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4 **Reconciling diverse lacustrine and terrestrial system**  
5 **response to penultimate deglacial warming in southern**  
6 **Europe**

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18

19 **ABSTRACT**

20 Unlike the most recent deglaciation, the regional expression of climate changes  
21 during the penultimate deglaciation remains understudied, even though it led into a  
22 period of excess warmth with estimates of global average temperature 1–2 °C, and sea

23 level ~6 m, above preindustrial values. We present the first complete high-resolution  
24 southern European diatom record capturing the penultimate glacial-interglacial transition,  
25 from Lake Ioannina (northwest Greece). It forms part of a suite of proxies selected to  
26 assess the character and phase relationships of terrestrial and aquatic ecosystem response  
27 to rapid climate warming, and to resolve apparent conflicts in proxy evidence for regional  
28 paleohydrology. The diatom data suggest a complex penultimate deglaciation driven  
29 primarily by multiple oscillations in lake level, and provide firm evidence for the regional  
30 influence of abrupt changes in North Atlantic conditions. There is diachroneity in lake  
31 and terrestrial ecosystem response to warming at the onset of the last interglacial, with an  
32 abrupt increase in lake level occurring ~2.7 k.y. prior to sustained forest expansion with  
33 peak precipitation. We identify the potentially important role of direct input of snow melt  
34 and glacial meltwater transfer to the subterranean karst system in response to warming,  
35 which would cause rising regional groundwater levels. This explanation, and the greater  
36 sensitivity of diatoms to subtle changes in temperature, reconciles the divergent lacustrine  
37 and terrestrial proxy evidence and highlights the sensitivity of lakes situated in  
38 mountainous karstic environments to past climate warming.

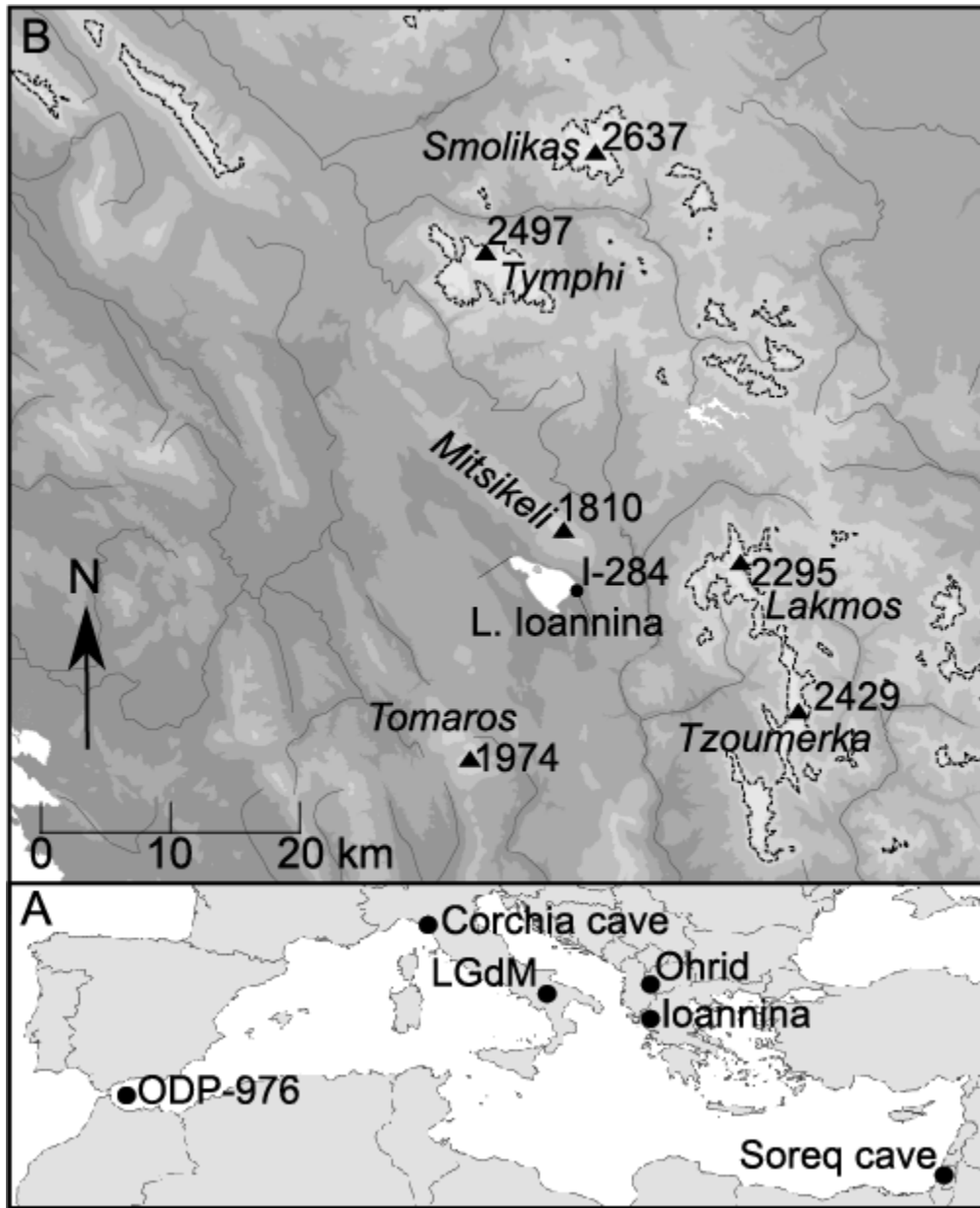
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## 40 **INTRODUCTION**

41       During the penultimate deglaciation [ca. 136–129 ka, the Marine Isotope Stage 6  
42 (MIS 6) to MIS 5 transition, Termination II] global climate shifted from one of the most  
43 extreme glaciations to one of the warmest interglacials. Recent high-resolution marine  
44 sediment records from the Iberian margin reveal a complex multiple-step climate  
45 transition in response to deglacial meltwater pulses into the North Atlantic associated

46 with Heinrich Stadial 11 (HS11; ca. 136–130 ka; Martrat et al., 2014; Marino et al.,  
47 2015), a pattern also seen in regional speleothem  $\delta^{18}\text{O}$  records (Drysdale et al., 2009;  
48 Grant et al., 2012). Episodes of low sea-surface temperatures (SSTs) and aridity at this  
49 time may have been caused by the expansion of North Atlantic cold water masses into  
50 lower latitudes (Martrat et al., 2014). Few data from this period are available from  
51 continental lake and peat bog archives. In Lago Grande di Monticchio, southern Italy,  
52 expansion of forests started at 130.6 ka; a short-lived (~250 yr) reduction in tree  
53 populations is apparent at 128.2–127.9 ka (Brauer et al., 2007). In Lake Ohrid (Albania-  
54 Macedonia), the absence of ice-rafted debris and rising calcite from ca. 130 ka indicate a  
55 transition to interstadial conditions, with onset of full interglacial conditions from ca. 127  
56 ka (Vogel et al., 2010), during which limnological shifts in productivity predated forest  
57 expansion (Lézine et al., 2010). The Soreq Cave (Israel)  $\delta^{18}\text{O}$  speleothem data (Grant et  
58 al., 2012) suggest an overall gradual and moderate increase in regional precipitation from  
59 ca. 139.5 ka. Sedimentological data and climate simulations indicate increasing  
60 seasonality through the penultimate late glacial (Brauer et al., 2007; Kutzbach et al.,  
61 2014). In this study, we return to Lake Ioannina (Epirus, northwest Greece; see the GSA  
62 Data Repository<sup>1</sup> for site details), a reference site for paleoclimate research in southern  
63 Europe (e.g., Frogley et al., 1999; Tzedakis et al., 2002, 2003; Wilson et al., 2008;  
64 Roucoux et al., 2011) to improve understanding of paleohydrology and terrestrial and  
65 aquatic responses to abrupt climate change during the penultimate deglaciation.

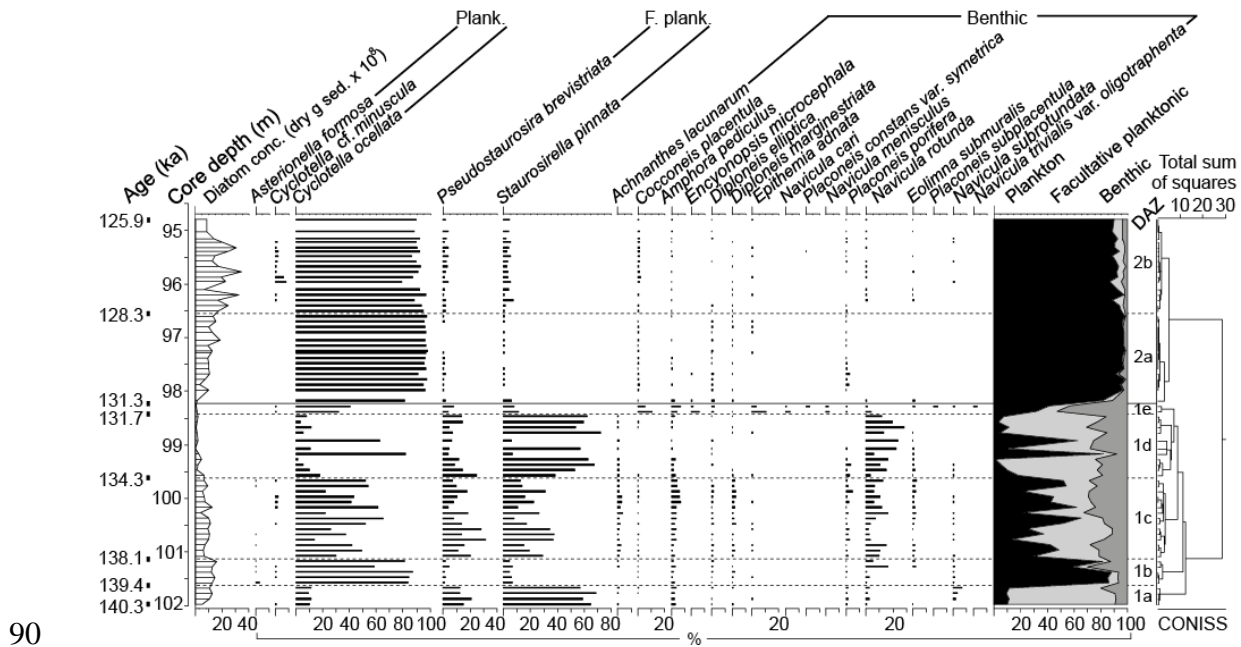
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67  
 68 **Figure 1.** A: Location of Ioannina (northwest Greece) and sites mentioned in the text. LGdM—Lago  
 69 Grande di Monticchio; ODP-976—Ocean Drilling Program Site 976. B: Sediment core site I-284 (39°45'N,  
 70 20°51'E) in relation to the present lake (470 m asl, above sea level) and surrounding topography. Areas of  
 71 land >1850 m asl (stippled line) correspond to the estimated equilibrium line altitude of glaciers in this area  
 72 during the penultimate glacial. Snow cover would have been permanent in the stippled areas. Glaciers  
 73 would have been larger than these stippled areas but with variable hypsometries depending on local  
 74 topoclimatic factors. Adapted from Wilson et al. (2013).

75 **CORE I-284 DIATOM RECORD**

76       The penultimate late glacial and last interglacial sections of sediment core I-284  
77 (Fig. 1) from the Ioannina basin have previously been the focus of multiproxy analysis  
78 (pollen, ostracod, calcite  $\delta^{18}\text{O}$ , and  $\delta^{13}\text{C}$ ; Frogley et al., 1999; Tzedakis et al., 2003). The  
79 I-284 time scale used here is constructed by aligning the percentage of temperate tree  
80 pollen to Corchia speleothem  $\delta^{18}\text{O}$  (Drysedale et al., 2009), on the premise that the amount  
81 of precipitation in southern Europe exerts a dominant control over both the composition  
82 of vegetation and the  $\delta^{18}\text{O}$  of speleothems (Tzedakis et al., 2002; Drysdale et al., 2009;  
83 see the Data Repository). Between 101.97 m and 94.80 m (ca. 140.3 and 125.9 ka), 70  
84 samples for diatom analysis were taken at 10 cm intervals (~200 yr resolution) or greater,  
85 sufficient to span the glacial-interglacial transition as determined from changes in  
86 arboreal pollen frequency and concentration (Tzedakis et al., 2003). Sample preparation  
87 for diatom analysis followed standard techniques (Battarbee, 1986; see the Data  
88 Repository).  
89



90  
 91 **Figure 2.** Summary diatom diagram of taxa present with relative frequencies of  $\geq 2\%$ . Diatom assemblage  
 92 zones (DAZ), as determined by CONISS (constrained incremental sum of square cluster analysis), and  
 93 DAZ boundary ages are also shown. Plank.—plankton; F.—facultative; conc.—concentration; sed.—  
 94 sediment.

95  
 96 Two major biostratigraphic zones can be defined: diatom assemblage zone (DAZ)  
 97 1 (101.97–98.23 m, ca. 140.3–131.3 ka) and DAZ 2 (98.23–94.80 m, ca. 131.3–125.9 ka)  
 98 (Fig. 2). Diatom concentrations are generally low during DAZ 1, which contains  
 99 relatively high frequencies of benthic (particularly *Navicula rotunda* Hustedt) and  
 100 facultative planktonic species (small Fragilariaceae: *Staurosirella pinnata* [Ehrenberg]  
 101 Williams and Round, and *Pseudostaurosira brevistriata* [Grunow] Williams and Round),  
 102 but with distinct peaks (to  $>80\%$  abundance) in planktonic taxa, dominated by classic  
 103 forms (with three ocelli) of *Cyclotella ocellata* Pantocsek, and accompanied by large,  
 104 nonclassic forms with complex central area structure. Five subzones (DAZ 1a–DAZ 1e)  
 105 can be defined based on the interchanging dominance of these taxa. DAZ 1b

106 (101.62–101.12 m, ca. 139.4–138.1 ka) is notable in the consistent dominance of *C.*  
107 *ocellata*. A marked increase in relative abundance of *C. ocellata* occurs at the DAZ 1-  
108 DAZ 2 boundary ca. 131.3 ka at the expense of littoral taxa. Diatom concentrations in  
109 DAZ 2 are typically higher than in DAZ 1. *Cyclotella ocellata* is dominant throughout.  
110 The transition from DAZ 2a to DAZ 2b is marked by a slight increase in facultative  
111 planktonic and benthic taxa (e.g. *Cocconeis placentula* Ehrenberg, and *N. rotunda*). From  
112 previous research on the glacial diatom flora of Ioannina (e.g., Wilson et al., 2008, 2013)  
113 and other Mediterranean, relatively shallow, aquifer-fed, alkaline lakes, including Lake  
114 Dojran (Macedonia-Greece; Zhang et al., 2014) and Lake Prespa (Macedonia-Greece;  
115 Cvetkoska et al., 2014a), the small Fragilariaceae are indicative of shallow lake  
116 conditions with extended seasonal ice cover in a cold, arid glacial climate. *C. ocellata* has  
117 broad ecological preferences (in part because it is likely to represent a species complex),  
118 but in these systems, appears to indicate oligotrophic-mesotrophic conditions, particularly  
119 when accompanied by large, nonclassic forms (Cvetkoska et al., 2014a). The large  
120 Ioannina morphotypes await taxonomic description, but show affinities with recently  
121 described Mediterranean taxa separated from the *C. ocellata* complex, comprising *C.*  
122 *prespanensis* Cvetkoska, Hamilton, Ognjanova-Rumenova and Levkov, *C. paraocellata*  
123 Cvetkoska (Cvetkoska et al., 2014b), and *C. paleo-ocellata* Vossel and Van de Vijver  
124 (Vossel et al., 2015).

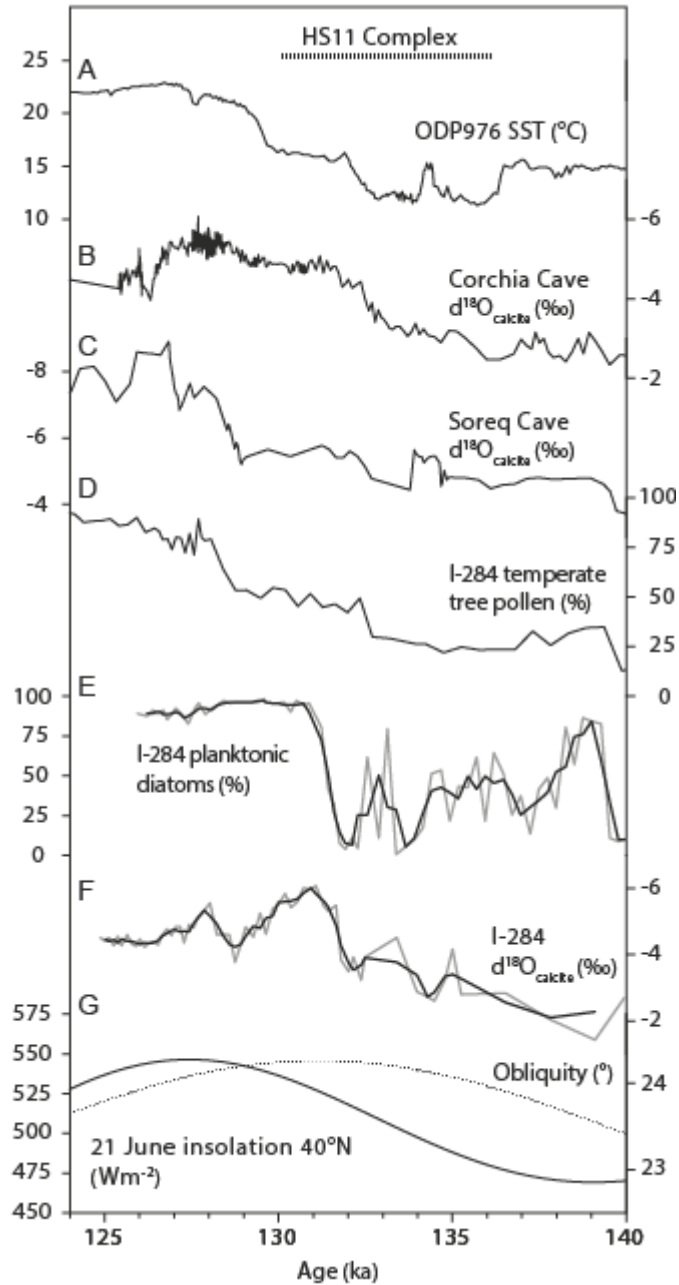
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## 126 **PENULTIMATE DEGLACIATION**

127 The high frequency of benthic and facultative planktonic taxa between ca. 140.3  
128 and 131.3 ka (DAZ 1) suggests that the water depth at the core site was relatively

129 shallow, in a cold, arid climate. However, *C. ocellata* dominance suggests sustained  
130 higher lake levels between 139.4 and 138.1 ka (DAZ 1b). This interval coincides with a  
131 marked initial expansion in arboreal pollen from ~17% to 37% (Fig. 3), indicating an  
132 initial phase of forest expansion coeval with an inferred increase in regional precipitation  
133 (Grant et al., 2012) marking the start of the late glacial. During a period of reduced tree  
134 populations at Ioannina (ca. 137–132.5 ka), the high abundance of small Fragilariaceae  
135 and slight increase in benthic taxa suggest a return to shallow lake conditions with greater  
136 seasonal ice cover in a cold, arid climate. This is coeval with an interval of minimum  
137 SSTs in the Alboran Sea and Portuguese margin ca. 136–132 ka (Martrat et al., 2014;  
138 Fig. 3). Therefore, there is strong evidence for both terrestrial and aquatic ecosystem  
139 response at Ioannina to cooler and drier conditions associated with changes in the North  
140 Atlantic during HS11. Warming events may have punctuated stadials associated with  
141 Heinrich events, including HS11 (Martrat et al., 2014). The diatom record at Ioannina  
142 also shows short-lived peaks in *C. ocellata* at the expense of small Fragilariaceae. This  
143 may suggest short-lived episodes of higher lake levels (Wilson et al., 2008; Jones et al.,  
144 2013; Cvetkoska et al., 2014a), possibly accompanied by a longer open-water season  
145 with earlier spring ice melt (cf. Wilson et al., 2013). Lower resolution  $\delta^{18}\text{O}$  data in this  
146 section of the core prevents a robust and detailed comparison with the diatom record, but  
147 the tendency is for plankton peaks to be matched with lower  $\delta^{18}\text{O}$  values indicative of  
148 increased lake levels. Reduced forest populations and the increase in steppe elements  
149 during this interval (ca. 137–133 ka) indicate that these episodes were probably not  
150 related to increases in regional precipitation. Instead, the source of hydrological input  
151 may be from late winter pulses of groundwater flow from meltwater flooding.





152

153 **Figure 3.** Comparison of sediment core I-284 paleoecological and isotopic records with regional data sets.

154 HS11—Heinrich Stadial 11. A: Ocean Drilling Program (ODP) Site 976 alkenone-derived sea-surface

155 temperature (SST), western Alboran Sea (Martrat et al., 2014). B: Corchia cave (Italy) speleothem  $\delta^{18}\text{O}$

156 (inverted axis) (Drysdale et al., 2009). C: Soreq (Israel) speleothem  $\delta^{18}\text{O}$  (inverted axis) (Grant et al.,

157 2012). D: Temperate tree pollen (minus *Pinus* and *Juniperus*) at Ioannina (core I-284; Tzedakis et al., 2002,

158 2003). E: Ioannina (core I-284) planktonic diatom frequency. F: Ioannina (core I-284)  $\delta^{18}\text{O}_{\text{calcite}}$  (inverted

159 axis) (Frogley et al., 1999). Black lines in E and F show the 3-point running mean, gray lines show actual  
160 data. G: 21 June insolation at 40°N and obliquity (Berger, 1978). All data are plotted on their own time  
161 scales.

162

163 The rapid transition to prolonged dominance of *C. ocellata* at the DAZ 1-DAZ 2  
164 boundary (ca. 131.3 ka) indicates water column stability in a sustained phase of high lake  
165 level (Cvetkoska et al., 2014a). A concomitant rapid decrease in  $\delta^{18}\text{O}$  values from ca.  
166 131.7 ka provides independent evidence of rapid lake-level rise (Fig. 3). Only a moderate  
167 increase in regional precipitation (Grant et al., 2012) and an associated intermediate  
168 expansion in tree populations at Ioannina are apparent from 132.5 ka (Fig. 3). A sharp  
169 rise in Alboran SSTs from ca. 129.5 ka (Martrat et al., 2014) is closely followed by a  
170 contemporaneous marked increase in regional precipitation (Drysedale et al., 2009; Grant  
171 et al., 2012) and in southern European tree populations between 129 ka and 128 ka  
172 (Tzedakis et al., 2003; Brauer et al., 2007). This marked increase in regional precipitation  
173 occurs 2.7 k.y. after the rapid rise in Ioannina lake level. Therefore, there is an apparent  
174 inconsistency in the timing of the main increase in regional precipitation as inferred from  
175 Ioannina lake-level changes and from changes in vegetation during the penultimate late  
176 glacial.

177 To explain this divergence, we suggest that regional groundwater levels may have  
178 risen during the penultimate late glacial as a result of the transfer of Pindus mountain  
179 glacial meltwater to the subterranean karst system, which is well developed in this area  
180 (see the Data Repository), and by input from snow melt. During the penultimate glacial,  
181 large glaciers existed on Mount Tymphi, with frontal moraines on the southern slopes  
182 situated ~25–30 km north of Ioannina (Hughes et al., 2007). A total of 14 glaciers

183 covered an area of 21.3 km<sup>2</sup> on Mount Tymphi, with an average equilibrium line altitude  
184 of 1862 m asl (above sea level). Similar-sized glaciers would have also formed on Mount  
185 Lakmos/Peristeri (2295 m asl), <15 km east of Ioannina, and the neighboring  
186 Tzoumerka/Athamanika Massif (2429 m asl), both of which have a glacial  
187 geomorphology similar to that of Mount Tymphi. These massifs currently record the  
188 largest precipitation totals in Greece (Fotiadi et al., 1999), and, if precipitation  
189 distribution was similar in glacial stages, then this would have been favorable for the  
190 formation of some of the largest glaciers in Greece (Fig. 1). Permanent snow fields and  
191 possibly small niche glaciers are likely to have formed on the slopes of Mount Mitsikeli  
192 (1813 m asl), the most immediate mountain catchment to Lake Ioannina. An increase in  
193 lake sediment calcite content at Lakes Ioannina and Ohrid ca. 132 ka and ca. 130 ka,  
194 respectively (Frogley, 1997; Vogel et al., 2010), and an absence of ice-rafted debris in  
195 Ohrid from ca. 130 ka (Vogel et al., 2010) indicate regional climate warming, even  
196 though freshwater flux from ice sheets may have prolonged stadial conditions in the  
197 North Atlantic. A warming climate would increase snow and ice melt rates, resulting in  
198 glaciers retreating upvalley to higher elevations, particularly if associated with increased  
199 rainfall in this humid, refugial location (Tzedakis et al., 2002). Moraine calcite cements  
200 in the mountains of both Greece and Montenegro yield corrected U-series ages dating to  
201 the last interglacial, with the earliest and most precise ages yielding a tight range (n = 5)  
202 ca. 124.6–120.2 ka (maximum error at 2σ = 5.3%) (Hughes et al., 2007, 2010, 2011).  
203 This indicates that glaciers had retreated from their most extensive MIS 6 positions by  
204 this time and that the moraines had stabilized, with their surfaces developing respiring  
205 soils, promoting the formation of secondary carbonate cements. Glacier retreat in

206 response to rising temperatures during the penultimate late glacial would have led to karst  
207 reactivation and the release of significant amounts of meltwater discharge to surface  
208 waters and groundwater aquifers through the karst (cf. Adamson et al., 2014). The  
209 combination of accelerated subterranean and surface water input would account for the  
210 rapid rise in lake level at Ioannina ca. 131.7 ka. In this context, lacustrine and terrestrial  
211 proxies would not be responding to a common driving mechanism. If local conditions are  
212 playing an important role in modulating lake response to climate change at Ioannina, then  
213 no apparent conflict between the lacustrine and terrestrial proxy evidence remains.

214         According to the pollen record, the onset of the last interglacial at Ioannina is  
215 placed ca. 128.6 ka, in line with a rapid shift in climate conditions from a number of  
216 Mediterranean records for that time (Fig. 3). From ca. 128.3 ka (DAZ 2b), the diatoms  
217 suggest minor lake-level reduction. This is in agreement with overall higher  $\delta^{18}\text{O}$  values,  
218 perhaps reflecting increased summer aridity and evaporation and a reduction or cessation  
219 in snowmelt and glacial meltwater input, coeval with an expansion in sclerophyllous  
220 woodland (Tzedakis et al., 2003). Taken together, these indicators of summer conditions  
221 are in line with the general framework of accentuated seasonality of precipitation during  
222 the early interglacial (Milner et al., 2012).

223

## 224 **CONCLUSIONS**

225         Diatom evidence for multiple oscillations in lake level, and possibly thermal  
226 regime, at Lake Ioannina (northwest Greece) provide firm evidence for the regional  
227 influence of abrupt changes in the North Atlantic during the HS11 stadial, and add to  
228 growing regional evidence for a complex penultimate deglacial. Snowmelt and glacial

229 meltwater transfer are identified as primary driving mechanisms for an abrupt increase in  
230 lake level almost 3 k.y. prior to regional forest expansion and associated peak  
231 precipitation at the onset of the last interglacial. This finding has wider implications in  
232 demonstrating that, under certain boundary conditions, lakes in mountainous karstic  
233 environments are highly sensitive to past climate warming because of the role of local  
234 glaciers in controlling regional groundwater levels.

235

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245

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347 <sup>1</sup>GSA Data Repository item 2015xxx, site details, methods, chronology, diatom data, are  
348 available online at [www.geosociety.org/pubs/ft2015.htm](http://www.geosociety.org/pubs/ft2015.htm), or on request from  
349 [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO  
350 80301, USA.

351

352 **DATA RESPOSITORY**

353

354 **STUDY SITE DETAILS**

355           The Ioannina basin is a polje thought to have formed during the Late Pliocene to  
356 Early Pleistocene (Clews 1989). The basin is c. 30 km long and up to 15 km wide, with a  
357 bedrock of Mesozoic and early Cenozoic limestones overlain by Pliocene and Quaternary  
358 lake sediment deposits. Artificial drainage has resulted in a reduced lake area of 22 km<sup>2</sup>,  
359 with a mean water depth of 4–5 m (but up to 11 m in places). Mt. Mitsikeli (1,810 m  
360 above sea level, a.s.l.) forms the NW edge of the basin. To the SE, the topography slopes  
361 towards Mt. Tomaros (1,974 m a.s.l.), and the Ionian Sea is located 40 km beyond. Lake  
362 Ioannina forms the base level of a karst aquifer that underlies Mt. Mitsikeli.  $\delta^{18}\text{O}$  and  $\delta\text{D}$   
363 analysis of modern lake water demonstrates evaporative enrichment (Wilson et al., 2013),  
364 although the low mean water conductivity (0.3 mS cm<sup>-1</sup>) is within the range of modern  
365 eutrophic waters and suggests that mechanisms currently exist which maintain a  
366 freshwater state (Wilson et al., 2008). The modern lake lacks a surface outflow; the  
367 freshwater state may result from subterranean outflows via periodically unblocked  
368 sinkholes (Higgs et al., 1967) and/or natural outflows through small streams sinking  
369 beneath the limestone (Waltham, 1970). Lake Ioannina remained fresh throughout the  
370 Late Pleistocene to mid-Holocene despite fluctuations in level (Wilson et al., 2008; Jones  
371 et al., 2013), confirming the long-term hydrological influence of groundwater in this  
372 karstic system, and the potential for considerable groundwater throughflow.

373

374

375 **METHODOLOGY**

376 Core I-284 (39°45'N, 20°51'E) from the Ioannina basin was recovered in 1989 by the  
377 Greek Institute of Geology and Mineral Exploration. Preparation of samples for diatom  
378 analysis followed standard techniques, using hot H<sub>2</sub>O<sub>2</sub> and HCl, with Naphrax™ as a  
379 slide mountant (Battarbee, 1986). During the preparation of oven-dried, weighed  
380 sediment samples of c. 0.1 g for diatom analysis, known quantities of plastic  
381 microspheres were added at the final stage for calculation of absolute diatom  
382 concentrations (Battarbee and Kneen, 1982), variations in which may reveal changes in  
383 diatom productivity, sedimentation rates and/or diatom preservation (Wolfe, 1997). Other  
384 details are given in the main text. Diatoms were analysed at x1000 magnification, using a  
385 Zeiss Axioscop 2 *plus* binocular microscope under phase contrast. Diatom preservation  
386 was sufficient to allow  $\geq 500$  valves to be counted per level. Identification is based on  
387 Krammer and Lange-Bertalot (1986, 1988, 1991a, b) and Levkov et al. (2007), adopting  
388 current diatom nomenclature. Stratigraphic zone boundaries were defined using CONISS  
389 (Grimm, 1987) on square-root transformed data. Diatom data from core I-284 are  
390 presented in Table S1.

391

392 **DEVELOPMENT OF CHRONOLOGICAL FRAMEWORK**

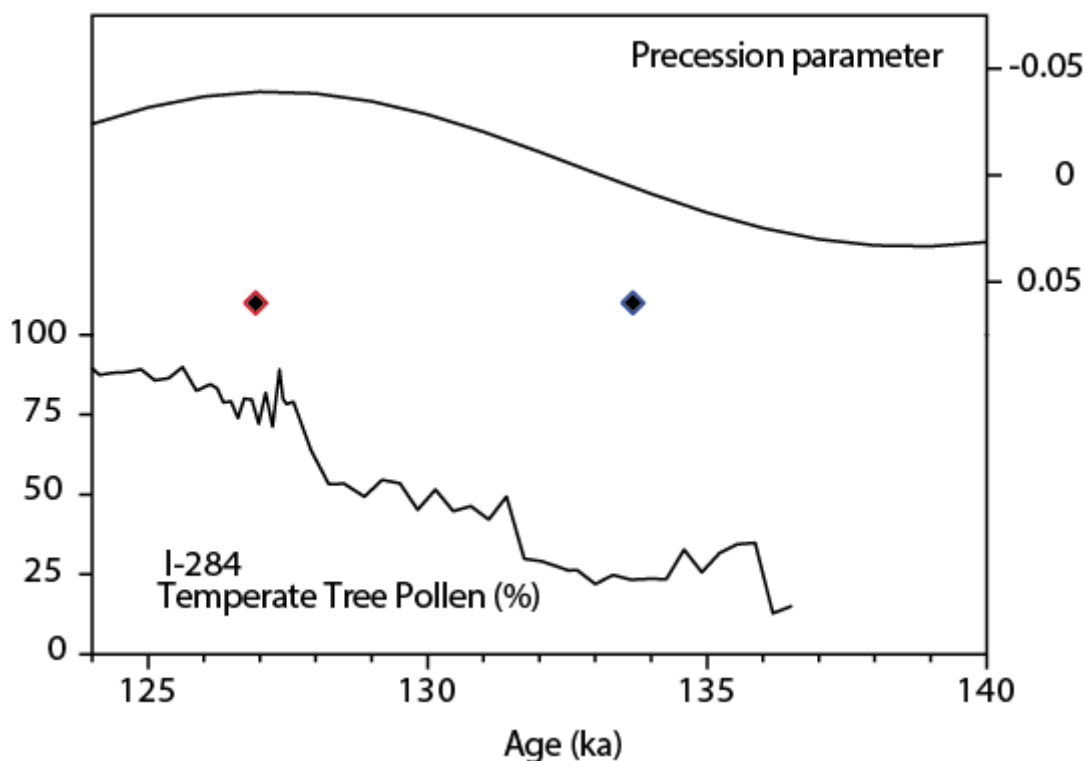
393 A persistent handicap in the study of the Last Interglacial has been the lack of  
394 precise absolute timescales from lake sediment sequences. While palaeomagnetic  
395 evidence and U-series dates on sediments have been used to provide a broad  
396 chronostratigraphical context, i.e. assignment to the right chronostratigraphic stage (e.g.

397 Frogley et al., 1999), they are not sufficiently precise to allow a precise timescale and a  
398 detailed assessment of phase relationships with other reference climate records.

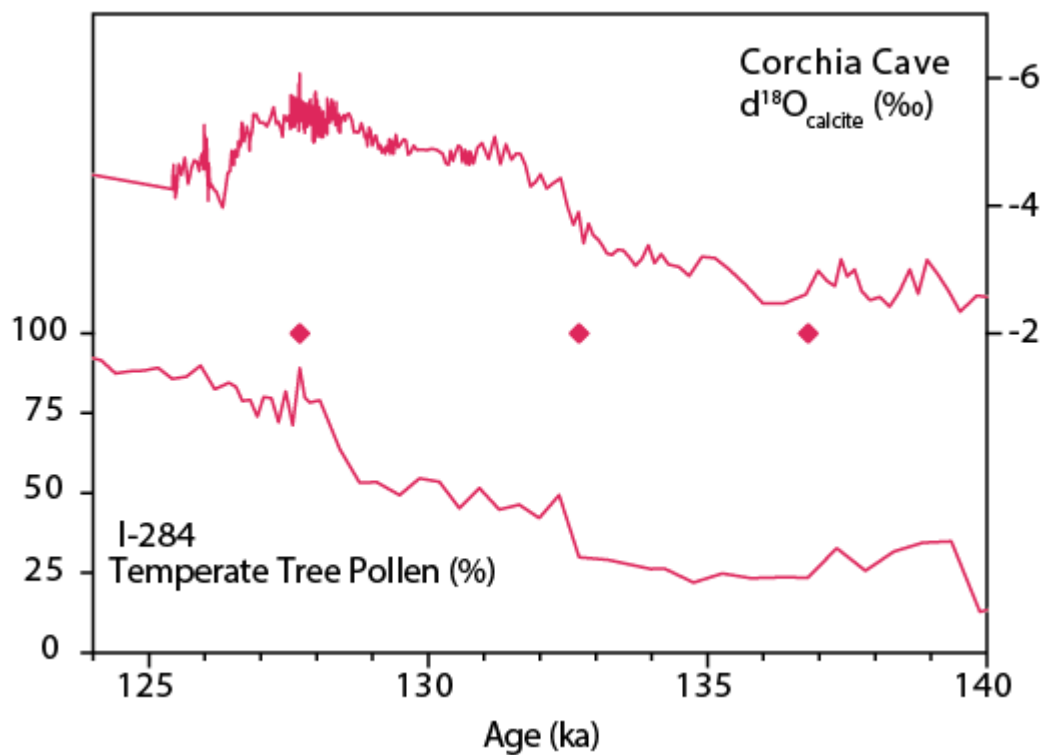
399 An ideal situation would be annually laminated sequences anchored by  
400 tephrochronological markers, but given that these are a rare occurrence (e.g. Brauer et al.,  
401 2007), alternative approaches to developing terrestrial chronologies for the majority of  
402 sequences need to be explored: (1) direct pollen-orbital tuning, using recurrent patterns of  
403 vegetation change associated with climate conditions linked to specific orbital  
404 configurations (Magri and Tzedakis, 2000; Tzedakis et al., 2002, 2003); (2) alignment to  
405 speleothem records, on the basis that changes in the amount of precipitation would affect  
406 synchronously vegetation composition and speleothem  $\delta^{18}\text{O}$  signatures; (3) alignment to  
407 marine chronologies by correlating to pollen records from marine cores. The underlying  
408 hypothesis in alignment approaches (2) and (3) is that in records lying within the same  
409 climate province, isotopic and vegetation changes would be sufficiently time-parallel to  
410 permit the linking of records.

411 Recently Govin et al. (in review) applied these different approaches to the Last  
412 Interglacial section of the Ioannina sequence, NW Greece, to compare their relative  
413 offsets and uncertainties (Fig. S1–S4). More specifically, in addition to the original  
414 chronology based on pollen-orbital tuning (Tzedakis et al., 2002, 2003), the Ioannina 284  
415 record was aligned to the speleothem  $\delta^{18}\text{O}$  record from Corchia Cave, Italy (Drysdale et  
416 al., 2009), and the pollen record from marine sequence MD95-2042 from the Portuguese  
417 margin (Shackleton et al., 2003) on the  $\text{GL}_T\text{-syn}$  chronology of Barker et al. (2011).  
418 Combined uncertainties arising from resolution and alignment errors and absolute dating  
419 errors in the reference sequence are 2.0–2.3 kyr for orbital tuning, 1.0–1.7 kyr for

420 alignment to Corchia and 1.5–1.7 kyr for alignment to MD95-2042 on the  $GL_T_{syn}$   
421 timescale. This sensitivity analysis reveals convergence on the timing of the interglacial  
422 onset (~128.1–128.6 ka). By comparison, there is a wider spread of ages for the onset of  
423 the lateglacial stadial (134.3–136.8 ka) due to alignment uncertainties in the penultimate  
424 glacial section of the sequences. Nonetheless, all ages fall within the chronological  
425 uncertainties of the different approaches. Here, we have used the alignment to Corchia  
426 Cave, as it represents the best-dated record in relative geographical proximity.  
427



428  
429 **Figure. S1.** Direct pollen-orbital tuning, using patterns of vegetation change associated with climate  
430 conditions linked to specific orbital configurations: the late glacial tree population minimum is aligned  
431 with the timing of perihelion passage in March (blue diamond) and the maximum in mediterranean  
432 sclerophylls with the timing of perihelion passage in June (red diamond) (Magri and Tzedakis, 2000;  
433 Tzedakis et al., 2002, 2003). Precession parameter(reversed axis) from Berger (1978).

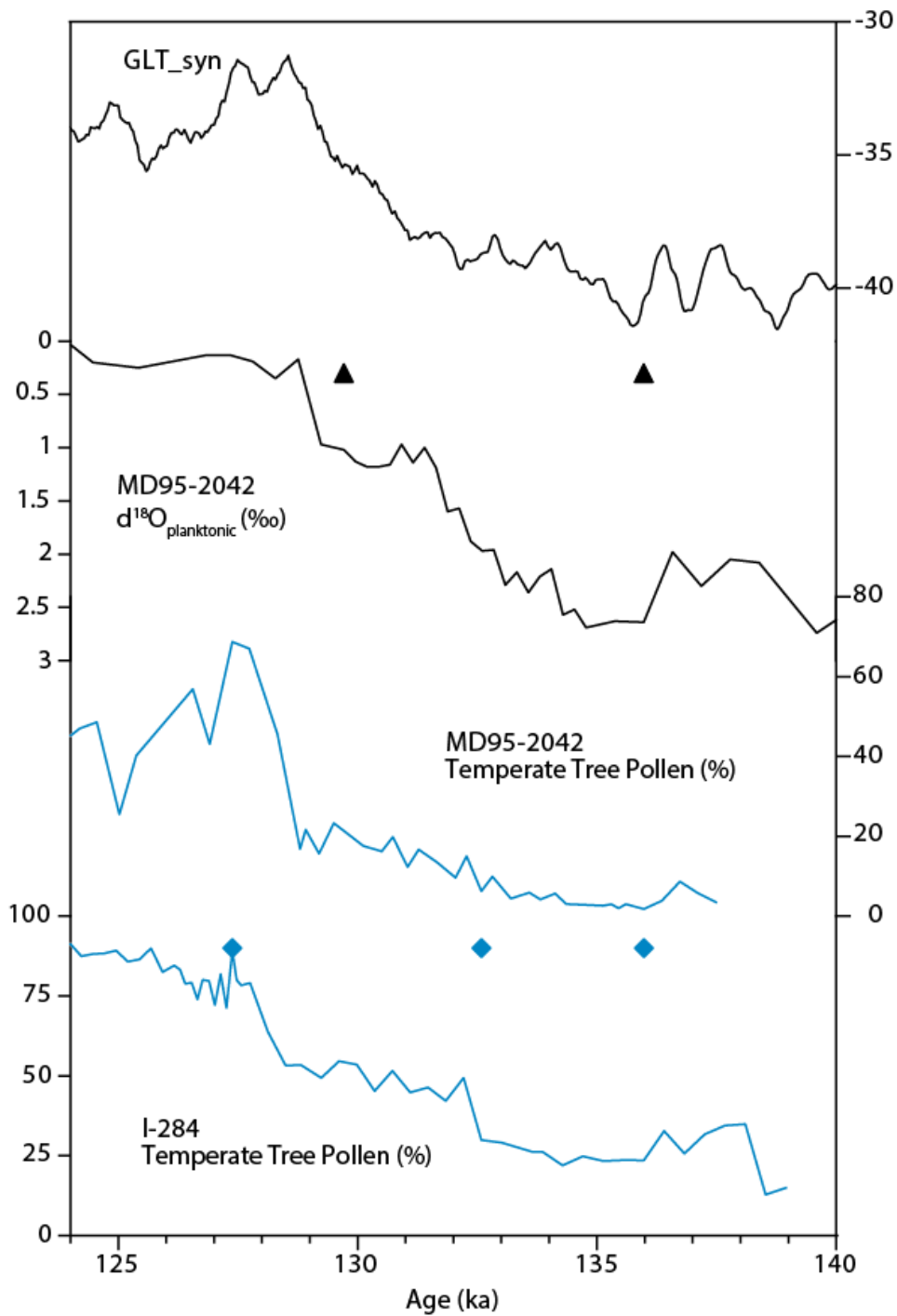


435

436 **Figure S2.** Alignment of the I-284 pollen record to Corchia Cave calcite δ<sup>18</sup>O record (Drysedale et al.,

437 2009). Diamonds denote the position of alignment points.

438

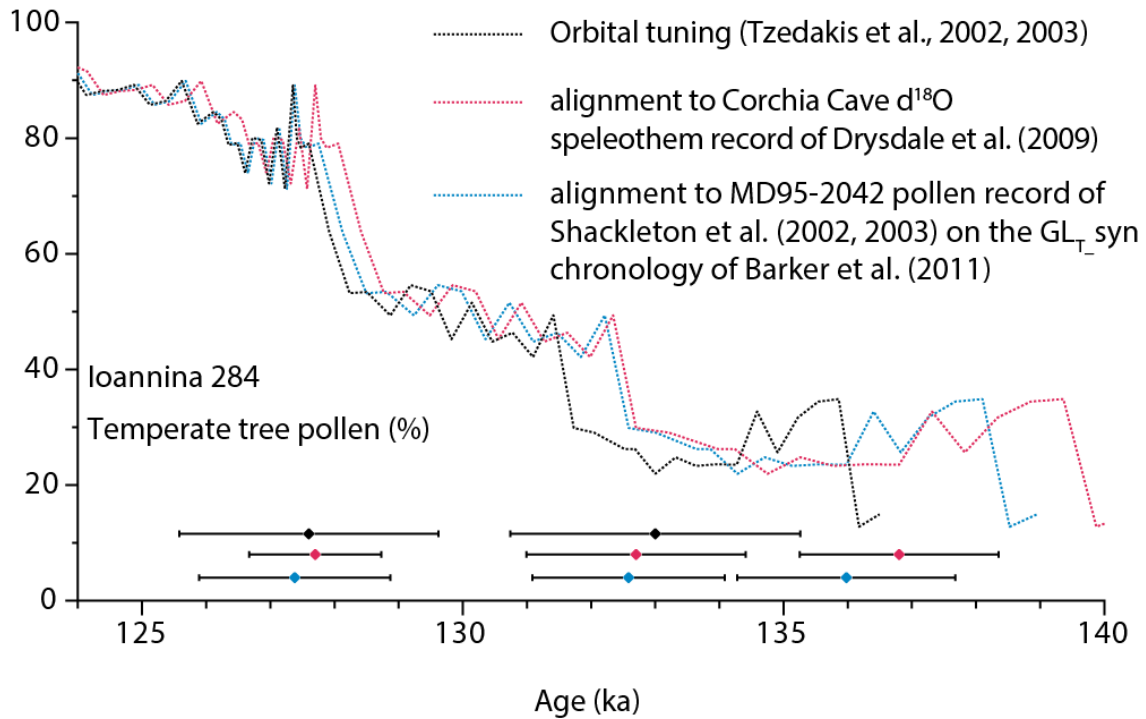


439

440 **Figure S3.** Alignment of the I-284 pollen record to the pollen record of marine sequence MD95-2042 on  
 441 the Portuguese margin (Shackleton et al., 2002, 2003). The timescale of MD95-2042 is based on alignment  
 442 of its planktonic  $\delta^{18}\text{O}$  record on the GLT\_syn chronology of Barker et al. (2011). Diamonds and triangles  
 443 denote the position of alignment points.

444





445

446 **Figure S4.** Comparison of different alignment methods to develop chronologies for the I-284 record.

447 Diamonds at the base of the diagram denote the position of control points for each scheme with the  
 448 combined 1s chronological uncertainties arising from resolution, alignment errors and absolute dating  
 449 errors (modified from Govin et al., in review).

450

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Table S1. Relative abundance of dominant ( $\geq 2\%$ ) diatom species listed by sample depth in core I-284. Diatom concentration data and the total number of valves counted are also shown.

I-284 core depth (m)	Diatom concentration (dry g sed. x10 <sup>8</sup> )	<i>Asterionella formosa</i>	<i>Cyclotella cf. minuscula</i>	<i>Cyclotella ocellata</i>	<i>Pseudostaurosira brevistriata</i>	<i>Staurosirella pinnata</i>	<i>Achnanthes lacunarum</i>	<i>Cocconeis placentula</i>	<i>Amphora pediculus</i>	<i>Encyonopsis microcephala</i>	<i>Diploneis elliptica</i>	<i>Diploneis marginistriata</i>	<i>Epithemia adnata</i>	<i>Navicula cari</i>	<i>Navicula constans</i> var. <i>symmetrica</i>	<i>Navicula menisculus</i>	<i>Placoneis porifera</i>	<i>Navicula rotunda</i>	<i>Eolimna submuralis</i>	<i>Placoneis subplacentula</i>	<i>Navicula subrotundata</i>	<i>Navicula trivialis</i> var. <i>oligotraphenta</i>	Plankton	Facultative planktonic	Benthic	Total valves counted
94.80	8.7	0	0	90	2	4	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	90	6	4	529	
95.02	8.8	0	0	88	4	4	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	88	7	4	537	
95.15	13.9	0	0	92	2	2	0	1	0	0	1	0	0	0	0	0	1	0	0	0	0	92	4	4	527	
95.22	21.0	0	1	90	1	5	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	91	6	3	520	
95.32	30.5	0	0	90	3	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	91	7	2	524	
95.39	24.8	0	2	92	1	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	94	4	2	520	
95.48	14.8	0	2	86	3	5	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	88	9	3	520	
95.58	12.5	0	1	90	3	3	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	91	5	4	512	
95.67	17.4	0	0	93	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	93	5	1	500	
95.77	34.7	0	1	91	1	3	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	92	5	4	510	
95.87	19.2	0	6	87	1	3	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	93	5	3	528	
95.96	22.6	0	8	79	4	5	0	1	0	0	0	1	0	0	0	0	0	0	0	0	1	87	9	5	502	
96.10	6.9	0	0	93	1	4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	93	5	2	503	
96.20	32.4	0	0	97	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	97	1	2	538	
96.30	16.5	0	0	88	2	7	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	89	9	3	505	

96.40	24.4	0	0	93	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	93	3	4	538
96.50	17.6	0	0	95	2	1	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	95	3	2	539
96.60	13.2	0	0	98	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	98	1	2	516
96.70	15.2	0	0	96	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	96	1	3	515
96.80	9.9	0	0	97	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	97	0	3	501
96.90	13.0	0	0	97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	97	0	3	516
97.05	18.9	0	0	97	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	97	0	3	506
97.15	9.4	0	0	97	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	97	0	3	518
97.25	12.7	0	0	99	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	99	0	1	517
97.28	12.0	0	0	97	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	97	1	2	501
97.38	9.7	0	0	96	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	96	1	3	506
97.48	10.0	0	0	96	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	96	1	3	494
97.58	10.1	0	0	97	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	97	0	3	509
97.68	10.7	0	0	91	2	1	0	0	0	0	1	0	0	0	0	3	0	0	0	0	0	0	91	2	7	528
97.78	7.4	0	0	98	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	98	1	2	532
97.88	3.6	0	0	95	0	0	0	1	1	0	1	0	0	0	0	2	0	0	0	0	0	0	95	1	5	500
97.98	9.9	0	0	96	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	96	1	3	507
98.18	1.3	0	0	81	2	6	0	0	2	0	2	1	0	0	0	0	0	1	0	0	0	0	81	8	11	508
98.28	0.8	0	1	41	7	8	0	5	7	1	2	0	3	1	3	2	1	1	1	4	1	3	42	15	43	508
98.38	1.2	0	0	32	4	11	0	10	4	6	2	1	11	4	0	3	1	4	0	0	0	0	32	15	53	518
98.47	2.5	0	0	8	14	62	1	0	2	0	0	0	0	0	0	0	12	0	0	0	0	0	8	76	16	508
98.57	1.3	0	0	4	14	59	0	0	1	0	0	0	0	0	0	0	20	0	0	0	0	0	4	74	23	510
98.67	1.1	0	0	11	4	54	0	0	1	0	0	0	0	0	0	0	28	0	0	0	0	0	11	58	31	507
98.77	1.3	0	0	5	7	72	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	5	79	16	501
98.92	2.4	0	0	62	6	6	1	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	62	12	26	525
99.07	0.4	0	0	11	4	57	0	0	1	0	0	0	0	0	0	1	22	1	0	0	0	0	11	61	28	498
99.17	2.6	0	0	82	4	6	0	0	0	0	0	0	0	0	0	0	6	1	0	0	0	0	82	10	8	524
99.27	5.0	0	0	1	12	63	1	0	3	0	0	0	0	0	0	1	17	1	0	0	0	0	1	74	24	509

99.37	1.9	0	0	6	8	67	1	0	1	0	1	0	0	0	0	0	3	10	0	0	0	0	6	76	19	503
99.47	1.4	0	0	10	14	53	1	0	2	0	0	0	0	0	0	0	1	15	1	0	0	0	10	67	23	508
99.57	7.0	0	0	18	25	38	1	0	3	0	0	1	0	0	0	0	3	3	0	0	0	0	18	63	19	514
99.67	6.8	0	0	52	7	13	1	0	4	0	0	2	0	0	0	0	1	13	3	0	0	0	52	19	29	519
99.77	9.3	0	0	54	9	14	1	0	4	0	1	2	0	0	0	0	2	6	2	0	0	0	54	23	23	517
99.87	5.3	0	0	22	18	31	1	0	6	0	2	3	0	0	0	0	5	6	2	0	0	0	22	49	29	528
99.97	6.9	0	2	43	10	16	3	0	6	0	1	3	0	0	0	0	1	11	1	0	0	0	45	26	29	507
100.07	7.3	0	1	41	8	22	3	0	7	0	0	1	0	0	0	0	2	5	1	0	0	0	43	30	27	529
100.17	12.6	0	1	61	4	10	1	0	4	0	0	2	0	0	0	0	0	12	1	0	0	0	62	14	24	507
100.27	3.9	0	0	22	19	26	4	0	3	0	0	1	0	0	0	0	1	17	2	0	0	0	22	45	33	507
100.37	10.0	0	0	65	8	8	1	0	4	0	1	2	0	0	0	0	0	7	1	0	0	0	65	16	19	508
100.47	11.7	0	0	52	13	17	1	0	2	0	1	3	1	0	0	0	1	3	1	0	0	0	52	31	17	504
100.57	9.2	0	0	26	28	34	1	0	3	0	0	0	0	0	0	0	2	2	0	0	0	0	26	63	12	517
100.67	11.0	0	0	37	13	38	1	1	2	0	1	1	0	0	0	0	1	3	0	0	0	0	37	51	12	573
100.77	10.3	0	0	14	31	37	1	0	4	0	0	0	0	0	0	0	3	3	0	0	1	0	14	68	17	502
100.87	7.3	0	0	42	16	15	2	0	2	0	1	1	0	0	0	0	0	15	1	0	0	0	42	30	28	514
100.97	6.4	0	0	49	11	19	2	0	1	0	0	2	0	0	0	0	1	10	1	0	0	0	49	30	21	522
101.07	6.9	0	0	30	20	29	1	0	2	0	1	1	0	0	0	0	2	10	0	0	1	0	30	49	21	509
101.17	15.8	0	0	81	2	5	1	0	2	0	1	0	0	0	0	0	0	5	1	0	0	0	81	6	13	505
101.27	12.5	0	1	58	4	7	1	0	3	0	1	0	0	0	0	0	0	16	2	0	1	0	59	11	30	526
101.37	11.9	0	0	87	1	5	0	0	1	0	1	2	0	0	0	0	1	0	0	0	0	0	88	6	7	500
101.47	14.4	0	1	85	1	6	0	0	1	0	0	1	0	0	0	0	0	2	0	0	1	0	85	7	7	513
101.57	12.7	3	0	83	1	6	0	0	2	0	0	0	0	0	0	0	0	1	0	0	1	0	86	7	7	535
101.67	10.7	0	0	11	12	57	1	0	3	0	0	1	0	0	0	0	1	2	0	0	6	0	11	69	20	515
101.77	13.1	0	0	9	12	69	0	0	2	0	0	0	0	0	0	0	1	1	0	0	3	0	9	81	10	534
101.87	10.7	0	0	11	21	59	0	0	2	0	0	0	0	0	0	0	1	2	0	0	2	0	11	80	9	510
101.97	5.5	0	0	10	15	65	0	0	3	0	0	1	0	0	0	0	1	0	0	0	0	0	10	80	10	508