcite was estimated from experimentally
 205 calibrated conversion curves (Hardy and Tucker, 1988).

206 X-ray fluorescence (XRF) analysis of elemental sediment chemistry was carried out
 207 on split half cores by a field portable XRF spectrometer, which produces one single
 208 dispersive energy spectra for each 3 mm sampling point on the core surface, with data in
 209 parts per million.

210 Diatom samples were prepared using standard methods adapted from Battarbee et al.
 211 (2001), described in detail in Woodbridge and Roberts (2010).

212

213 3.3 Numerical analyses

214

215 To model aragonite precipitation dynamics in Nar Gölü, the palaeo-temperature equation of
 216 Kim et al. (2007) is used:

217

$$218 \quad T = (17.88 * 1000) / (1000 * \text{LN}((1000 + \delta^{18}\text{O}_{\text{aragonite}}) / (1000 + \delta^{18}\text{O}_{\text{lakewater}})) + 30.77) - 273.15 \quad (1)$$

219

220 where $\delta^{18}\text{O}_{\text{aragonite}}$ and $\delta^{18}\text{O}_{\text{lakewater}}$ are expressed against VSMOW and T in °C.

221

222 To model calcite precipitation dynamics, the palaeo-temperature equation of Hays and
 223 Grossman (1991) is used:

224

$$225 \quad T = 15.7 - 4.36 * (\delta^{18}\text{O}_{\text{calcite}} - \delta^{18}\text{O}_{\text{lakewater}}) + 0.12 * (\delta^{18}\text{O}_{\text{calcite}} - \delta^{18}\text{O}_{\text{lakewater}})^2 \quad (2)$$

226

227 where $\delta^{18}\text{O}_{\text{calcite}}$ is expressed against VPDB, $\delta^{18}\text{O}_{\text{lakewater}}$ against VSMOW and T in °C.

228

229 Diatom data have been used to infer EC using a combined salinity training set
230 (comprising data from East Africa, North Africa and Spain) provided by the European
231 Diatom Database (EDDI) (Juggins, 2014). Training sets and models were selected based on
232 the percentage of fossil sample species represented in the modern data set, the number of sites
233 in which these species are present and the model performance (r and RMSEP), and the
234 models were run using C2 software (Juggins, 2003). The combined salinity EDDI modern
235 training set was identified as possessing the highest number of matching analogue diatom
236 species in the Nar Gölü fossil assemblage (74.4%; species not in the training set include
237 *Clupeoparvus anatolicus*, a species endemic to Nar Gölü; Woodbridge et al., 2010). Weighted
238 averaging with inverse deshrinking was identified as the model with highest predictive ability
239 ($r=0.85$) and lowest prediction errors (RMSEP = 0.47). Detrended Correspondence Analysis
240 (DCA) was also applied to the diatom percentage data because the length of the axis was >2
241 units (Lepš and Šmilauer, 2003).

242 Monthly instrumental meteorological data from a nearby station at Niğde (155 m
243 altitudinal difference, 45 km from Nar Gölü) have been used to create a hydro-climatic index
244 of moisture availability (precipitation/evaporation; P/E). Because of the 8-10 year residence
245 time of the lake water (Jones et al., 2005), we calculated a cumulative weighted 8-year P/E
246 index.

247

248 **4. Results**

249

250 4.1 Basic limnological and sedimentological information

251

252 EC and major ion data show that the lake is oligosaline, with a mean conductivity value over
253 the past 15 years of $3,270 \mu\text{Scm}^{-1}$ (Tables 1 and 2) and $\delta^{18}\text{O}_{\text{lakewater}}$ values that are higher than

254 freshwater $\delta^{18}\text{O}_{\text{spring}}$ values (Figure 2), indicating that the lake waters are evaporated relative
255 to spring waters. A former lake high-stand is evident from carbonate-encrusted rocks and
256 strandline deposits, surveyed at 5 m above the 2010 water level, or 2 m above the lake
257 elevation in 2000, and provides physical evidence of the tendency of the lake level to
258 fluctuate. The sediments of Nar Gölü comprise alternating organic and carbonate layers
259 (varves; Ojala et al., 2012), with an organic and carbonate couplet shown to represent one
260 year of sedimentation based on analysis of sediment traps, thin sections and independent
261 dating of the sediment cores by ^{210}Pb and ^{137}Cs (Jones et al., 2005; Woodbridge and Roberts,
262 2010).

263

264 Figure 2

265

266 Tables 1 and 2

267

268 4.2 Intra-annual variability

269

270 Figure 3 shows the intra-annual variability in water chemistry from samples taken
271 between June 2011 and July 2012. Within the data available, $\delta^{18}\text{O}_{\text{lakewater}}$ values peak at –
272 0.13‰ in mid-September 2011 before falling to –1.76‰ in mid-March 2012 and then
273 increasing to –0.39‰ in mid-July 2012. EC values also peak in mid-September 2011 at 3,540
274 μScm^{-1} , before decreasing to 2,190 μScm^{-1} in late February 2012 (when there was heavy
275 snowfall and partial lake icing) and increasing again to 3,500 μScm^{-1} by July 2012. pH values
276 decreased from 8.1 in June 2011 to 7.3 in February 2012 before increasing to 8.0 by June
277 2012. Magnesium concentrations decreased from 9.3 meqL^{-1} in September 2011 to a
278 minimum of 3.2 meqL^{-1} in late February 2012 and then increased to 16.5 meqL^{-1} by July

279 2012, whereas calcium concentrations showed the opposite trend, shifting from 2.2 meqL⁻¹ in
280 June 2011 to 4.0 meqL⁻¹ in late February 2012 to 1.2 meqL⁻¹ in July 2012.

281 Because the lake is monomictic, depth profiles, as well as surface samples, were
282 taken. In the summer, the waters of Nar Gölü are thermally and isotopically stratified, with
283 warmer and isotopically more positive waters in the epilimnion, followed by a shift at ~7 m
284 to colder and isotopically more negative values in the hypolimnion (Figure 4). The degree of
285 stratification becomes more pronounced from the spring to summer. While no depth profiles
286 were taken during the autumn or winter at Nar Gölü, temperature loggers show that the lake
287 is thermally mixed between November and March, with the same temperatures at 5 m and 21
288 m during the winter and then diverging in the spring (Figure 3 for 2011-12, but also observed
289 for other years; Eastwood et al., unpublished data).

290

291 Figure 3

292

293 Figure 4

294

295 4.3 Inter-annual trends

296

297 When considering inter-annual trends, samples collected from the same time of year
298 over multiple years are used to remove possible issues caused by the significant intra-annual
299 variability in the system presented in section 4.2. July is the month for which most data are
300 available. Samples from the lake centre are considered most representative of overall lake
301 conditions, because shallow water edge samples may be more affected by evaporation,
302 particularly in summer months. Nonetheless, the difference between centre and edge
303 $\delta^{18}\text{O}_{\text{lakewater}}$ samples is only $\pm 0.3\text{‰}$ (1σ , $n=4$) in years where both were taken, which is small

304 considering the size of the inter-annual isotopic shifts seen in the record. Therefore, edge
305 samples from 2000 and 2005 have been combined with centre samples from other years to
306 provide a more complete record. As Figure 5 shows, $\delta^{18}\text{O}_{\text{lakewater}}$ values increased from –
307 3.20‰ in July 2000 to –0.24‰ in July 2010. Over this period, the lake level fell by
308 approximately 3 m and lake water volume shrank by ~20%. Measured July surface EC values
309 increased from 3,300 μScm^{-1} in 2001 to 3,500 μScm^{-1} in 2012 (Figure 5), while lake surface
310 pH from the same month rose from ~7.5 in 2001 to >8 in 2008, before declining to 7.8 by
311 2012 (Table 1).

312 The $\delta^{18}\text{O}_{\text{lakewater}}$ increase for the period 2000-2010 was matched by an increase in
313 sediment core $\delta^{18}\text{O}_{\text{carbonate}}$ values from –3.7‰ to –0.5‰. There is a close relationship between
314 sediment trap and core $\delta^{18}\text{O}_{\text{carbonate}}$ values from the same years, with both showing an increase
315 over the period of study (Figure 5). Sediment trap samples collected from different depths in
316 the same years (2002 and 2004) have $\delta^{18}\text{O}_{\text{carbonate}}$ values that are the same within analytical
317 reproducibility. There are small differences between sediment trap and core $\delta^{18}\text{O}_{\text{carbonate}}$
318 values from 2003, 2004 and 2005 but the trends are the same in both data sets. Between 2006
319 and 2007 there was a start of a trend towards a reduction in the Ca/Sr ratio and a shift from
320 calcite to aragonite in lake sediment carbonates (Figure 5).

321

322 Figure 5

323

324 EC inferred from sedimentary diatom assemblages (diatom-inferred electrical
325 conductivity; DI-EC) underestimates modern measured lake EC (Figure 6) (reasons for this
326 will be proposed in sections 5.2 and 5.3, partly related to the fact *C. anaticus* is not
327 included in the modern training set), but DI-EC trends do broadly match those from
328 measurements taken during the monitoring period. A change in sedimentary diatom

329 assemblages began earlier than the DI-EC increase, with *C. anaticus* and *Synedra acus*
330 replacing *Nitzschia paleacea* as the dominant taxa after 2001 (Figure 6).

331

332 Figure 6

333

334 The closest meteorological station to Nar Gölü with a long-term data set is at Niğde.
335 Annual precipitation in this area was at or below the long-term average (339 mm) from 1997
336 to 2008, with the exception of 2001. In addition, the 1990s saw a significant ($>3^{\circ}\text{C}$) rise in
337 average summer temperatures (Turkish State Meteorological Service, pers. comm).

338

339 5. Discussion

340

341 5.1 Intra-annual variability at Nar Gölü

342

343 The seasonal variability in surface water $\delta^{18}\text{O}$ and conductivity shown in Figure 3 can be
344 explained by two main factors. Firstly, the water in the lake as a whole has lower $\delta^{18}\text{O}$ in the
345 autumn, winter and spring, as these are the main seasons for rainfall and snowfall, input of
346 which will lower $\delta^{18}\text{O}_{\text{lakewater}}$ (Dean et al., 2013). Although not quantified, observational data
347 show that lake levels were visibly higher in the spring than during the following summers.
348 $\delta^{18}\text{O}_{\text{lakewater}}$ in 2012 was lowest in mid-March and the photo diary (SI Figure 1) shows this
349 was the time in that year of snowmelt from the catchment. Rainfall is also greatest in the
350 spring (Kutiel and Türkeş, 2005). Secondly, stratification of lake waters in the summer leads
351 to more positive $\delta^{18}\text{O}$ values in surface waters than at depth because the hypolimnion is
352 unaffected by evaporative processes. Comparison of the depth profiles from April, June, July
353 and September (Figure 4) show that the isocline becomes more enhanced as the year

354 progresses, with a 1.00‰ difference between surface and bottom water $\delta^{18}\text{O}$ values in
355 September 2011 compared to a 0.75‰ difference in July 2010, 0.24‰ in June 2011 and
356 0.23‰ in April 2013.

357 Given the seasonal variability in $\delta^{18}\text{O}_{\text{lakewater}}$, we need to establish the timing of
358 carbonate precipitation to allow for proper interpretation of the palaeo-record. Carbonate
359 precipitation in surface waters is demonstrated by the observation that sediment traps at 5 m
360 depth are encrusted in carbonate when changed each year, whereas deeper ones are not.
361 Variability in $\delta^{18}\text{O}_{\text{carbonate}}$ with depth in one of the sediment traps suggests carbonate
362 precipitation under changing temperatures and/or $\delta^{18}\text{O}_{\text{lakewater}}$ (Figure 7), i.e. that carbonate
363 precipitation occurs at different times of the year. However, $\delta^{18}\text{O}_{\text{carbonate}}$ measured in the
364 sediment record from a whole-year varve will be weighted towards the time of maximum
365 precipitation. Observations suggest this occurs between May and early July. Firstly, in July,
366 calcium values at the surface are lower than at depth, suggesting draw-down of calcium
367 carbonate from the surface waters (Reimer et al., 2009), whereas in April 2013 calcium
368 concentration was still higher in surface waters than at depth, suggesting this draw-down had
369 yet to occur (Table 2). Secondly, analysis of the stratigraphy of Nar Gölü sediment traps
370 collected in July shows carbonate deposited on top of organic matter, while sediment traps
371 collected in April show organic matter on top of carbonate (Figure 8), suggesting that the
372 carbonate for that year had yet to precipitate.

373

374 Figure 7

375

376 Figure 8

377

378 Additionally, it is possible to run Eqs. 1 and 2 using various $\delta^{18}\text{O}_{\text{lakewater}}$ and
379 temperature scenarios, and then to compare the calculated equilibrium $\delta^{18}\text{O}_{\text{carbonate}}$ values
380 from these equations to measured $\delta^{18}\text{O}_{\text{carbonate}}$ from the sediment core. By seeing where the
381 calculated values match the measured values, it is possible to investigate better the timing of
382 carbonate precipitation. Before doing this, equilibrium precipitation and a lack of diagenetic
383 effects need to be demonstrated. It is not unknown for carbonate to precipitate out of
384 equilibrium with lake waters (Fronval et al., 1995; Teranes et al., 1999). During the July 2012
385 field season, carbonate in the form of aragonite was seen precipitating from the waters in a
386 ‘white-out’ event (as seen in other lakes; Romero-Viana et al., 2008; Sondi and Juracic, 2010;
387 Viehberg et al., 2012) around the edges of the lake (SI Figure 2). Comparison of the
388 $\delta^{18}\text{O}_{\text{carbonate}}$ value from this aragonite precipitate (-1.3‰) to the $\delta^{18}\text{O}_{\text{carbonate}}$ value predicted
389 using Eq. 1 (-1.8‰ , using the $\delta^{18}\text{O}_{\text{lakewater}}$ (-0.39‰) and temperature ($+25.6^\circ\text{C}$) values
390 measured from a water sample taken at the same time), show that it formed in equilibrium
391 within analytical and equation error. Diagenesis may alter the carbonate isotope signal
392 between precipitation and deposition (Teranes and Bernasconi, 2000). However, at Nar Gölü,
393 there are only small differences between the $\delta^{18}\text{O}_{\text{carbonate}}$ values of trap and core sediments
394 from the same year (Figure 5) and the inter-annual trends are very similar, which suggests
395 minimal alteration of the $\delta^{18}\text{O}_{\text{carbonate}}$ signal during and after deposition.

396 Based on the observations already outlined, we assume that most carbonate is
397 precipitated sometime after April but before the end of July and in surface waters. Therefore,
398 we use likely surface water temperature and $\delta^{18}\text{O}_{\text{lakewater}}$ values from May to July to calculate
399 potential $\delta^{18}\text{O}_{\text{carbonate}}$ values. Temperatures vary from year to year, but temperature loggers
400 suggest temperatures change from $\sim+12.5^\circ\text{C}$ in the beginning of May to $\sim+17.5^\circ\text{C}$ in mid-
401 June to $\sim+20.0^\circ\text{C}$ in the beginning of July to $\sim+22.5^\circ\text{C}$ in mid-July (Figure 3). Consequently,
402 temperatures ranging from $+12.5^\circ\text{C}$ to $+22.5^\circ\text{C}$ and $\delta^{18}\text{O}_{\text{lakewater}}$ at 0.2‰ intervals from the

403 measured July values for individual years are used. Varves from 2001-2006 were composed
404 of calcite, whereas varves from 2007-2010 were >75% aragonite, so Eqs. 2 and 1 were used
405 respectively. In the majority of years, at $\sim +20^{\circ}\text{C}$ and a $\delta^{18}\text{O}_{\text{lakewater}}$ value from July, or 0.2‰
406 lower, the measured $\delta^{18}\text{O}_{\text{carbonate}}$ values match the $\delta^{18}\text{O}_{\text{carbonate}}$ predicted from the equations
407 (Figure 9). These temperature and $\delta^{18}\text{O}_{\text{lakewater}}$ values are both representative of conditions
408 around the end of June and the beginning of July, suggesting carbonate precipitation peaks at
409 this time and that $\delta^{18}\text{O}_{\text{carbonate}}$ in the sediment record should reflect $\delta^{18}\text{O}_{\text{lakewater}}$ at these times.

410

411 Figure 9

412

413 5.2 Inter-annual trends at Nar Gölü

414

415 Nar Gölü experienced a period of falling lake levels between 2000 and 2010. It is possible
416 that this was partly caused by depletion of regional groundwater levels and steepening of the
417 hydraulic gradient north of the lake watershed. The lake may also be recovering from
418 groundwater disturbance due to the drilling of the borehole in 1990. Additionally, climate
419 changes will have had a significant control on water balance through this period. Based on
420 the climate data given in section 4.3, the combination of less precipitation and hotter
421 summers 1997-2008 would have reduced direct precipitation and shallow groundwater inflow
422 and increased water losses through evaporation from the lake surface. The cumulative
423 weighted 8-year P/E index from Niğde reached maximum values in 1997, decreasing to a
424 minimum in 2005-2008 (Figure 5) (matched by the lake level decrease of ~ 3 m) and then rose
425 again in 2009 and 2010 (at which time the lake level stabilised). Whatever the precise causes
426 of the observed lake-level fall (climate and/or pumping of groundwater), the results show that
427 this is reflected in the monitoring and sedimentary record. There are close parallels with

428 monitoring studies of lakes Mogan and Eymir on the edge of Ankara (Özen et al., 2010).
429 Although these two lakes have been impacted by nutrient pollution and other human actions,
430 they also showed a very clear hydrological response to the same drought conditions recorded
431 at Nar Gölü, from 2004 to 2007, demonstrating a region-wide hydrological response of lake
432 ecosystems to climatic forcing. Our monitoring shows that decreasing water levels of Nar
433 Gölü between 2000 and 2010 were associated with an increase in $\delta^{18}\text{O}_{\text{lakewater}}$ of $\sim 3\text{‰}$ and in
434 lake surface water EC of $\sim 600 \mu\text{Scm}^{-1}$ (although more EC measurements in the early 2000s
435 would have been required to clarify that there was indeed a period of low EC at this time).

436 Changes in $\delta^{18}\text{O}_{\text{lakewater}}$ are generally driven by changes in $\delta^{18}\text{O}_{\text{precipitation}}$ and/or
437 modification by evaporation within-lake (Leng and Marshall, 2004 and references therein).
438 Here, $\delta^{18}\text{O}_{\text{spring}}$ values are seen to represent local precipitation since they plot on the meteoric
439 water line (Figure 2) and have remained more or less stable over the study period (Table 1),
440 indicating that changes in $\delta^{18}\text{O}_{\text{precipitation}}$ could not be driving the increase in $\delta^{18}\text{O}_{\text{lakewater}}$.
441 Rather, the strong relationship between $\delta^{18}\text{O}_{\text{lakewater}}$ and lake depth (Figure 5) adds weight to
442 the suggestion that $\delta^{18}\text{O}_{\text{lakewater}}$ trends are driven by changing water balance (e.g. Jones et al.,
443 2005).

444 To observe how this signal has been transferred to the palaeo-limnological record,
445 isotopic, geochemical and biological proxies have been analysed for individual lake varves
446 from short sediment cores. There is a good match between changes in hydro-climate, lake
447 depth and the $\delta^{18}\text{O}_{\text{carbonate}}$ record (Figure 5). Equilibrium precipitation and a lack of diagenetic
448 effects have already been demonstrated (section 5.1). Assuming there is always equilibrium
449 precipitation and diagenesis never significantly alters the isotope signal, two factors should
450 control $\delta^{18}\text{O}_{\text{carbonate}}$: $\delta^{18}\text{O}_{\text{lakewater}}$ and the temperature-dependent carbonate-water fractionation
451 effect. The very strong, positive relationship between $\delta^{18}\text{O}_{\text{lakewater}}$ and $\delta^{18}\text{O}_{\text{carbonate}}$ ($r=+0.99$,
452 $n=8$, $p<0.005$) and the weighting of carbonate precipitation to the summer months indicates

453 that $\delta^{18}\text{O}_{\text{lakewater}}$ (as we have shown, itself driven by water balance) is the key driver of
454 $\delta^{18}\text{O}_{\text{carbonate}}$.

455 There is evidence of an increase in the summer Mg/Ca ratio (Table 2), caused by
456 concentration of magnesium due to evaporation and loss of calcium by precipitation of
457 calcium carbonate (Kelts and Talbot, 1990). There was also a shift in the sediment core from
458 calcite precipitation 1997-2006 to mostly aragonite precipitation 2007-2010. Shifts from
459 calcite to aragonite precipitation may be associated with an increase in the Mg/Ca ratio of
460 lake water (Müller et al., 1972; Kelts and Hsü, 1978; Ito, 2001), which favours the
461 precipitation of aragonite over calcite (Berner, 1975; De Choudens-Sanchez and Gonzalez,
462 2009). At Nar Gölü, the recent switch from calcite to aragonite precipitation and the decrease
463 in the Ca/Sr ratio (Figure 5) (Tesoriero and Pankow, 1996) supports the interpretation of
464 these proxies as indicative of a negative hydrological trend. Of note, in comparison to the
465 $\delta^{18}\text{O}_{\text{carbonate}}$ trends, there is a threshold response from calcite to aragonite.

466 Comparison of measured EC with DI-EC shows similar overall trends, but there is an
467 offset in absolute values (Figure 6). The intra-annual data provide a partial explanation as to
468 why DI-EC is lower than measured EC in Nar Gölü. Whereas the EC measurements shown
469 on Figure 6 were taken in July, much of the diatom growth is believed to occur earlier in the
470 year, when EC is substantially lower (Figure 3). The availability of measured EC data
471 unfortunately do not allow us to observe the actual nature of the inferred shift in conductivity
472 post 2006, in terms of timing and rate. Some individual diatom species change earlier than
473 the shift in the DI-EC record, albeit at a gradual rate, for example *C. anatolicus*. The
474 observed trends in diatom assemblages may indicate a response to controls other than
475 conductivity and/or salinity, for example changing lake habitat availability (Barker et al.,
476 1994), and care must be taken when using such biological indicators as a proxy of mean
477 annual conductivity (Juggins, 2013). An increase in marginal environments as lake-levels

478 fall, for example, may explain increases in periphytic taxa such as *A. minutissimum*
479 (Woodbridge and Roberts, 2011) and/or a change in seasonal mixing regime during the
480 period of lake-level decrease.

481 In summary, there is a correspondence through the 2000s between measured
482 hydrological parameters on the one hand, and lake chemistry and hydro-biology
483 reconstructed from sedimentary proxy data on the other, although parameters show different
484 responses in terms of type (threshold vs. linear) and sensitivity to change. The P/E ratio was
485 highest (most positive water balance) in 1997, with a marked decline after 2003, ending in
486 2008. The lake-level decline ended in 2010. $\delta^{18}\text{O}_{\text{lakewater}}$ and EC show a rise through the
487 2000s with the former stabilising after 2008 in a similar way to the P/E trend (Figure 5). The
488 shift to higher $\delta^{18}\text{O}_{\text{carbonate}}$ from 2000 also starts to slow after 2008. In contrast, carbonate
489 mineralogy and Ca/Sr data show threshold responses and DI-EC shows a less clear trend than
490 $\delta^{18}\text{O}_{\text{carbonate}}$, although changes are more linear when looking at the abundance of individual
491 diatom species.

492

493 5.3 Implications for the interpretation of palaeo-records

494

495 Monitoring work as described here is primarily carried out to improve interpretations of long-
496 term palaeo-hydrological records, such as those previously published from this site (Jones et
497 al., 2006; Woodbridge and Roberts, 2011; Dean et al., 2013). In the case of Nar Gölü, the
498 magnitude of the variability in $\delta^{18}\text{O}_{\text{carbonate}}$ and DI-EC recorded through the monitoring period
499 covers much of the variability seen in $\delta^{18}\text{O}_{\text{carbonate}}$ and DI-EC over the last 1,720 years (shown
500 by the shaded boxes on Figure 10).

501

502 Figure 10

503
504 Viewing the monitored changes within the longer-term context of the palaeo-record
505 highlights a number of points of interest. There is a relative lack of response in the DI-EC
506 record compared to $\delta^{18}\text{O}_{\text{carbonate}}$ data (Jones et al., 2006) through most of the record. In
507 contrast, changes in diatom assemblages, reflected by the diatom zonation (derived by
508 stratigraphically-constrained cluster analysis; Woodbridge and Roberts, 2011), do correlate
509 well with shifts in $\delta^{18}\text{O}$ (Figure 10), with *Achnanthydium minutissimum* increasing at
510 AD1400, showing the same relationship as observed through the monitoring period. This
511 shift in diatom species does not significantly alter the DI-EC reconstruction, potentially
512 because *A. minutissimum* and other non-planktonic species respond to habitat availability as
513 well as to EC in this system. The strength of the DI-EC reconstruction is also reduced by the
514 lack of environmental knowledge about *Clipeoparvus anatolicus*, a dominant species in the
515 assemblage, but a newly described species from Nar Gölü (Woodbridge et al., 2010), which
516 is not included in the modern training set. The ordination of diatom taxa via DCA provides a
517 summary representation of species changes at Nar Gölü. The DCA axis 1 score does,
518 however, show a pattern similar to the DI-EC, only showing significant changes around
519 AD500 as *Cyclotella meneghiniana* and *Staurosira construens* var *venter* are replaced by an
520 assemblage dominated by *N. paleacea* (Woodbridge and Roberts, 2011). DCA axis 2 records
521 change around AD1400 as *A. minutissimum* and *Synedra acus* become more dominant in the
522 record (Figure 10).

523 The lake monitoring described here, in conjunction with a multiproxy record of past
524 hydro-climatic change, substantially reduces the possibility of interpretive errors of the
525 palaeo-record. Our monitoring data, and the discussion of the DI-EC here and in Woodbridge
526 and Roberts (2011), suggest that care is needed when using the DI-EC reconstruction in terms
527 of absolute values of conductivity change. By superimposing the range of variability in

528 different proxies during the period of lake monitoring with that shown in the palaeo-record, it
529 is also possible to identify which periods in the past potentially lack a modern analogue. The
530 similarity between the shifts in the monitoring period and at AD1400 now allows partial
531 quantification of this change. Although there is no direct analogue of the changes at AD500,
532 the record points to a lake-level increase, associated with a shift in the diatom assemblage,
533 with a magnitude that was larger than changes in the reverse direction ~AD1400 (Figure 10)
534 and that observed in recent times.

535

536 **6. Conclusions**

537

538 Using the example of Nar Gölü, we have highlighted how monitoring data can be used to test
539 assumptions and to help produce more robust interpretations of the sediment record, although
540 our findings could be tested further by a larger dataset based on multiple annual
541 measurements. Due to the varved nature of the sediments, it has been possible to compare
542 $\delta^{18}\text{O}$ from core sediments to $\delta^{18}\text{O}$ from trap sediments to $\delta^{18}\text{O}$ from water samples from
543 specific years. While Nar Gölü is a non-outlet lake in a semi-arid region and therefore
544 $\delta^{18}\text{O}_{\text{lakewater}}$ is likely to reflect water balance, monitoring is still vital to test this and to assess
545 the response rate and magnitude of the different palaeo-hydrological proxies. The strong
546 relationship between $\delta^{18}\text{O}_{\text{carbonate}}$, $\delta^{18}\text{O}_{\text{lakewater}}$ and changes in lake depth, and the apparent
547 equilibrium precipitation of the carbonate, indicate that $\delta^{18}\text{O}_{\text{carbonate}}$ at Nar Gölü is likely to
548 provide a reliable indicator of regional hydro-climatic change over longer time periods.
549 Based on modern response times, $\delta^{18}\text{O}$ can offer a hydro-climatic signal of decadal-scale
550 resolution at this lake. Other palaeo-hydrological proxies, including DI-EC and carbonate
551 mineralogy, exhibit more complex or less easily quantified responses to changes in water
552 balance, with a less linear response between climate change and proxy records. However,

553 these proxies offer complementary data, which provide a cross-check when conducting
554 palaeo-hydrological reconstructions.

555 In the ‘natural laboratory’ that is offered by Nar Gölü, conditions make it possible to
556 critically test the chain of connection from present to past, and from the lake waters to the
557 palaeo-record. Our analyses link together the timescales of monitoring and observation on the
558 one hand, with those of palaeo-hydrological reconstruction on the other. The conclusions
559 drawn from this study are site-specific, and in other lakes other proxies may exhibit the
560 clearest relationship to hydro-climate. Nonetheless, our analysis does provide a critical test of
561 causal relationships that are often assumed, rather than demonstrated, to be the case.

562

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564

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587

588 **References**

589

590 Akbaşlı, A (1992) Nigde-Sofular Acigol (Narligol) sicak su sondajlari (Nar-1, MTA-1, MTA-
591 2, MTA-3) kutu bitirme raporu. MTA Rapor Arsivi no 9407, Ankara

592 Barker, PA, Roberts, N, Lamb, HF, van der Kaars, S, Benkaddour, A (1994) Interpretation of
593 lake-level change from diatom life form in Lake Sidi Ali, Morocco. *J Paleolimnol* 12:
594 223-234

595 Battarbee, RW, Jones, VJ, Flower, RJ, Cameron, NG, Bennion, H (2001) Cht 8: Diatoms. In:
596 Smol, J (ed) (2001) *Tracking Environmental Change Using Lake Sediments, Vol 3:*
597 *Terrestrial, Algal and Siliceous Indicators.* Kluwer Academic Publishers, Netherlands.
598 155-202

599 Berner, RA (1975) The role of magnesium in the crystal growth of calcite and aragonite from
600 sea water. *Geochim Cosmochim Ac* 39: 489-504

- 601 De Choudens-Sanchez, V, Gonzalez, LA (2009) Calcite and aragonite precipitation under
602 controlled instantaneous supersaturation: elucidating the role of CaCO₃ saturation state
603 and Mg/Ca Ratio on calcium carbonate polymorphism. *J Sediment Res* 79: 363-376
- 604 Dean, JR, Jones, MD, Leng, MJ, Sloane, HJ, Roberts, CN, Woodbridge, J, Swann, GEA,
605 Metcalfe, SE, Eastwood, WJ, Yiğitbaşıoğlu, H (2013) Palaeo-seasonality of the last two
606 millennia reconstructed from the oxygen isotope composition of carbonates and diatom
607 silica from Nar Gölü, central Turkey. *Quaternary Sci Rev* 66: 35-44
- 608 Fritz, SC (2008) Deciphering climatic history from lake sediments. *J Paleolimnol* 39: 5-16
- 609 Fritz SC, Cumming BF, Gasse F, Laird K (2010) Diatoms as indicators of hydrologic and
610 climatic change in saline lakes. In: Stoermer EF, Smol JP (eds) *The Diatoms:
611 Applications for the Environmental and Earth Sciences*. Cambridge University Press,
612 Cambridge, pp 186-208
- 613 Fronval, T, Jensen, NB, Buchardt, B (1995) Oxygen-isotope disequilibrium precipitation of
614 calcite in Lake Arreso, Denmark. *Geology* 23: 463-466
- 615 Gevrek, A, Kazanci, N (2000) A Pleistocene, pyroclastic-poor maar from central Anatolia,
616 Turkey: influence of a local fault on a phreatomagmatic eruption. *J Volcanol Geotherm
617 Res* 95: 309-317
- 618 Glew, JR, Smol, JP, Last, WM (2001) Sediment core collection and extrusion. In: Last, WM,
619 Smol, JP (eds) *Tracking Environmental Change Using Lake Sediments. Volume 1: Basin
620 Analysis, Coring and Chronological Techniques*. Kluwer, Dordrecht, pp 73-105
- 621 Hardy, R, Tucker, M (1988) X-ray powder diffraction of sediment. In: Tucker M (ed)
622 *Techniques in Sedimentology*. Blackwell, Oxford, pp 191-228
- 623 Hays, PD, Grossman, EL (1991) Oxygen isotopes in meteoric calcite cements as indicators of
624 continental paleoclimate. *Geology* 19: 441-444

- 625 Hem, JD (1970) Study and Interpretation of the Chemical Characteristics of Natural Water.
626 United States Government Printing Office, Washington
- 627 Hollander, DJ, McKenzie, JA (1991) CO₂ control on carbon-isotope fractionation during
628 aqueous photosynthesis: a paleo-pCO₂ barometer. *Geology* 19: 929-932
- 629 IAEA/WMO (2014) Global Network of Isotopes in Precipitation. Available:
630 <http://www.iaea.org/water> Accessed: 4 January 2014
- 631 Ito, E (2001) Application of stable isotope techniques to inorganic and biogenic carbonates.
632 In: Last, WM, Smol, JP (eds) *Tracking Environmental Change Using Lake Sediments.*
633 *Volume 2: Physical and Geochemical Methods.* Kluwer, Dordrecht, pp 351-371
- 634 Jones, MD, Leng, MJ, Roberts, CN, Turkes, M, Moyeed, R (2005) A coupled calibration and
635 modelling approach to the understanding of dry-land lake oxygen isotope records. *J*
636 *Paleolimnol* 34: 391-411
- 637 Jones, MD, Roberts, CN, Leng, MJ, Turkes, M (2006) A high-resolution late Holocene lake
638 isotope record from Turkey and links to North Atlantic and monsoon climate. *Geology*
639 34: 361-364
- 640 Juggins, S (2003) C2 version 1.3: software for ecological and palaeoecological data analysis
641 and visulisation. Department of Geography, University of Newcastle.
- 642 Juggins, S (2013) Quantitative reconstructions in palaeolimnology: new paradigm or sick
643 science? *Quaternary Science Reviews* 64: 20-32
- 644 Juggins, S (2014) European Diatom Database Online. Available:
645 <http://craticula.ncl.ac.uk/Eddi/jsp/index.jsp> Accessed: 1 June 2014
- 646 Kelts, K, Hsü, J (1978) Freshwater carbonate sedimentation. In: Lerman, A (ed) *Lakes:*
647 *Geology, Chemistry and Physics.* Springer-Verlag, New York, pp 295-323

- 648 Kelts, K, Talbot, M (1990) Lacustrine carbonates as geochemical archives of environmental
649 change and biotic/abiotic interactions. In: Tilzer, M, Serruya, C (eds) Large Lakes:
650 Ecological Structure and Function. Springer-Verlag, Berlin, pp 288-315
- 651 Kim, ST, O'Neil, JR, Hillaire-Marcel, C, Mucci, A (2007) Oxygen isotope fractionation
652 between synthetic aragonite and water: influence of temperature and Mg²⁺
653 concentration. *Geochim Cosmochim Acta* 71: 4704-4715
- 654 Kutiel, H, Türkeş, M (2005) New evidence for the role of the North Sea-Caspian Pattern on
655 the temperature and precipitation regimes in continental Central Turkey. *Geogr Ann A*
656 87A: 501-513
- 657 Langbein, WB (1961) Salinity and hydrology of closed lakes. United States Geological
658 Survey professional paper. 412. US Government Printing Office, Washington
- 659 Leng, MJ, Marshall, JD (2004) Palaeoclimate interpretation of stable isotope data from lake
660 sediment archives. *Quaternary Sci Rev* 23: 811-831
- 661 Leng, MJ, Roberts, N, Reed, JM, Sloane, HJ (1999) Late Quaternary palaeohydrology of the
662 Konya Basin, Turkey, based on isotope studies of modern hydrology and lacustrine
663 carbonates. *J Paleolimnol* 22: 187-207.
- 664 Lepš, J, Šmilauer, P (2003) *Multivariate Analysis of Ecological Data Using CANOCO*.
665 Cambridge University Press, Cambridge
- 666 Magny, M (2006) Holocene fluctuations of lake levels in west-central Europe: methods of
667 reconstruction, regional pattern, palaeoclimatic significance and forcing factors.
668 *Encyclopedia of Quaternary Geology*, Elsevier, Vol. 2, pp 1389-1399
- 669 Müller, G, Forstner, U, Irion, G (1972) Formation and diagenesis of inorganic Ca-Mg
670 carbonates in lacustrine environment. *Naturwissenschaften* 59: 158-164
- 671 Ojala, AEK, Francus, P, Zolitschka, B, Besonen, M, Lamoureux, SF (2012) Characteristics of
672 sedimentary varve chronologies - a review. *Quaternary Sci Rev* 43: 45-60

- 673 Özen, A, Karapınar, B, Kucuk, I, Jeppeson, E, Beklioğlu, M (2010) Drought-induced changes
674 in nutrient concentrations and retention in two shallow Mediterranean lakes subjected to
675 different degrees of management. *Hydrobiologia* 646: 61-72
- 676 Reed, JM, Mesquita-Joanes, F, Griffiths, HI (2012) Multi-indicator conductivity transfer
677 functions for Quaternary palaeoclimate reconstruction. *J Paleolimnol* 47: 251-575
- 678 Reimer, A, Landmann, G, Kempe, S (2009) Lake Van, eastern Anatolia, hydrochemistry and
679 history. *Aquat Geochem* 15: 195-222
- 680 Romero-Viana, L, Julia, R, Camacho, A, Vicente, E, Miracle, MR (2008) Climate signal in
681 varve thickness: Lake La Cruz (Spain), a case study. *J Paleolimnol* 40: 703-714
- 682 Saros, JE (2009) Integrating neo- and palaeolimnological approaches to refine interpretations
683 of environmental change. *J Paleolimnol* 41: 243-252
- 684 Smith, R (2010) A Geophysical Survey of Nar Golu, Cappadocia, Turkey. MSc thesis,
685 Plymouth University.
- 686 Sondi, I, Juracic, M (2010) Whiting events and the formation of aragonite in Mediterranean
687 karstic marine lakes: new evidence on its biologically induced inorganic origin.
688 *Sedimentology* 57: 85-95
- 689 Teranes, JL, Bernasconi, SM (2000) The record of nitrate utilization and productivity
690 limitation provided by delta N-15 values in lake organic matter - a study of sediment trap
691 and core sediments from Baldeggersee, Switzerland. *Limnol Oceanogra* 45: 801-813
- 692 Teranes, JL, McKenzie, JA, Bernasconi, SM, Lotter, AF, Sturm, M (1999) A study of oxygen
693 isotopic fractionation during bio-induced calcite precipitation in eutrophic Baldeggersee,
694 Switzerland. *Geochim Cosmochim Ac* 63: 1981-1989
- 695 Tesoriero, AJ, Pankow, JF (1996) Solid solution partitioning of Sr^{2+} , Ba^{2+} , and Cd^{2+} to
696 calcite. *Geochim Cosmochim Ac* 60: 1053-1063

- 697 Tian, J, Nelson, D, Hu, F (2011) How well do sediment indicators record past climate? An
698 evaluation using annually laminated sediments. *J Paleolimnol* 45: 73-84
- 699 Van Dorn, WG (1956) Large-volume water samplers. *Transactions of the American*
700 *Geophysical Union* 37: 682-684
- 701 Viehberg, FA, Ulgen, UB, Damci, E, Franz, SO, On, SA, Roeser, PA, Cagatay, MN, Litt, T,
702 Melles, M (2012) Seasonal hydrochemical changes and spatial sedimentological
703 variations in Lake Iznik (NW Turkey). *Quatern Int* 274:102-111
- 704 Woodbridge, J, Roberts, N (2010) Linking neo- and palaeolimnology: a case study using
705 crater lake diatoms from central Turkey. *J Paleolimnol* 44: 855-871
- 706 Woodbridge, J, Roberts, N, Cox, EJ (2010) Morphology and ecology of a new centric diatom
707 from Cappadocia (central Turkey). *Diatom Research* 25: 195-212
- 708 Woodbridge, J, Roberts, N (2011) Late Holocene climate of the Eastern Mediterranean
709 inferred from diatom analysis of annually-laminated lake sediments. *Quaternary Sci Rev*
710 30: 3381-3392
- 711 Yiğitbaşıoğlu, H, Dean, JR, Eastwood, WJ, Roberts, N, Jones, MD, Leng, MJ, Türkeş, M (in
712 press) A 600 year-long drought index for central Anatolia. *MedCLIVAR Conference 2014*
713 extended abstract
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722 **Tables**

723

724 **Table 1** $\delta^{18}\text{O}$ from lake surface waters and the upper spring in the catchment, and EC and pH

725 values from surface lake waters

	$\delta^{18}\text{O}_{\text{lakewater}}$ surface centre ‰ VSMOW	$\delta^{18}\text{O}_{\text{lakewater}}$ surface edge ‰ VSMOW	$\delta^{18}\text{O}$ upper spring ‰ VSMOW	EC μScm^{-1}	pH
Mar. 1997		-3.20			
Aug. 1999		-2.95		2500	7.4
July 2000		-3.22			
July 2001	-2.64		-10.55	3300	7.9
Mar. 2002		-3.14	-10.63		
July 2002	-2.42		-10.70		
July 2003	-2.50		-10.59		
May 2004	-2.73				
July 2005		-1.88			
Sep. 2006	-0.87	-1.67	-10.56	3390	7.8
July 2008	-0.57		-10.60	3380	8.3
May 2009	-1.17	-1.46		3430	8.5
July 2009	-0.56		-10.63	3370	8.2
July 2010	-0.24		-10.65	3430	8.5
June 2011	-0.81		-10.55	3390	8.2
Sep. 2011	-0.19	-0.13	-10.63	3540	8.1
Feb. 2012		-1.25		2190	7.3
June 2012		-0.75			
July 2012	-0.34	-0.39	-10.74	3500	7.8
April 2013	-0.90		-10.57	3720	7.7
April 2014	-1.10		-10.61	3333	

726

727 **Table 2** Major ion data from surface lake water samples

	Concentration meqL ⁻¹						
	SO ₄ ⁻²	Cl ⁻	Na ⁺	K ⁺	Mg ²⁺	Ca ⁺²	Mg/Ca
Aug. 1999	3.2	27.4	16.5	3.7	8.5	3.0	2.8
July 2009	3.6	20.1	14.6	3.8	10.1	2.1	4.8
July 2010	3.8	22.7	16.2	3.6	15.4	1.0	15.4
June 2011	2.9	20.2	13.7	4.0	8.8	2.2	4.0
Sep. 2011	4.4	22.4	19.0	3.8	9.4	3.2	2.9
Feb. 2012	3.0	20.2	4.1	0.0	3.2	4.0	0.8
July 2012	4.1	23.9	16.9	3.8	16.5	1.2	13.8
April 2013	3.6	20.2	19.8	3.6	7.1	3.6	2.0

728

729 **Figure captions**

730

731 **Figure 1** Nar Gölü catchment, shaded grey, with bathymetric map showing the alluvial fan in
732 the southern part of the lake and the variability in depth. **Figure 2** δD - $\delta^{18}O$ plot, with data
733 from the Ankara GNIP station 1964-2009 (IAEA/WMO 2014) defining the meteoric water
734 line. Spring waters plot on the meteoric water line, whereas lake waters plot on a local
735 evaporation line.

736 **Figure 3** Intra-annual variability in $\delta^{18}O$, EC, pH and magnesium and calcium concentrations
737 from water samples taken from the lake edge between June 2011 and July 2012, and data
738 from temperature loggers at 5 m and 21 m depth from the same time period (the convergence
739 of the lines in November signifies the thermal mixing of the lake and the divergence in March
740 the stratification of the lake).

741 **Figure 4** Depth profiles of isotope and geochemical variables from different times of the year
742 (although note profiles were not all taken in the same year), showing the changes in thermo-,
743 chemo- and iso-clines from spring to summer.

744 **Figure 5** $\delta^{18}O_{\text{lakewater}}$ (from July surface water samples), measured EC (from July surface
745 water samples), $\delta^{18}O_{\text{carbonate}}$ from NAR10 core and sediment traps, XRF-derived Ca/Sr ratio
746 (see section 3.2 for details) and % aragonite vs. calcite from NAR10 core, plotted with
747 changes in maximum lake depth and 8-year cumulative weighted P/E ratio from Niğde (data
748 provided by the Turkish Meteorological Service).

749 **Figure 6** Major diatom taxa and DI-EC in NAR06 (Woodbridge and Roberts, 2010) and
750 NAR10 cores (new data), and measured EC (from July surface water samples).

751 **Figure 7** Intra-annual variability in $\delta^{18}O_{\text{carbonate}}$ as recorded in a sediment trap in the lake at 5
752 m depth between summer 2001 and summer 2002.

753 **Figure 8** Sediment trap deployed in April 2013 and collected in April 2014, showing the
754 seasonality of sedimentation in Nar Gölü.

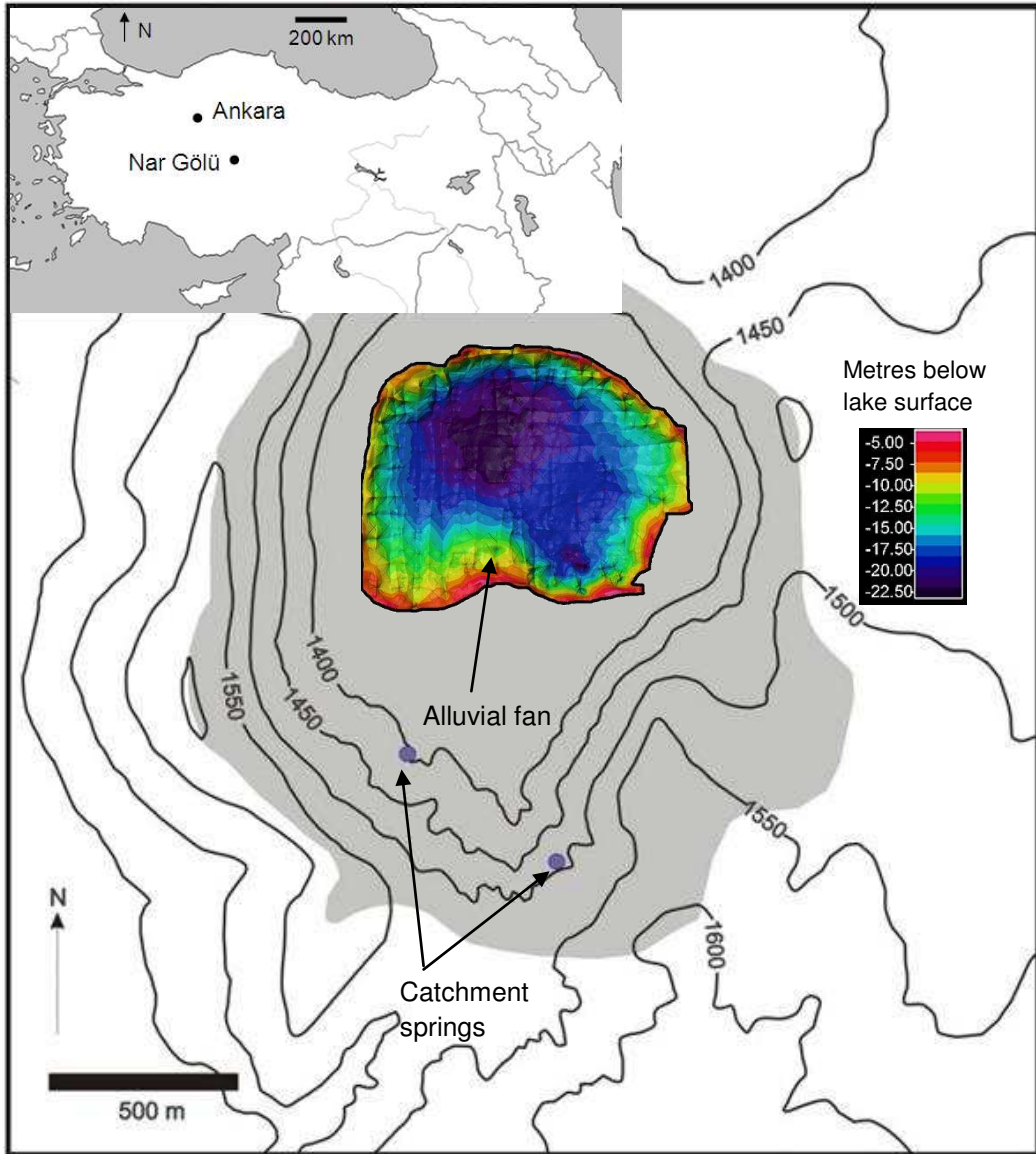
755 **Figure 9** Predicted $\delta^{18}\text{O}_{\text{carbonate}}$ values from Eqs. 1 and 2 compared to measured $\delta^{18}\text{O}_{\text{carbonate}}$
756 from NAR10 core, using a variety of lake surface temperature and $\delta^{18}\text{O}_{\text{lakewater}}$ values that
757 represent conditions in the lake from July back to May.

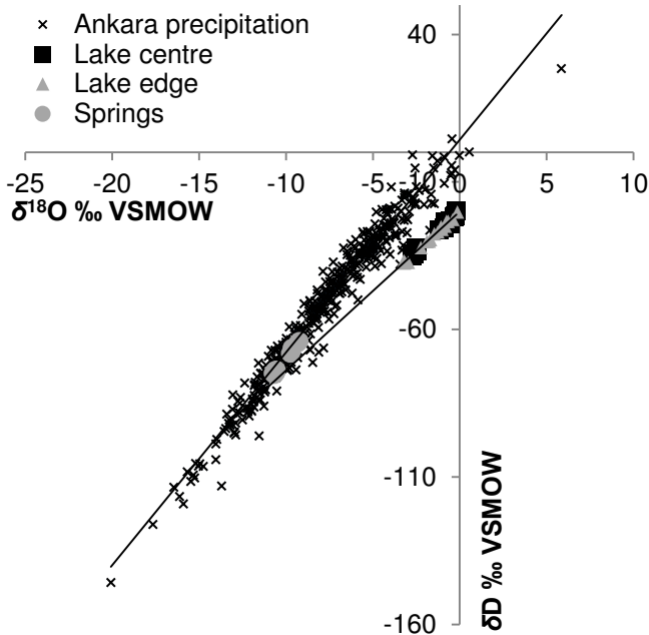
758 **Figure 10** 1,720-year records of diatom species (Woodbridge and Roberts, 2011) and
759 $\delta^{18}\text{O}_{\text{carbonate}}$ (Jones et al., 2006) from the NAR01/02 cores. The variability in DI-EC and
760 $\delta^{18}\text{O}_{\text{carbonate}}$ seen during the monitoring period from the NAR10 core are shown by the shaded
761 boxes. Diatom zones from Woodbridge and Roberts (2011) are shown.

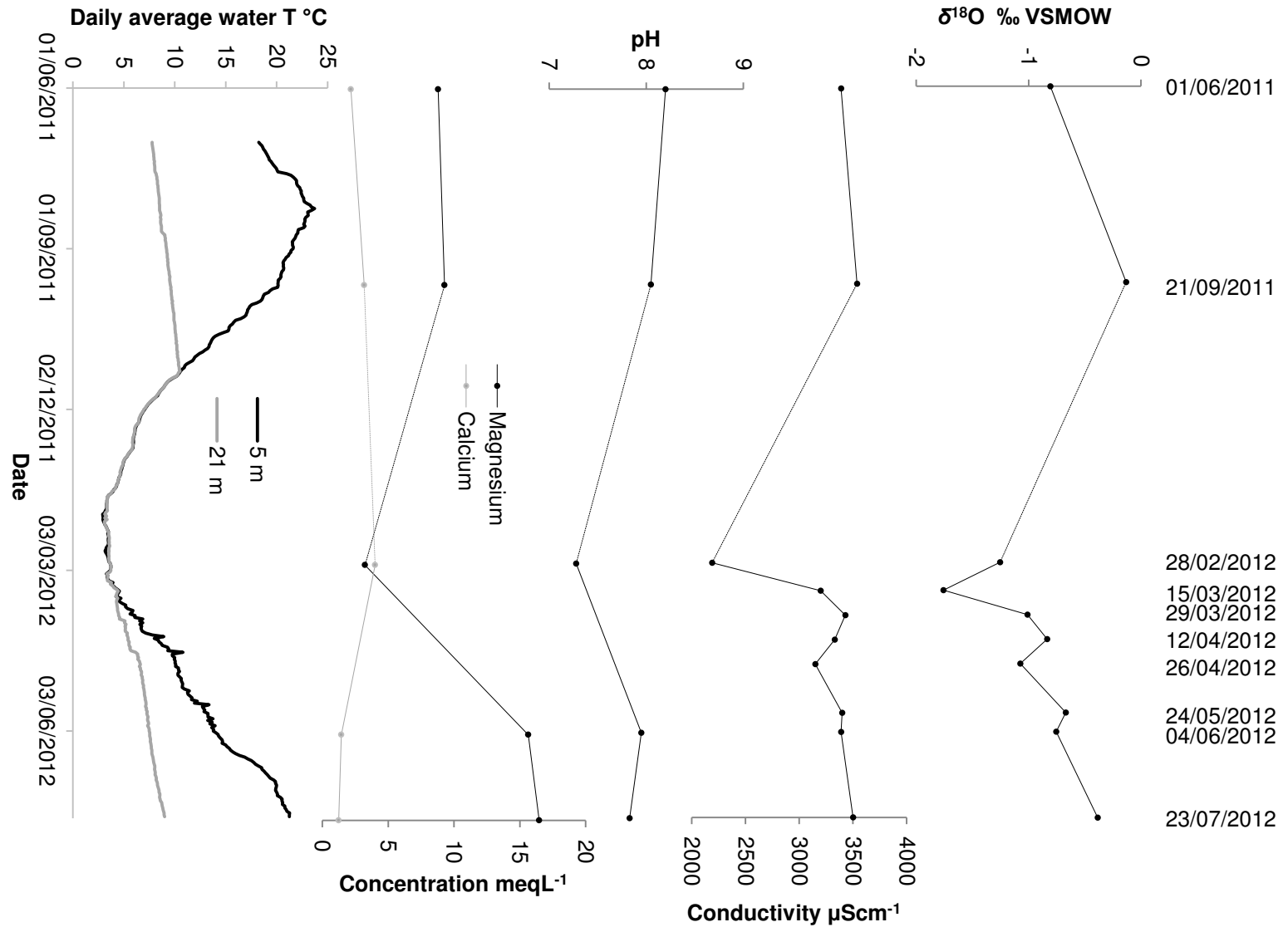
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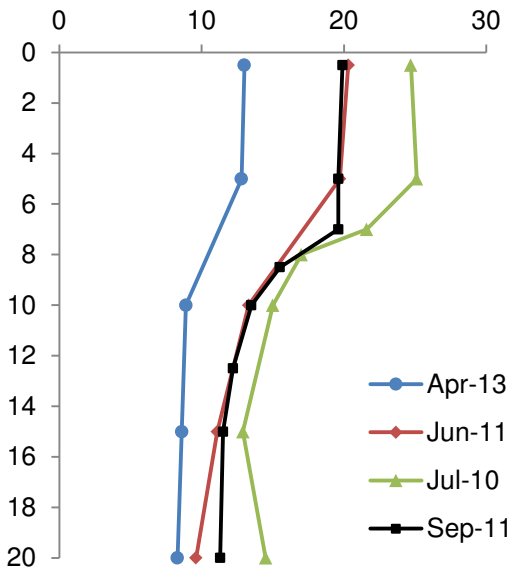
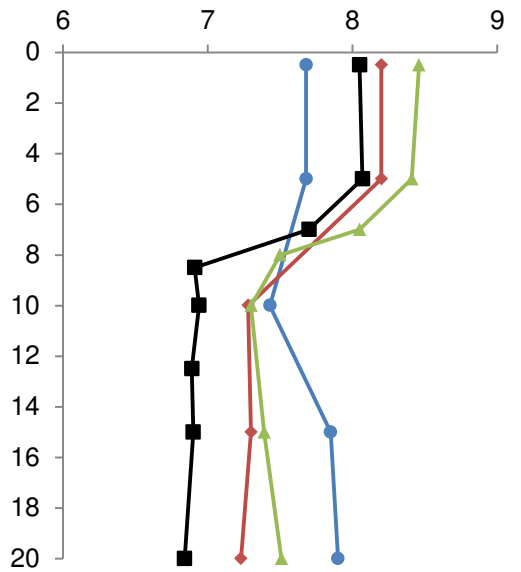
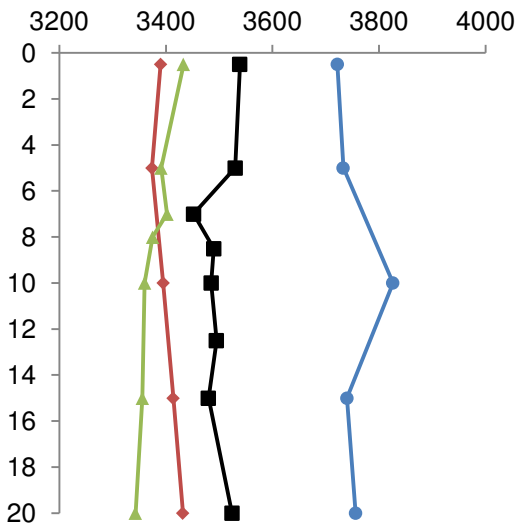
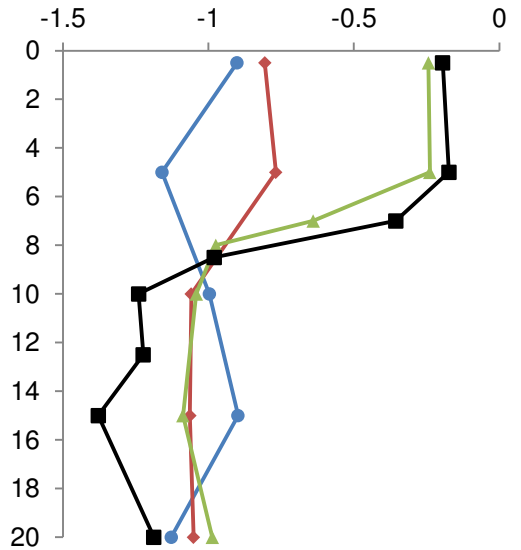
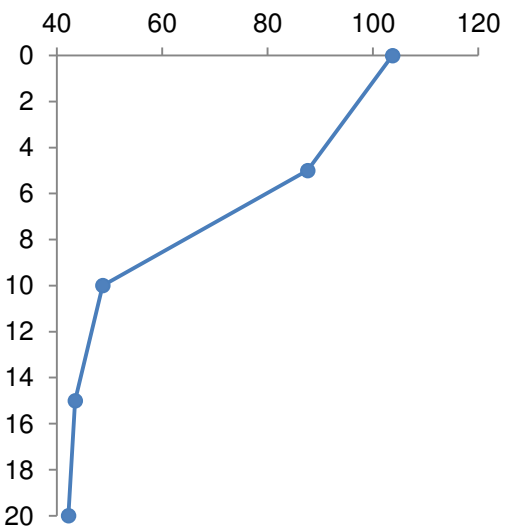
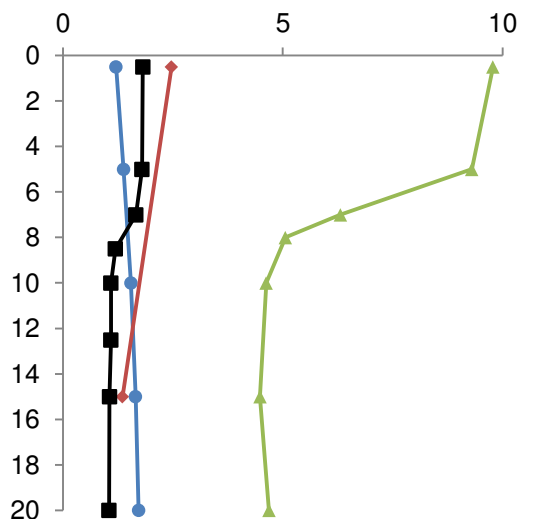
763 **SI Figure 1** Photographs of Nar Gölü between March and April 2012.

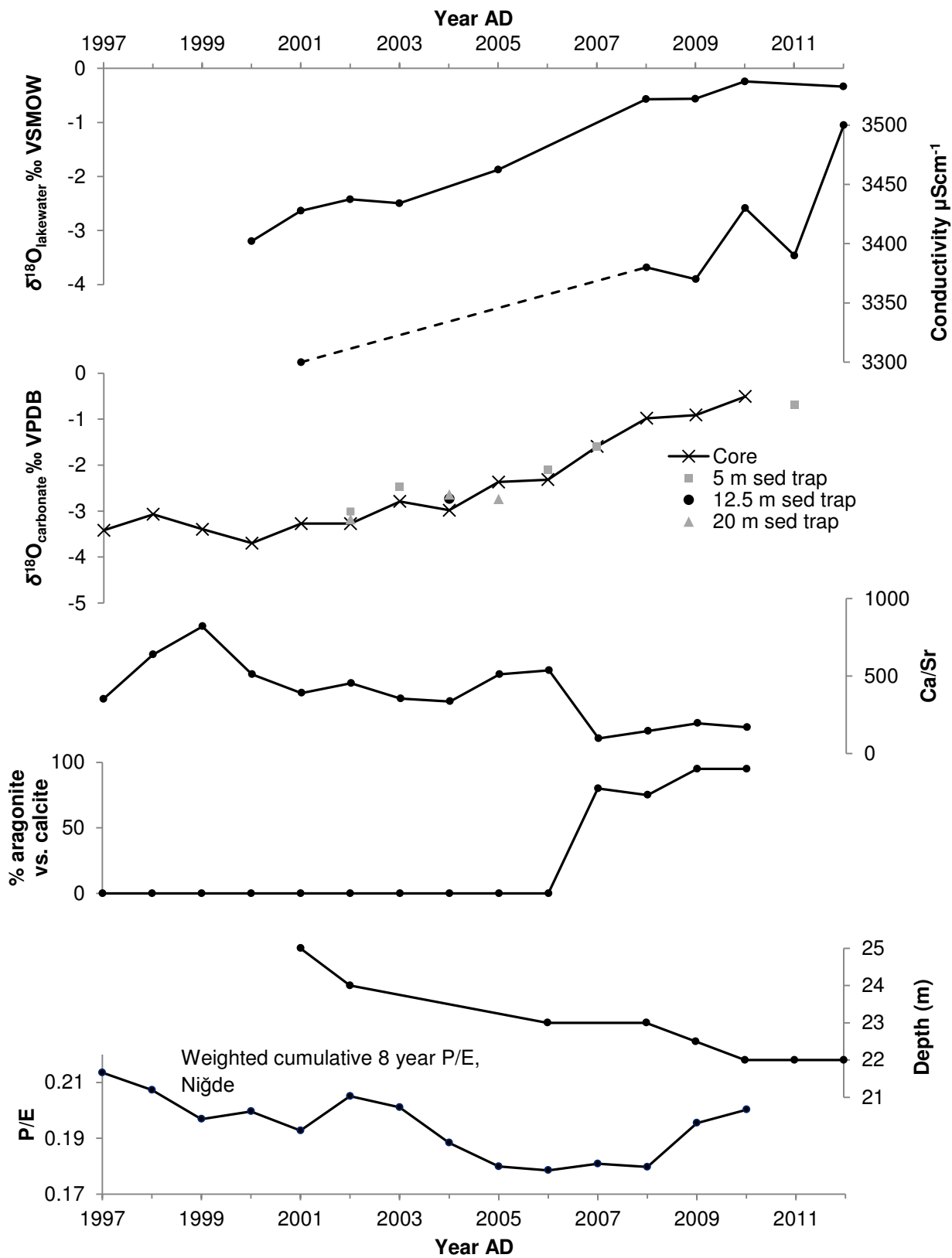
764 **SI Figure 2** ‘White-out’ around the edges of Nar Gölü in July 2012, and inset SEM image
765 identifying this as aragonite.

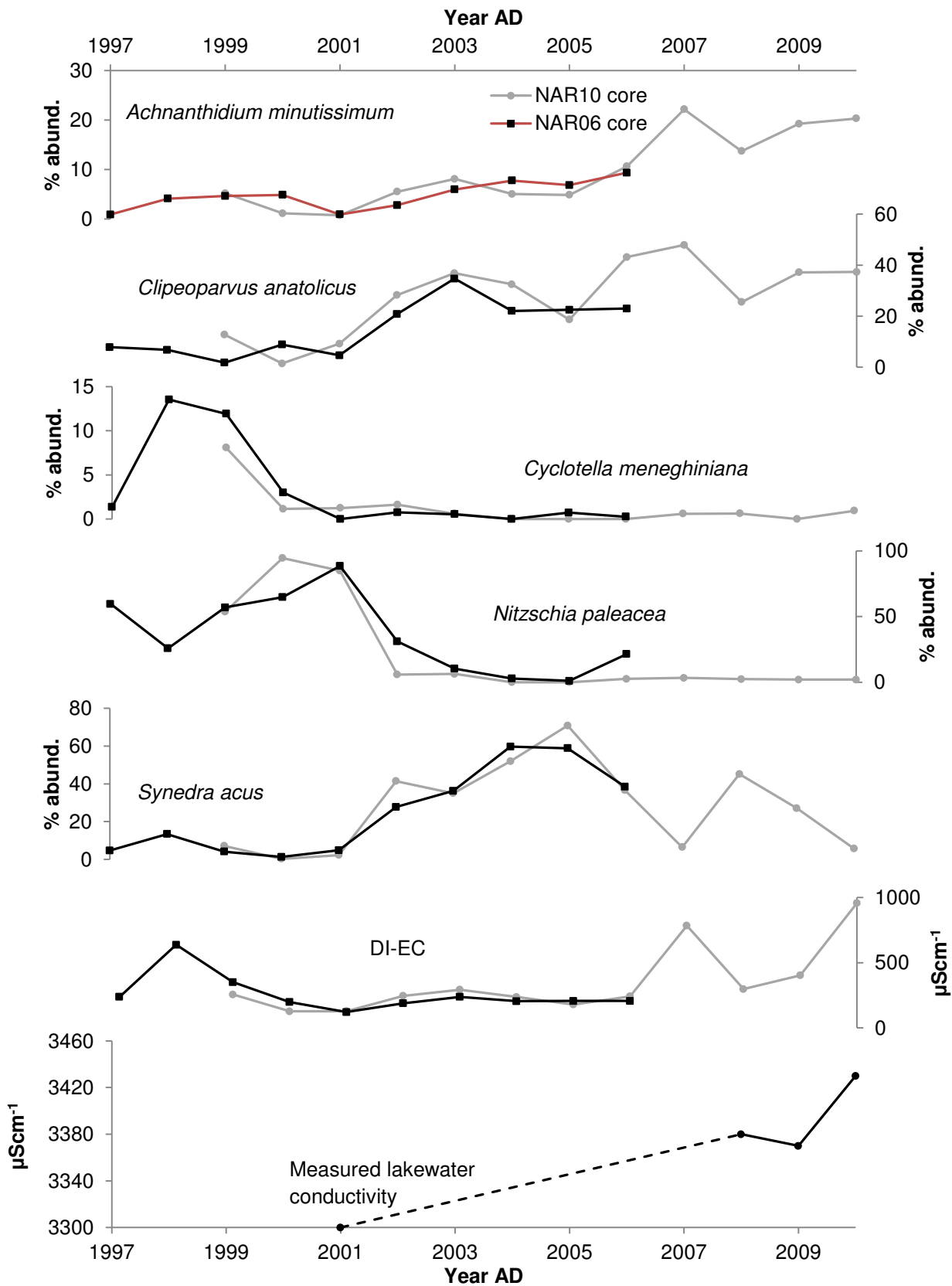






Temperature °C**pH****Conductivity μScm^{-1}**  **$\delta^{18}\text{O}$ ‰ VSMOW****Dissolved oxygen %****Mg/Ca meqL⁻¹**





$\delta^{18}\text{O}_{\text{carbonate}} \text{‰ VPDB}$

-4.0

-3.0

-2.0

0

5

10

15

20

25

30

35

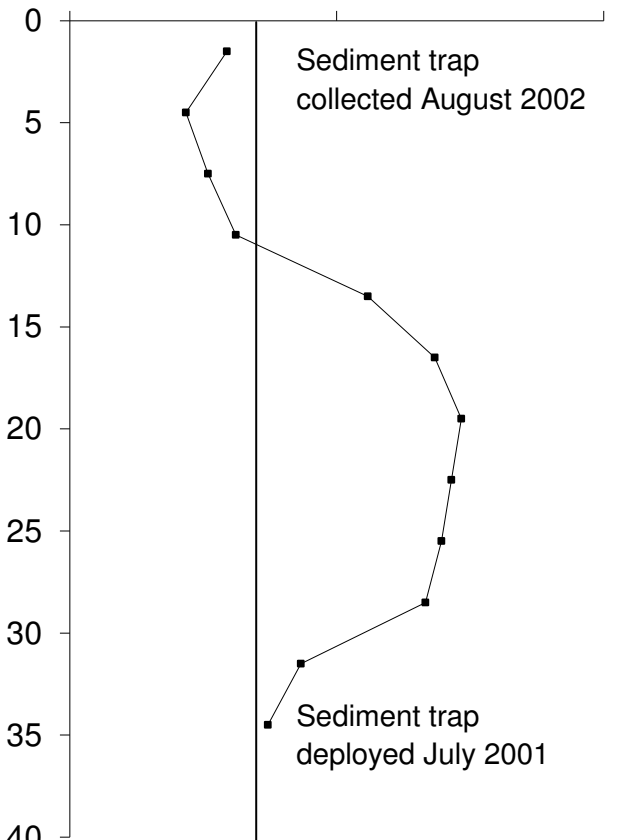
40

Depth cm

Sediment trap
collected August 2002

Sediment trap
deployed July 2001

$\delta^{18}\text{O}_{\text{carbonate}}$ value of
2002 core sediment
(-3.3‰)



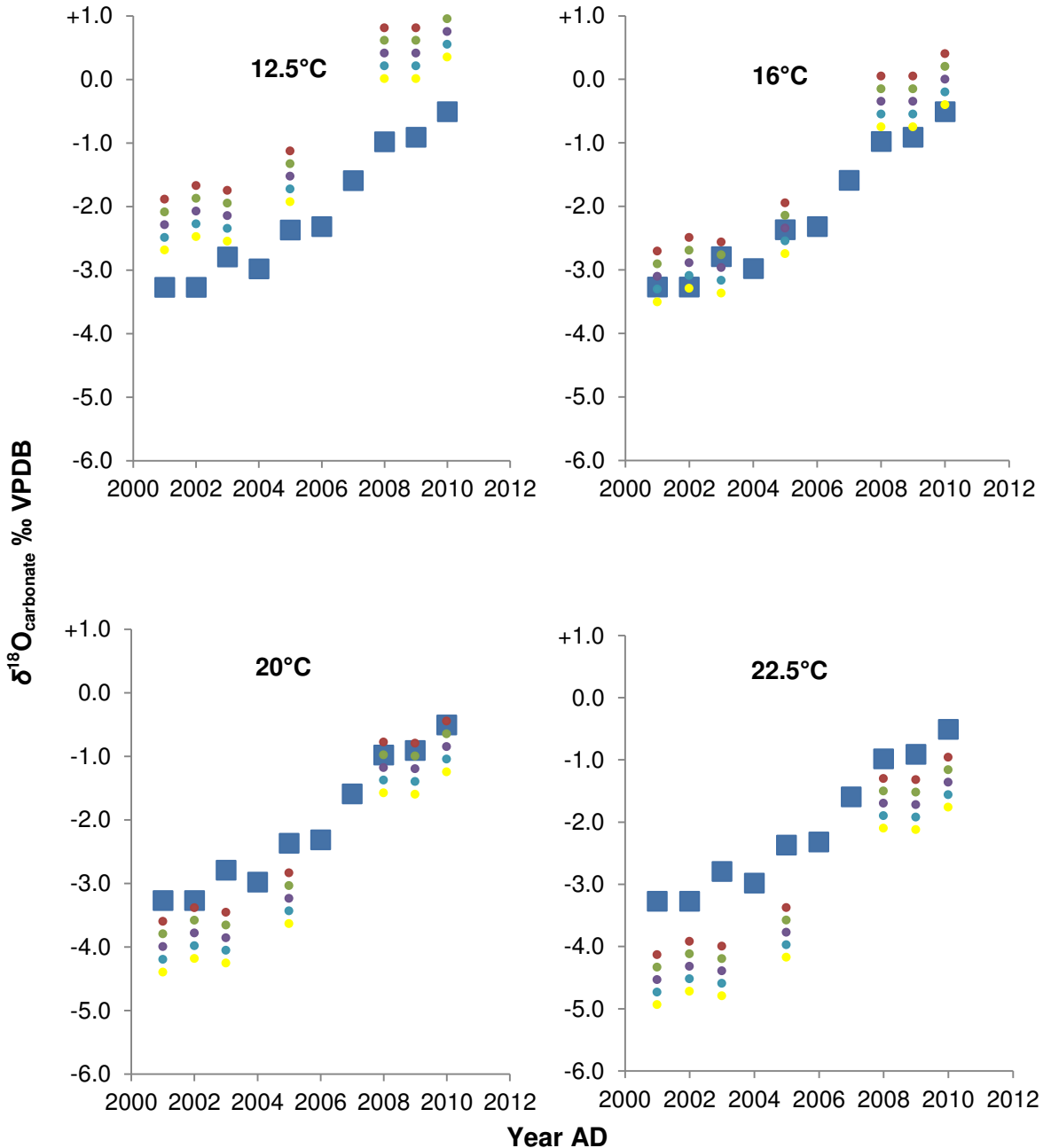
Organic material
deposited prior to
retrieval in April 2014

Carbonate presumed
to have been
deposited in summer
2013

Organic material
deposited after
deployment in April
2013



- Measured
- Predicted with July $\delta^{18}\text{O}_{\text{lw}} -0.2\text{‰}$
- Predicted with July $\delta^{18}\text{O}_{\text{lw}} -0.4\text{‰}$
- Predicted with July $\delta^{18}\text{O}_{\text{lw}} -0.6\text{‰}$
- Predicted with July $\delta^{18}\text{O}_{\text{lw}} -0.8\text{‰}$

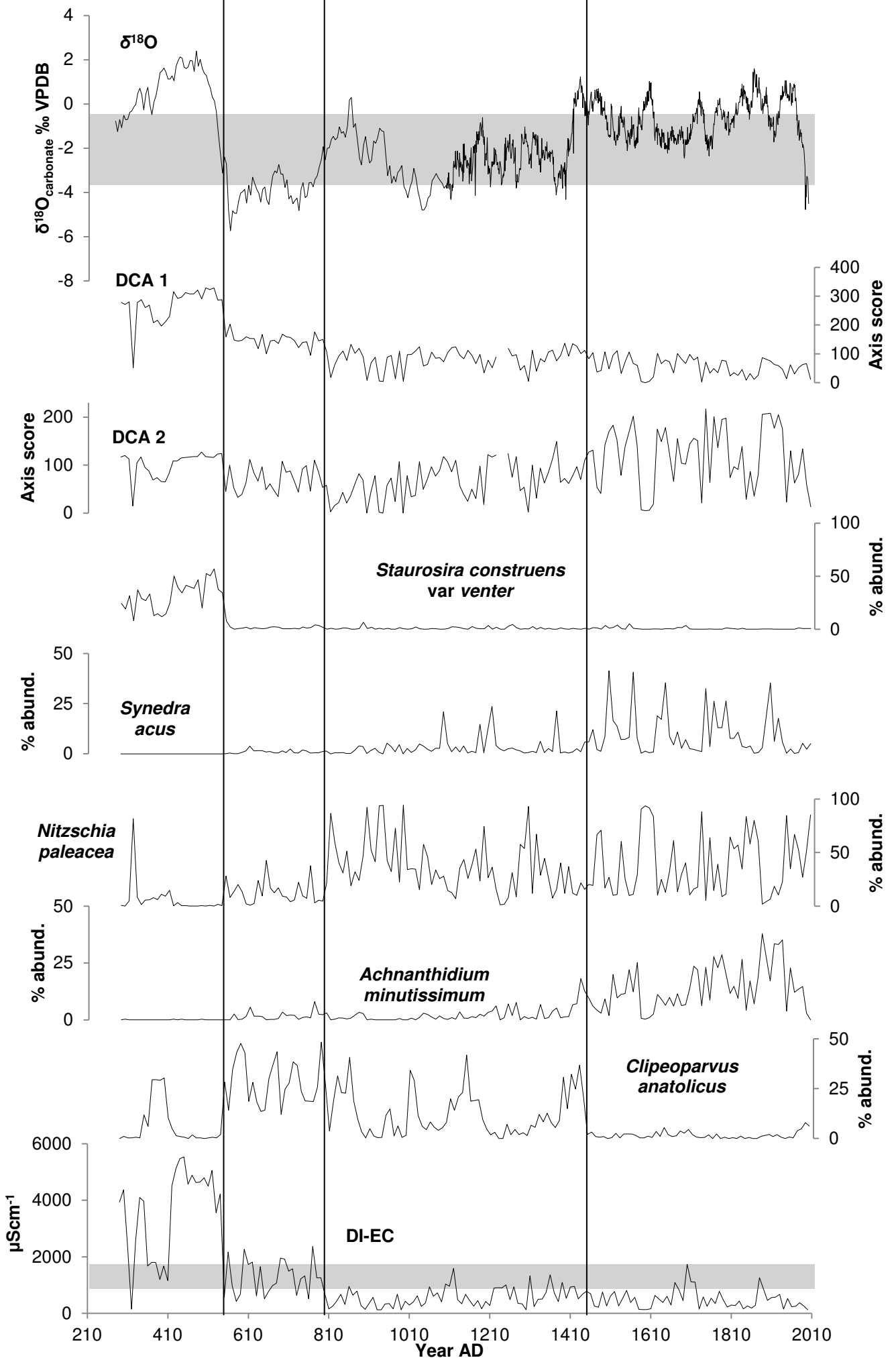


ND1

ND2

ND3

ND4

Nar Gölü
diatom zones

5 March 2012

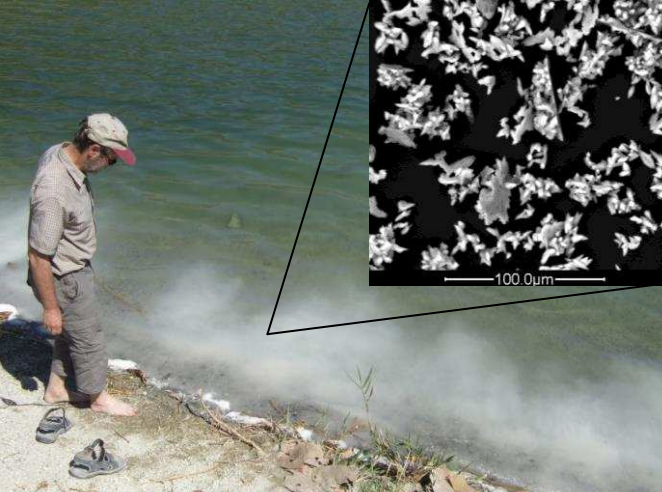


19 March 2012



11 April 2012





100.0µm