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WARM SUMMERS AND RICH BIOTIC COMMUNITIES DURING

N-HEMISPHERE DEGLACIATION

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ABSTRACT

Detailed studies on fossil remains of plants or animals in glacial lake sediments are rare. As a result, environmental conditions right at the moment of deglaciation of the large N-Hemisphere ice-sheets remain largely unknown. Here we study three deglacial phases of the Fennoscandian Ice Sheet as a unique, repeated element in a long sediment record preserved at Sokli in northern Finland. We summarize extensive multi-proxy data (diatoms, phytoliths, chironomids, pollen, spores, non-pollen palynomorphs, macrofossils, lithology, loss-on-ignition, C/N) obtained on glacial lake sediments dated to the early Holocene (ca. 10 kyr BP), early MIS 3 (ca. 50 kyr BP) and early MIS 5a (ca. 80 kyr BP). In contrast to the common view of an unproductive ice-marginal environment, our study reconstructs rich ecosystems both in the glacial lake and along the shores with forest on recently deglaciated land. Higher than present-day summer temperatures are reconstructed based on a large variety of aquatic taxa. Rich biota developed due to the insolation-induced postglacial warming and high nutrient levels, the latter resulting from erosion of fresh bedrock and sediment, leaching of surface soils, decay of plant material under shallow water conditions, and sudden decreases in lake volume. Aquatic communities responded quickly to deglaciation and warm summers and reflect boreal conditions, in contrast to the terrestrial ecosystem which responded with some delay probably due to time required for slow soil formation processes. Birch forest is reconstructed upon deglaciation of the large LGM ice-sheet and shrub tundra following the probably faster melting smaller MIS 4 and MIS 5b ice-sheets. Our study shows that glacial lake sediments can provide valuable palaeo-environmental data, that aquatic biota and terrestrial vegetation rapidly accommodated to new environmental conditions during deglaciation, and that glacial lake ecosystems, and the carbon stored in their sediments, should be included in earth system modeling.

Keywords: glacial lake sediment, ice-marginal environment, climate, ecosystem response, carbon storage, Fennoscandian Ice Sheet

1 Introduction

Glacial lake sediments are a persistent element in the geological record (Carrivick and Tweed, 2013; Lunkka et al., 2015) and former extents of glacial lakes have been mapped in different regions globally (Lundqvist, 1972; Björck, 1995; Dyke, 2004; Glasser et al., 2016). Particularly the drainage of large glacial lakes has received significant attention as it has the potential of influencing ocean circulation and climate on a global scale (Broecker and Denton, 1990; Barber et al., 1999).

Extensive ice-marginal retreat in the Fennoscandian and Laurentide Ice Sheets occurred at the last peak of high-latitude summer insolation around ca. 10 kyr cal BP (Dyke, 2004; Stroeven et al., 2016). The postglacial warming allowed for the production of large amounts of meltwater and, with the land-surface inclined towards the retreating ice-fronts due to isostatic depression, glacial lakes were formed extensively (Fig. 1). Although the sediments deposited in these lakes and fossil remains stored in them form a potential natural archive for palaeo-environmental and -climatic studies, the biotic content of glacial lake sediments has been rarely analyzed in detail. The lack of fossil analysis on glacial lake sediments is probably due to the generally low fossil content and often broken/corroded nature of fossil remains (e.g. Lunkka et al., 2015), making the analysis particularly time-consuming. Also, fossil remains are often considered as redeposited from older deposits as the ice-marginal environment is classically interpreted as harsh and unproductive (e.g. Stroeven et al., 2016). The difficulty of recovering the minerogenic glacial lake sediment at the base of Holocene peat or gyttja sequences with the help of conventional hand-coring adds yet another reason for the lack of studies on these sediments.

The north-eastern margin of the Fennoscandian Ice Sheet receded from the Sokli basin in northern Finland (Fig. 1) several times during Marine Isotope Stages (MIS) 5 to 1. Glacial lake deposits dated to early MIS 5e, 5a, and 3 and the early Holocene are found here in stratigraphic sequence with glacial till beds and non-glacial lacustrine and fluvial deposits. During each deglaciation episode there was a progression of lake stages associated with deglaciation (stage 1), maximum extent of the glacial lake (stage 2), and glacial lake drainage (stage 3). The Sokli sequence uniquely preserves lake sediments from four deglaciation episodes due to a non-typical bedrock setting combined with frozen-bed conditions at the base of the Fennoscandian Ice Sheet (Helmens et al., 2007a, and references therein).

3

88   The Sokli sedimentary sequence provides an exceptional opportunity to study the ice-marginal

89   environment during the retreat of a continental ice-sheet as a repeating element in the Late Quaternary

90   geological record at a single site. We here integrate multi-proxy data (diatoms, phytoliths, chironomids,

91   pollen, spores, NPP's (non-pollen palynomorphs), macrofossils, lithology, LOI (loss-on-ignition), C/N)

92   that are available for the glacial lake sediments in the Sokli basin dated to the early Holocene (Shala et

93   al., 2014a, 2014b, 2017) and early MIS 3 (Engels et al., 2008; Bos et al., 2009; Helmens et al., 2009),

94   and further compare this extensive data-set with newly obtained data for multiple proxies from the

95   glacial lake sediments of early MIS 5a age. The overall coarse-grained glacial lake sediment found at

96   the base of the MIS 5e gyttja deposit contains very few fossil remains (Plikk et al., 2016) and is not

97   included in this study. The aim of our study is to reconstruct in detail biota in the glacial lake, along its

98   shores and on the surrounding land, as well as successive developments in these ecosystems upon

99   deglaciation and glacial lake evolution, for a series of Late Quaternary deglaciation episodes at the same

100   site. Furthermore, the multi-proxy data are used to make climate inferences. Our study provides valuable

101   paleo-environmental data and new understanding on the aquatic and terrestrial productivity of the ice-

102   marginal environment during N-Hemisphere deglaciation.

103

104   **2 Environmental and stratigraphic setting**

105

106   **2.1 The study site**

107

108   The Sokli site is situated in the northern boreal forest of north-eastern Finland (lat. 67°48' N, long. 29°18'

109   E, elevation ca. 220 m a.s.l.) and on the main water divide that separates drainage into the Barents and

110   White Seas to the east and the Baltic Sea to the southwest (Fig. 1). Bedrock in the region is Precambrian

111   Shield with the exception of the immediate surroundings of the study site which is underlain by a

112   Paleozoic magma-intrusion known as Sokli Carbonatite Massif (Fig. 2B). The Sokli wetland (Sokliaapa)

113   is drained by the Sokli rivulet (Soklioja), the latter flowing south-westwards into the Yli-Nuortti river.

114   Within the Sokli basin, Lake Loitsana occupies a depression associated with a NW-SE trending esker

115   chain.

4

116   Present climate at Sokli is cold boreal with mean July and February temperatures at 13°C and -

117   14°C, respectively; mean annual precipitation amounts to 500-550 mm (Drebs et al., 2002). Lakes in

118   the area are ice-covered between October and end of May. Birch (*Betula pubescens* and *B. pendula*),

119   pine (*Pinus sylvestris*) and spruce (*Picea abies)* are the dominant tree species. Mires of the aapa-type

120   (i.e. a patterned fen) with *Sphagnum* spp., *Rubus chamaemorus*, Ericales, *Betula nana* (dwarf birch),

121   *Salix* spp*.* and *Carex* spp*.* are extensively present in the region. Spruce reaches its northern limit some

122   100 km north of Sokli. Farther north, pine forest predominates, succeeded northwards and upwards by

123   birch-pine forest and then sub-arctic birch forest. The forest limit, which is situated some 300 km north

124   of Sokli, is formed by the polycormic mountain birch *B. pubescens* subsp. *czerepanovii*, syn. *tortuosa*.

125   The vegetation of the tundra region beyond the forest limit is low-arctic dwarf-shrub tundra dominated

126   by *B. nana* and Ericales.

127

128   **2.2 Late Quaternary stratigraphy in the Sokli basin**

129

130   An unconsolidated sedimentary sequence up to ca. 30 m in thickness, including several organic units

131   and till beds, is present in the central part of the Sokli Carbonatite Massif where two main fault zones

132   cross (Fig. 2A, B). The unusually long Sokli sediment record, which spans the last ca. 140 kyr, has been

133   protected from glacial erosion due to its sheltered position in a steep depression formed in the deeply-

134   weathered rocks of the Sokli Massif.

135   The composite lithological log in Figure 2A is based on a series of boreholes collected between

136   1996-2010 (Fig. 2B) and is an updated version from lithological columns earlier presented in Helmens

137   et al. (2000, 2007a). The Sokli sediments have been dated by AMS ^{14}C dating on macrofossils of

138   terrestrial plants, TL and IRSL dating, and OSL dating on quartz using SAR dose protocol (Helmens et

139   al., 2000, 2007a; Alexanderson et al., 2008). OSL dates on quartz yielded large standard errors mainly

140   due to small sample sizes, relatively poor luminescence characteristics, and uncertainties in dose-rate

141   determinations. The OSL ages are, however, in sequence and (together with ^{14}C ages) group according

142   to stratigraphic units (Fig. 2A); furthermore, the absolute chronology is in agreement with earlier made

143 land-sea comparisons (Fig. 2C; Helmens *et al*., 2000, 2007a; Alexanderson et al., 2008). The

144 stratigraphy in the Sokli basin (Fig. 2A, right side) is according to Helmens (2014).

145   A diatom gyttja deposit up to 9 m in thickness, and dated to the Eemian Interglacial (MIS 5e),

146 stretches as a marker horizon near the base of the Sokli basin infill (Plikk et al., 2016; Fig. 2). The diatom

147 gyttja overlays coarse-grained glacio-lacustrine sediment resting on till (MIS 6; Ilvonen, 1973). A sand

148 and gravel deposit of fluvial origin (MIS 5d) separates the MIS 5e lake sediment from sandy gyttja that

149 was deposited in an oxbow lake during MIS 5c (Helmens et al., 2012). The upper part of the Sokli

150 sedimentary sequence consists of till interlayered with two additionally well-sorted, fine-grained

151 lacustrine sequences (MIS 5a and MIS 3). The deposition of glacio-lacustrine silt and clay in early MIS

152 5a was followed by the accumulation of gyttja (this study). The glacio-lacustrine sediment of early MIS

153 3 age is capped by till (Helmens et al., 2009). Lake Loitsana holds a 7m-thick gyttja deposit underlain

154 by a glacio-lacustrine deposit of early Holocene age (Shala et al., 2014a, 2014b). Glaciation of the Sokli

155 basin is dated to MIS 5b, MIS 4 and late MIS 3-2 (Helmens et al., 2007a).

156

157 **2.3 The Sokli Ice Lake**

158

159 The Late Quaternary glacial lake sediments preserved in the Sokli basin were deposited in the Sokli Ice

160 Lake (Fig. 1). Figure 3 gives a schematic representation of the evolution of the later stages of the Sokli

161 Ice Lake, i.e. from the moment of deglaciation of the Sokli site (Lake Stage 1) until its final drainage

162 through the Nuortti canyon (Lake Stage 3). Glacier meltwater was trapped between the hills of the Värriö

163 tunturi and the retreating ice-margin during the early stages of the glacial lake (Johansson, 1995).

164   The ice-marginal retreat pattern in Figure 3 is guided by NW-SE oriented eskers that are dated to

165 the last deglaciation in the early Holocene (Johansson, 2007; Shala et al., 2014a). Importantly, a similar

166 evolution of these final stages of the Sokli Ice Lake has been reconstructed for early MIS 3 (Helmens et

167 al., 2009) based on N-S trending, till-covered eskers in the region dated by OSL at 65 ± 13 kyr BP

168 (Johansson, 2007). The direction of ice-marginal retreat in early MIS 5a was to the northwest

169 (Johansson, 1995) and, also during this deglaciation episode, the glacial lake evolution was probably

170 similar as during the early Holocene. The reconstruction in Figure 3 is based on geomorphologic (e.g.

171 meltwater channels) and DEM (Digital Elevation Model) data and corresponds to the one originally

172 presented in Johansson (1995). As the area invoked in the glacial lake reconstruction is relatively small

173 (ca. 30 x 30 km), possible errors generated due to non-uniform isostasy are considered to be insignificant

174 (cf. Jansson 2003).

175   During each deglaciation episode, the Sokli Ice Lake varied in surface area and water depth

176 depending on the position of the ice-front and the location of spillways/overflow sites (Fig. 3). During

177 Lake Stages 1 and 2, the level of the glacial lake was controlled by the col at the head of the Törmäoja

178 canyon which has a present elevation of 240 m. The glacial lake reached its maximum spatial extension

179 during Lake Stage 2. Opening of the Nuortti canyon resulted in partial (Lake Stage 3; col at 220 m

180 elevation) and final drainage of the Sokli Ice Lake.

181

182 **3 Methods**

183

184 A total of 2 m of glacial lake silts and clays, below 7 m of gyttja, was retrieved with the Russian peat

185 corer from ice-covered Lake Loitsana. The 1-2 m thick early MIS 3 and MIS 5a glacial lake deposits,

186 which underlie the LGM (Last Glacial Maximum) till, were recovered using heavy-equipment

187 percussion drilling from the frozen surface of the Sokli wetland. Methods used for multi-proxy analysis

188 on the sediments of early MIS 5a age follow those applied to the glacial lake sediments of early MIS 3

189 and early Holocene age. The latter are presented in Helmens et al. (2009) and Shala et al. (2014a, 2014b)

190 (siliceous microfossils and LOI); Engels et al. (2008) and Shala et al. (2014b) (chironomids); Bos et al.

191 (2009) and Shala et al. (2014b, 2017) (pollen/spores/NPP's and macrofossils); and Shala et al. (2014b)

192 (C/N). For all three time-slices (early Holocene, MIS 3 and 5a), diatom and chironomid diversities are

193 calculated using Hill's N_2 (effective number of occurrences; Hill, 1973).

194   A minimum of 500 diatom valves, 50 chironomid head capsules and ca. 400 terrestrial pollen

195 grains were identified in each sample from the early MIS 5a glacial lake deposit. The sample size for

196 the macrofossil analysis was mainly 10-15 cm^3. Furthermore, we submitted two samples from gyttja

197 found overlying the early MIS 5a deglacial sediment for AMS ^{14}C dating.

4 Results and Discussion

199

200 **4.1 Timing and duration of the Sokli Ice Lake**

201

202 ^{14}C dating on seeds of tree birch encountered in the youngest glacial lake deposit has provided an age

203 of ca. 10.5 kyr cal BP for the last deglaciation of the Sokli basin (Shala et al., 2014a, 2014b). This date

204 is in accordance with the early Holocene deglaciation chronology for north-eastern Fennoscandia as

205 presented in Johansson (2007) and Stroeven et al. (2016). It also shows that the *Betula* seeds occur in-

206 situ, i.e. they are not reworked from older deposits. The in-situ preservation of fossil remains in the

207 glacial lake sediment is further demonstrated by ^{14}C ages on wood from the early MIS 3 sediment

208 sequence (Helmens et al., 2000, 2007b) which are in line with OSL dating results (Alexanderson et al.,

209 2008; Figs. 2 and 4B). The latter deglaciation episode probably occurred at ca. 53 kyr BP during

210 prominent Greenland Interstadial (GI) 14 (Helmens et al., 2007b; Helmens and Engels, 2010). New [14]C

211 datings of macrofossils from gyttja that overlies the oldest glacial lake deposit gave, as expected, infinite

212 ages (Table 1). This episode of deglaciation has been earlier dated to early MIS 5a based on OSL dating

213 of glacio-fluvial sand and gravel, that occur beneath the glacial lake sediment, at ca. 80 kyr BP and of

214 minerogenic sediment at the top of the overlying gyttja at ca. 74 kyr BP (Alexanderson et al., 2008; Figs.

215 2 and 4C).

216   The duration of the Sokli Ice Lake following the last deglaciation of the Sokli site is estimated at

217 less than 100 yr (Johansson, 2007; Stroeven et al., 2016; Fig. 3). A duration of some 400 kyr is inferred

218 based on ^{14}C dating evidence from the early Holocene glacial lake deposit in the Sokli basin (Shala et

219 al., 2014a, 2014b) and counting of the distinct, possibly annual laminae in the glacial lake sediment of

220 early MIS 3 age (Helmens et al., 2009). However, the 50 to 100-year error margins on the [4]C dates (Fig.

221 4A), and the large spread in calendar ages for the earliest Holocene, hamper a detailed age determination

222 for glacial lake duration.

223

224

4.2 Aquatic and telmatic ecosystem changes in the ice-marginal environment during deglaciation

The evolution of the Sokli Ice Lake as depicted in Figure 3 can be clearly traced in the sediment sequence of each deglaciation episode (early Holocene, MIS 3 and 5a; Fig. 4). The ice-marginal retreat during Lake Stages 1 and 2 is recorded by an upward-fining sequence of sandy and silty sediment grading into rhythmically laminated silts and clays at the base of each glacial lake sequence. Following the decrease in level and size of the glacial lake associated with the opening of the Nuortti canyon (Lake Stage 3), silts (early Holocene) and silts grading into sandy sediment (early MIS 3 and 5a) were deposited at the coring-sites. Lacustrine sedimentation is recorded to continue with the accumulation of organic silts followed by gyttja in the Sokli basin during early MIS 5a, and gyttja in Lake Loitsana in the early Holocene. The early MIS 3 glacial lake sediments were found to be covered by till. Furthermore, the Sokli Ice Lake evolution has been traced in XRF-based geochemical data available for the early Holocene glacial lake sediment (Shala et al., 2014a). The latter shows a decrease in sediment input enriched in elements (Ca, S and Nb) typical for the local bedrock (Sokli Carbonatite Massif) during Lake Stage 2, i.e. when the Sokli Massif became entirely submerged in the expanding glacial lake (Fig. 3).

The biotic proxy diagrams obtained from the early Holocene (Fig. 4A), early MIS 3 (Fig. 4B) and early MIS 5a glacial lake sediments (Fig. 4C) reveal marked compositional shifts in biotic assemblages in concordance with the changes in size and depth of the Sokli Ice Lake. This shows that biota responded quickly to environmental changes during deglaciation. It also provides further support for the in-situ preservation of fossil remains. Although the biotic data obtained for the different deglaciation episodes share many similarities, fossil assemblages and successive developments appear to be influenced by actual lake depth. Overall deepest lake conditions are reconstructed for early MIS 5a, and shallowest waters during the early Holocene. This can be expected due to continuing infilling of the Sokli basin and progressive lowering of the glacial lake outlet channels resulting from erosion. Below, the biotic records will be used to reconstruct in detail the aquatic and telmatic ecosystem composition in and along the shore of the Sokli Ice Lake during its evolution.

4.2.1 Glacial Lake Stages 1 and 2

254

255 The fossil content and diversity of fossil remains (expressed by e.g. Hill's N_2 values for diatoms and

256 chironomids) increase, both during the early Holocene (Fig. 4A) and early MIS 3 deglaciation episodes

257 (Fig. 4B), with increasing distance of the ice-margin from the coring-site (Lake Stages 1-2 in Fig. 3).

258 The overall meagre fossil content of the Lake Stage 1-2 sediments of early MIS 5a age (Fig. 4C) most

259 probably result from deep water conditions (suggested by relatively high planktonic diatom percentages)

260 and long distance to shore. Furthermore, C/N values (only measured for the Holocene (Fig. 4A))

261 gradually drop during Lake Stages 1-2 suggesting an increased in-lake productivity. It is less-likely that

262 the low C/N values in the latter part of Lake Stage 2 result from a decreased contribution of higher plants

263 since seeds of *Carex* and high pollen percentages of Cyperaceae and *Salix* indicate an expansion in the

264 wetland zone close to the coring-sites. In general, high C/N ratios (> 10) indicate input of organic matter

265 from higher plants (littoral/wetland/terrestrial), and low ratios (< 10) reflect input from phytoplankton

266 (Wetzel, 2001).

267 Turbulent waters and turbid water conditions occur close to ice-margins and significantly decrease

268 primary productivity (Henley et al., 2000). Also, the fossil record in the coarse-grained ice-marginal

269 sediment at the base of the studied sequences (Lake Stage 1) can be expected to be diluted due to high

270 sedimentation rates (Risberg et al., 1999) and plant/animal remains to be more easily destroyed in this

271 high-energy environment.

272 Chironomids that are recorded among the first colonizers of the Sokli Ice Lake during all three

273 time-slices (early Holocene, MIS 3 and 5a) are the deep-water taxa *Heterotrissocladius maeaeri*-type,

274 *Tanytarsus lugens*-type and *Procladius*. *H. maeaeri*-type is reported to have dominated the deep waters

275 of the late-glacial Baltic Ice Lake in southern Finland (Fig. 1; Luoto et al., 2010). Diatoms were mostly

276 Fragilariaceae and *Aulacoseira*. Fragilariaceae is a group of taxa that is characterized as pioneering and

277 opportunistic, since they colonize quickly, have high reproduction rates and are more adaptive to a

278 changing environment (Risberg et al., 1996; Lotter et al., 1999). The encountered planktonic

279 *Aulacoseira* species (*A. ambigua*, *A. subarctica*, *A. alpigena*) are all heavily silicified and most probably

280 reflect a large influx of Si into the glacial lake and enhanced levels of turbulence. A high Si-level is

281 further suggested by findings of *Tetracyclus glans* (Michel et al., 2006). Statoblasts of the bryozoan

282 *Fredericella indica* (Økland and Økland, 2001) and high abundances of pooid phytoliths and Tertiary

283 diatoms in the sediment indicate wave action and significant shore erosion. Tertiary diatoms are

284 exemplified by species like *Pliocaenicus costatus*, a relict freshwater taxon from the Pliocene, and

285 *Paralia sulcata* of marine-origin, their robust structure allowing for multiple phases of re-working

286 (Helmens et al., 20009, and references therein). The pioneering algal *Botrycoccus braunii*, algal type

287 T.225 (van Geel et al., 1989) and the cladoceran *Daphnia* (water-flea; recorded by ephippia) are

288 additionally well-represented among the first lake colonizers.

289 Occurrences of the diatom taxa *Epithemia adnata* and *Rhopalodia gibba* in the upper part of the

290 Lake Stage 2 sediment of early Holocene age suggest pH values exclusively above 7 (van Dam et al.,

291 1994). High abundances of ostracod remains indicate enhanced Ca-concentrations. This lake water

292 chemistry mostly probably resulted from rapid leaching of carbonates and other soluble minerals from

293 surface soils shortly after deglaciation (Engstrom et al., 2000). An enhanced level of nutrients in the

294 glacial lake during the latter part of Lake Stage 2 in early MIS 3, and particularly during early MIS 5a,

295 is further suggested by relatively high percentage values of *Stephanodiscus* species (*S. medius*, *S.*

296 *minutulus*, *S. neoastraea*, *S. alpinus*).

297 Although the recording of the bryozoan *F. indica* suggests stony shores with sparse aquatic

298 vegetation (Økland and Økland, 2005), macrofossils, pooid phytoliths and pollen indicate the presence

299 of the herbs *Rorippa palustris*, *Filipendula* and grasses (e.g. *Glyceria lithuanica*) as well as *Empetrum*

300 *nigrum*, *Carex*, *Juncus Equisetum* and *Sphagnum* in local shore or wetland habitats (i.e. telmatic habitat)

301 along the glacial lake shoreline.

302

303 *4.2.2 Glacial Lake Stage 3*

304

305 The local establishment of diverse aquatic and telmatic communities is recorded in the silty glacial lake

306 sediments of Lake Stage 3. This stage followed the opening of a new spillway which resulted in a drastic

307 decrease in water depth and size of the Sokli Ice Lake (Fig. 3). The margin of the Fennoscandian Ice

308 Sheet during Stage 3 was situated at a distance of less than 10 km from the coring-site (i.e. before

309 deglaciation of the Nuortti canyon in Fig. 3). The amount of macrofossils in lake sediments is strongly

310 influenced by taphonomic factors, e.g. with a close location of the shoreline sharply increasing

311 macrofossil abundances at the coring-site (Hannon and Gaillard, 1997; Väliranta, 2006), and

312 macrofossils are distinctly more abundant in the Lake Stage 3 sediment, particularly in the early

313 Holocene. Below, the Lake Stage 3 aquatic and telmatic ecosystems will be discussed separately for the

314 three deglaciation episodes.

315   Fossil remains in the early Holocene deposit (Fig. 4A) reflect a shallow lake and even further

316 shallowing, accompanied by an extension in the wetland zone (macrofossils of *Carex*, *B. nana*,

317 *Vaccinium*, *Typha* and *Ranunculus* sect. *Batrachium*), higher up in the Stage 3 silts. Characteristic is the

318 high representation in the macrofossil record of the shallow-water plant *Callitriche*

319 *cophocarpa*/*hermaphroditica*, the bryozoan *Plumatella repens* and *Daphnia*. Also, various littoral

320 chironomid taxa (*Polypedilum nubeculosum*-, *Microtendipes pedellus*-, *Dicrotendipes nervosus*-type)

321 are recorded. A large variety of *Potamogeton* species (*P. berchtoldii, P. filiformis, P. friesii, P.*

322 *obtusifolius, P. pectinatus*), aquatic Nymphaeaceae (*Nymphaea*, *Nuphar*), and the bryozoan *Cristatella*

323 *mucedo* are additionally well-represented in the upper part of the silt deposit. The pioneering, narrow-

324 leaved *Potamogeton* species thrive in shallow (0.1-1.5 m) water depths. *C. mucedo* (if produced locally)

325 suggest more coloured water with less wave action than *F. indica* (Økland and Økland, 2005).

326 Simultaneously to the trend in lake shallowing, rising nutrient levels are suggested by increasing

327 abundances of the chironomid taxon *Endochironomus albipennis*-type (Moller Pillot, 2009). The

328 occurrences of *C. mucedo*, Nymphaeceae and *Typha* indicate boreal conditions. In contrast to these rich

329 biotic communities, diatom assemblages in the early Holocene Stage 3 sediment are largely dominated

330 by *Staurosira construens* var. *venter*, showing peak values reaching > 85%. This might reflect the littoral

331 and periphytic (growing on plants) habitat preferences of this diatom species and/or tolerance to poor

332 light conditions (Bigler et al., 2003), the latter possibly resulting from erosion of the adjacent esker.

333   Shallowing of the glacial lake and accompanying rising nutrient levels are recorded in detail in

334 the thick early MIS 3 silty deposit. Initially, *F. indica* (Økland and Økland, 2005) and the chironomid

335 taxon *Ablabesmyia* (Vallenduuk et al., 2007) suggest moderate nutrient availability. Subsequently,

336 nutrient levels increase as indicated by high percentage values for *E. albipennis*-type combined with

occurrences of *P. friessi* and the macro-algae *Nitella*. The appearance of the cladoceran *Simocephalus* in the upper sandy part of the deposit suggests shallow, open water, eutrophic conditions and dense stands of vegetation (van Geel et al., 1983). Strongly reduced water depths during deposition of the upper sandy silts of Stage 3 are further indicated by enhanced values for the shallow-water algae *Spirogyra* and the littoral diatom taxon *Staurosirella pinnata*, as well as a distinct extension in the wetland zone. The latter is recorded by high abundances of bryophyte leaves, seeds of *Carex*, *Juncus*, *B. nana* and *E. nigrum*, increased percentage values for Cyperaceae pollen and a near continuous registration of hyphopodia of *Clasterosporium caricinum*, i.e. a fungus that parasitizes on *Carex* (van Geel et al., 1983).

Fossils in the silty Glacial Lake Stage 3 sediment of early MIS 5a age include macro-remains of *P. repens*, *Callitriche* (*C. cophocarpa*, *C. hermaphroditica C. hamulata*), narrow-leaved *Potamogeton* (including *P. compressus*) and the shallow-water plant *Ceratophyllum*. Characteristic is the combined appearance of *Tanytarsus pallidicornis*- and *Psectrocladius sordidellus*-type, i.e. chironomid taxa presently common in the sublittoral and littoral zones of boreal lakes mostly found living among *Phragmites* stands (Luoto, 2010). Nutrient availability was overall high as indicated by occurrences of *E. albipennis*-type, *Chironomus plumosus*-type (Brooks et al., 2001) and a high representation of *Stephanodiscus* among the diatoms. The enhanced nutrient level, and high chironomid species diversity (high Hill's N_2 values), might be related to inflow of running water close to the coring-site as also has been recorded in the MIS 5d-c deposit in the Sokli basin (Engels et al, 2010). Inflow of water is indicated by relatively high abundances of stream-inhabiting chironomid taxa (e.g. *Eukiefferiella* and *Rheocricotopus*) as well as the type of lamination of the silty deposit, i.e. laminae of varying grain-sizes (clay to fine sand) and thicknesses. Similar as during the early Holocene and MIS 3, a strong reduction in water depth during deposition of the uppermost sandy part of the MIS 5a silt deposit is reflected in the fossil record (littoral *M. pedellus*-type and *S. pinnata*; macrofossils of *Carex*, *Salix*, *B. nana*).

Interestingly, the diatom *Aulacoseira granulata* var. *angustissima* appears with peak values in the upper sandy sediment of Lake Stage 3 both during early MIS 5a and MIS 3 and, together with increased representations of the diatom taxa *Staurosirella leptostauron*, *Diploneis elliptica* and *Amphora libyca*, reflect alkaline waters with high Ca-concentrations (Gómez et al., 1995; Jones et al., 2004). This lake

365   water chemistry was recorded in the early Holocene glacial lake sequence already during the relatively

366   shallow-water Lake Stage 2. It is possible that the glacial lake volume during early MIS 3 and 5a became

367   only reduced enough during Lake Stage 3 in order for alkaline water conditions to be established.

368

369   *4.2.3 Early Loitsana and Sokli lakes*

370

371   The early Holocene sandy gyttja deposited in Lake Loitsana contains relatively high fossil abundances

372   of the chironomid taxa *Cricotopus intersectus-* and *Cricotopus cylindraceus*-type. These are typical

373   littoral taxa with an affinity for plants (Brooks et al., 2007; Luoto, 2010) and their occurrences might be

374   related to an influx of insect and plant remains (e.g. *Equisetum* tissue) by running water. Particularly

375   stream-inhabiting chironomids (e.g. *Rheotanytarsus*, *Eukiefferiella*, *Rheocricotopus*), but also

376   rheophilic diatom taxa (e.g. *Meridion circulare, Amphora pediculus*), indicate inflow of running water

377   nearby the coring-site. *Corynocera ambigua*, which has a complex ecology (Brodersen and Lindegaard,

378   1999), dominates the chironomid assemblage in the MIS 5a lake deposit in the Sokli basin. Nutrient

379   levels were high both in the early Loitsana and Sokli lakes (*E. albipennis*-type, *C. plumosus*-type,

380   *Stephanodiscus parvus*). This might have resulted from morphometric eutrophication (Hofmann 1998),

381   i.e. a condition created by a reduction in lake volume. In our study, the latter occurred when the Sokli

382   Ice Lake fully drained and lacustrine sedimentation continued in small depressions within the Sokli

383   basin.

384

385   **4.3 MIS 3 ice-sheet dynamics**

386

387   The glacial lake sequences of early Holocene, MIS 3 and MIS 5a age reveal remarkably similar

388   assemblages and successions in aquatic and telmatic biota, however, some additional, special features

389   are shown by the early MIS 3 glacial lake deposit. This most probably relates to different levels of ice-

390   sheet dynamics upon deglaciation. First, the glacial lake sediment of early MIS 3 age is interlayered

391   throughout the sequence with distinct clay laminae suggesting a continuing influence of the ice-sheet on

392   lake deposition, even in the case of a distal position. Secondly, the sediment and fossil record seems to

14

393 register a glacier re-advance phase which intersected the shallow Glacial Lake Stage 3. The latter is

394 demonstrated by the re-occurrence of deep water (increases in tycho-planktonic diatom taxa and the

395 deep-water chironomid taxon *T. lugens*-type), a large lake-size (*Aulacoseira islandica*; Serieyssol et al.,

396 2009), oligotrophic lake water conditions (*Cymbella aspera*; Krammer and Lange-Bertalot, 1986) and

397 significant shore erosion (> 50 % of phytoliths) (Fig. 4B). Re-advances of the ice-margin are commonly

398 recorded in glacial lake sediment sequences and are not necessarily climate-driven (Carrivick and

399 Tweed, 2013). Striking also is the co-occurrence of peak abundances of *Procladius* with a large variety

400 of algae (*B. braunii*, *Pediastrum*, *Tetraedon* cf. *minimum*, *Zygnema*, *Spirogyra*, T.225; high diatom-

401 inferred Hill's N_2) in the finely laminated clayey sediment at the end of Stage 2. This might reflect

402 density stratification, a process typical for glacial lakes (Carrivick and Tweed, 2013, and references

403 therein) in which sediment-loaded cold meltwater extends below warmer and more transparent river-fed

404 water. The river-fed water probably favoured a diverse algal community. *Procladius*, which is abundant

405 during this phase, is a ubiquitous chironomid taxon with a wide environmental tolerance including turbid

406 water inflows (Greffard et al., 2012) and is found in lakes with a large variability in limnological

407 conditions, such as hypolimnetic oxygen availability and water temperature (Brodersen et al., 2004). In

408 addition to these features, the till bed, and overlying glacio-fluvial gravels and sands, at the base of the

409 early MIS 3 deglacial sediment sequence shows large chucks of organic debris reworked from the

410 Eemian Interglacial (MIS 5e) gyttja in the Sokli basin (Helmens et al., 2000). All these features together

411 suggest active, warm-based ice in the course of early MIS 3 deglaciation.

412

413 **4.4 Terrestrial vegetation in the ice-marginal environment during deglaciation**

414

415 Pollen and macrofossil remains found in the glacial lake sediments further allow a detailed

416 reconstruction of terrestrial vegetation during the different episodes of deglaciation. Numerous seeds of

417 birch trees and pollen percentage values for *Betula pubescens/pendula* of up to 80 % in the shallow

418 Glacial Lake Stage 3 silts of early Holocene age (Fig. 4A) indicate the presence of birch forest on the

419 land adjacent to the Sokli Ice Lake (Shala et al., 2017). Birch trees already bordered the glacial lake

420 during Stage 2 (macrofossils present) and possibly Stage 1, i.e. in close proximity to the ice-margin.

421   Macrofossils are overall scarce in the latter sediments, probably due to the large lake size and long

422   distance to shore. Moreover, the large contribution of grasses to the pollen sum, which for a major part

423   might be derived from local shore habitats (high abundances of phytoliths), inhibits a precise pollen-

424   based reconstruction of the terrestrial vegetation during Lake Stages 1 and 2.

425   *B. pubescens/pendula* and *Pinus* are represented by pollen values of 30-50 % and 20 %,

426   respectively, in the glacial lake sediments of early MIS 3 and MIS 5a age (Fig. 4B-C). Whereas *B.*

427   *pubescens/pendula* dominates the pollen assemblages in modern calibration samples from the sub-arctic

428   birch forest in northern Fennoscandia, birch pollen percentages drop at the expense of pine pollen north

429   of the birch tree-line (Aario, 1940; Prentice, 1978). The increase in representation of pine relative to

430   birch occurs as the forest thins out, and *Pinus* pollen with its greater dispersal capability is being blown

431   in from the south. Therefore, the modern calibration data suggests the presence of tundra vegetation on

432   recently deglaciated terrain during early MIS 3 and 5a. According to Bos et al. (2009), the tundra

433   vegetation during early MIS 3 appears to have been remarkably similar to the present-day tundra in

434   northern Fennoscandia. Seeds of tree birch in the early MIS 5a glacial lake sediment indicate the

435   presence of birch trees in the tundra vegetation, and *B. pubescens/pendula* pollen percentage values

436   rising to 80 % in the overlying gyttja deposit registers the local establishment of birch forest. Pine forest

437   with larch is recorded in the younger part of the MIS 5a gyttja deposit (N. Kuosmanen, unpublished

438   data). Pollen and macrofossil data from interstadial organic-bearing sediment in northern Finland, dated

439   to MIS 3, register birch forest and the local presence of pine trees (Sarala et al., 2016).

440   *Betula* spp. are fast immigrants due to the advantage of an abundant production of wind-dispersed

441   fruits, rapid reproductive rates, fast growth rates and a young reproductive-maturity age (Birks, 1986).

442   Furthermore, rapid migration of trees over the deglaciated land was probably facilitated by the northern

443   location of glacial plant refugia (Väliranta et al., 2011; Tsuda et al., 2016). The existence of boreal tree

444   populations in northerly small pockets of environmentally favorable conditions, in some cases close to

445   the edge of the LGM ice-sheet, is being suggested by evidence from e.g. macrofossil charcoal

446   assemblages and ancient DNA (Willis and van Andel, 2004; Parducci *et al*., 2012). However, while

447   aquatic biota in the glacial lake show a mostly boreal character (see section 4.2), vegetation on land was

448   sub-arctic in nature probably due to time needed for soil forming processes (Väliranta et al., 2015).

449 Interestingly also, our study shows that forested conditions were achieved in the ice-marginal

450 environment during the early Holocene, whereas more open tundra vegetation seems to have

451 characterized this environment during early MIS 3 and 5a. This might be the result of the relatively slow

452 melting of the large LGM ice-sheet, allowing tree birch to migrate in congruent pace with the retreating

453 ice-margin.

454

455 **4.5 Climate during deglaciation**

456

457 There is overwhelming evidence in the fossil record from the early Holocene, MIS 3 and MIS 5a glacial

458 lake sediments at Sokli for warm summers during deglaciation. This result is in accordance with high

459 Milankovitch-forced summer insolation at high latitudes during all three time intervals (Berger and

460 Loutre, 1991; Fig. 2).

461 Table 2 summarizes estimates of mean July air temperature (T_{jul}) for the three deglaciation

462 episodes based on macrofossil and chironomid remains. Aquatic and telmatic plant indicator taxa

463 identified in the macrofossil records are given in the table together with (in parenthesis) lowest required

464 T_{jul} for current species presence in Finland (following Väliranta et al., 2015; Shala et al., 2017).

465 Additionally, chironomid taxa with warm temperature optima (i.e. warmer-than-today) are indicated;

466 the optima are based on the distribution patterns of chironomid taxa in the Finnish chironomid-

467 temperature calibration data-set (Luoto et al., 2014a, 2014b). The presence of these warm-indicating

468 plant and chironomid taxa (Table 2), as well as the quantitative chironomid-inferred T_{jul} records for early

469 MIS 3 (Engels et al., 2008), the early Holocene (Shala et al., 2017), and early MIS 5a (T. Luoto,

470 unpublished data), indicate mean July air temperatures similar (13 °C) or higher-than-today during all

471 three deglaciation episodes. Highest T_{jul} (ca. 15-15.5 °C) are inferred for the early Holocene deglacial

472 episode (Table 2; Shala et al., 2017). Furthermore, the aquatic and littoral plant macrofossil assemblages

473 encountered in the glacial lake sediments consistently suggest boreal conditions in the ice-marginal

474 environment (Bos et al., 2009; Väliranta et al., 2015; Shala et al., 2017; this study).

475 Warm summers in Fennoscandia during the early Holocene are also reported in e.g. Kullman

476 (1998), Luoto et al. (2014b) and Paus and Haugland (2017), and during early MIS 3 in Sarala et al.

477 (2016). The latter is inferred from findings of fossil remains of the aquatic taxa *Sagittaria sagitifolia*

478 (14.4 °C), Nymphaea and *Callitriche* in sediment dated to MIS 3. Quantitatively inferred climate

479 parameters based on fossil remains predating the LGM are scarce, not only in Fennsocandia but also on

480 the European mainland. Warm summers as well as warm winters are recorded by plant macrofossils and

481 insect remains at Oerel (northern Germany) during early MIS 5a (Behre et al., 2005).

482

483 **4.6 Comparisons with studies in North America**

484

485 One of the few detailed fossil analyses, including pollen, NPP's and macrofossils, on glacial lake

486 sediments in North America is presented in Boyd et al. (2003). This study focuses on the terminal stages

487 of Glacial Lake Hind, i.e. one of several interconnected proglacial lakes that formed across the Canadian

488 prairies in front of the retreating margin of the Laurentide Ice Sheet in the early Holocene. Glacial Lake

489 Hind discharged eastwards into Glacial Lake Agassiz (Fig. 1). Boyd et al. (2003) report a diverse

490 macrofossil assemblage in glacial lake clays and silts, representing a high diversity of emergent and

491 aquatic plants (e.g. various *Potamogeton* species such as narrow-leaved *P. filiformis*), and including

492 abundant needles of *Picea* and a bud scale of *Populus*. Peak values for pollen of the wetland plant *Typha*

493 in gyttja directly overlying the Glacial Lake Hind sediment indicates substantial postglacial warming

494 (Boyd et al., 2003).

495 Early Holocene warm summers in response to Milankovitch-forced insolation have earlier been

496 reported by Ritchie et al. (1983) based on pollen and macrofossil remains of *Typha* from 12 high-latitude

497 sites in northern Canada dated to ca. 6-12 kyr BP and clustering at 10.5 kyr BP. The results from Canada

498 are very similar to those obtained in the present study at Sokli indicating diverse aquatic biota, local

499 presence of trees and warm summers along the retreating margin of the large N Hemisphere ice-sheets

500 during deglaciation.

501

502

503

504

4.7 Glacial lake sediments and carbon storage

Although glacial lakes covered large parts of northern Europe and North America, contemporaneous glacial lakes generally were relatively small, confined to the deeper parts in the landscape. The glacial lakes went through complex evolutions as the topography changed and spill-ways opened-up along the retreating ice-margins (e.g. Dyke, 2004; Boyd et al., 2007; Johansson, 2007; Carrivick and Tweed, 2013). This is exemplified by the study of Jansson (2003) which mapped a total of 26 glacial lakes (65 sub-stages) in Labrador/Ungava, eastern Canada, during the early Holocene retreat of the Laurentide Ice Sheet.

Within the glacial lakes, protected bays were common features and, in combination with inflow of rivers draining unglaciated terrain, allowed for aquatic and telmatic biota to flourish in the lakes and along their shores (Boyd et al., 2003; Boyd, 2007; Bos et al., 2009; Helmens et al., 2009; Shala et al., 2014b; this study). Diverse biota was promoted by enhanced nutrient levels in the recently deglaciated terrain combined with insolation-induced warm summers. A close proximity to glacial plant refugia (e.g. Willis and van Andel, 2004) further facilitated the establishment of trees or open forest in the ice-marginal environment. Abundant macrofossils in the shallow glacial lake sediment of early Holocene age at Sokli, combined with the presence of birch forest in the catchment, led to an organic carbon content (LOI) in the sediment rising to 20 % (Fig. 4A; Shala et al., 2014a, 2014b). The sediment was found interlayered with thin organic laminae at a site close to the former glacial lake shore (Saunavuotso in Fig. 2B). This shows that postglacial carbon storage started within the glacial lake sediment, i.e. prior to the accumulation of peat that was initiated over large parts of central and eastern Canada (Dredge and Cowan, 1989) and northern Europe (e.g. Oksanen et al., 2001) due to the presence of the relatively impermeable glacial lake silts and clays. Although more regional studies are needed, the present study at Sokli reveals that aquatic biota and terrestrial vegetation quickly adapted to new environmental conditions during N-Hemisphere deglaciation and that glacial lake ecosystems, and the carbon stored in their sediments, should not be neglected in earth system modeling.

19

5 Conclusions

Our study shows that glacial lake sediments at the base of interglacial and interstadial deposits can provide important information on past environmental and climate conditions. These sediments have rarely been included in proxy-based palaeo-environmental studies, with the consequence that environmental and climate conditions during deglaciation of the large N-Hemisphere ice-sheets have largely remained unknown. Deglacial stages such as the LGM-Holocene transition are important testbeds in assessing climate sensitivity and the role of individual forcings and feedbacks in climate change (Shakun et al., 2012). In large parts of the N Hemisphere, the earliest evidence of the postglacial terrestrial and aquatic environments and climate are stored in glacial lake sediments. Our finding of distinct indicators of warm and productive conditions in the ice-marginal environment, immediately following deglaciation, is thus relevant for assessing the climate response and rates of ecosystem change during the critical glacial-interglacial transitions. Furthermore, the spatial extent and depth of glacial lake sediments, and their geochemistry, should be carefully assessed to quantify the carbon storage in glacial lake systems. Finally, paleo-environmental studies based on glacial lake sediments will benefit from studies in present-day ice-marginal environments, which, however, are currently scarce (Carrivick and Tweed, 2013).

Author Contributions

K.H. conceived the study and wrote the manuscript, with input from all authors. K.H., C.K., J.S.S., S.S., J.A.A.B., S.E., N.K., T.P.L. and M.V. performed laboratory analyses and, together with J.R. and J.W., made palaeo-environmental interpretations. A.O. made the glacial lake maps in Figure 1.

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802 Willis, K.J., van Andel, T.H., 2004. Trees or no trees? The environments of central and eastern Europe

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804 Table 1. AMS radiocarbon ages for the MIS 5a lake (gyttja) deposit at Sokli.

805

Borehole	Depth (m)	Material	Age (yr BP)	Laboratory No.
Sokli 2/2010	9.4	*Macrofossils of terrestrial plants(mostly seeds of birch)*	>47000	Poz-56337
Sokli 2/2010	9	*Macrofossils of terrestrial plants (mostly wood)*	>51000	Poz-56338

806

807

808 Table 2. Mean July air temperature (T_{jul}) estimates based on macrofossils of aquatic/telmatic plants
809 (minimum T_{jul} values) and chironomids (optimum T_{jul} values) for the different deglaciation episodes at
810 Sokli. Present-day T_{jul} at Sokli is 13 °C.

811

Deglaciation episode	Minimum T_{jul} (macrofossils)	Optimum T_{jul} (chironomids)
Early Holocene	*Typha* (15.7 °C) *Glyceria lithuanica* (15.7 °C) *Callitriche cophocarpa/ hermaphroditica* (13.7-14.0 °C) narrow-leaved *Potamogeton* spp. such as *P. friesii* (13.6 °C) Nymphaea (13.5 °C)	*Cricotopus cylindraceus*-type (15.4 °C) *Cricotopus intersectus*-type (15.1 °C) *Chironomus anthracinus*-type (14.7 °C) *Polypedilum nubeculosum*-type (14.5 °C) *Microtendipes pedellus*-type (13.4 °C) *Psectrocladius sordidellus*-type (13.1 °C)
Early MIS 3	*Callitriche hermaphroditica* (14.0 °C) narrow-leaved *Potamogeton* spp. (*P. friesii*; 13.6 °C)	*Chironomus anthracinus*-type (14.7 °C) *Cladotanytarsus mancus*-type (14.4 °C) *Polypedilum nubeculosum*-type (14.5 °C) *Microtendipes pedellus*-type (13.4 °C)
Early MIS 5a	*Ceratophyllum* (14.1 °C) *Callitriche hermaphroditica* (14.0 °C) *Callitriche cophocarpa* (13.7 °C) narrow-leaved *Potamogeton* spp. (*P. compressus, P. berchtoldii*; 13.6 °C)	*Chironomus anthracinus*-type (14.7 °C) *Cladotanytarsus mancus*-type (14.4 °C) *Polypedilum nubeculosum*-type (14.5 °C) *Microtendipes pedellus*-type (13.4 °C) *Psectrocladius sordidellus*-type (13.1 °C)

Figure captions

813

814 Fig. 1. The extent of glacial lakes in northern Europe (**A**) and North America (**B**) during the last

815 deglaciation around 10 kyr cal BP. **A** shows the maximum extent of the Ancylus Lake in the Baltic Sea

816 basin at 10 kyr cal BP (Björck, 1995). The other lakes are time-transgressive. The extent of Ice Lakes

817 along the western margin of the Fennoscandian Ice Sheet, and the glacial retreat chronology, are

818 according to Stroeven et al. (2016, and references therein), whereas Ice Lakes along the northern and

819 eastern margin of the ice-sheet follow Johansson (2007) and Ojala et al. (2013, and references therein),

820 respectively. The Sokli Ice Lake which is the subject of this study is highlighted. **B** shows the total

821 cumulative area covered by Glacial Lake Agassiz in North America in the time interval 13-8 kyr cal BP

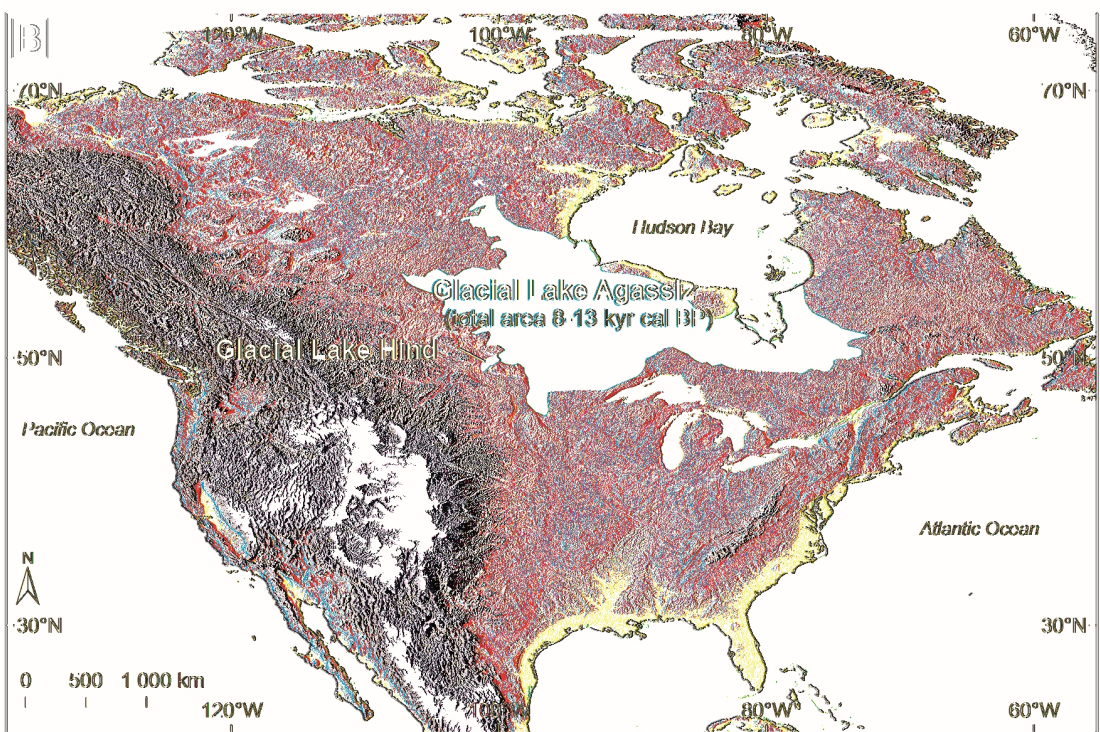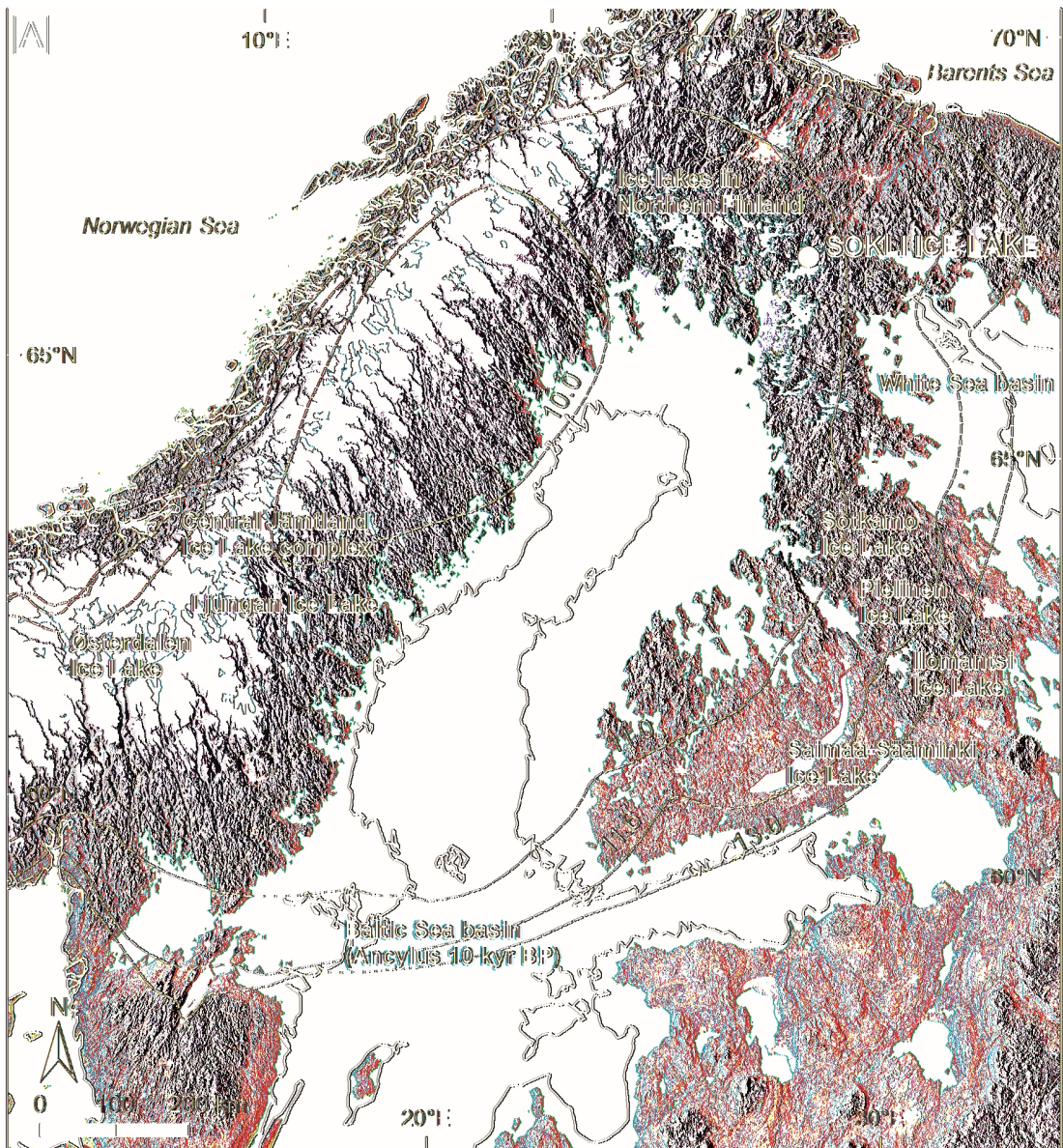822 (Teller and Leverington, 2004).

823

824 Fig. 2. **A** New composite lithological column for the Late Quaternary sedimentary sequence in the Sokli

825 basin with to the right the local stratigraphy according to Helmens (2014). The location within the Sokli

826 basin of boreholes which are indicated along the left side of the lithological log is given in **B**. The

827 correlation of the Sokli record with the marine global oxygen-isotope stack (Lisiecki and Raymo, 2005)

828 and high-latitude July insolation (Berger and Loutre, 1991) (**C**) is based on stratigraphy and absolute

829 dating evidence (^{14}C, OSL, TL and IRSL dates); absolute dates are indicated to the left of the lithological

830 column in **A** (see text). Deglacial sediment intervals that are the subject of the present study, dated to

831 the early Holocene, early MIS 3 and early MIS 5a, are highlighted by pink boxes.
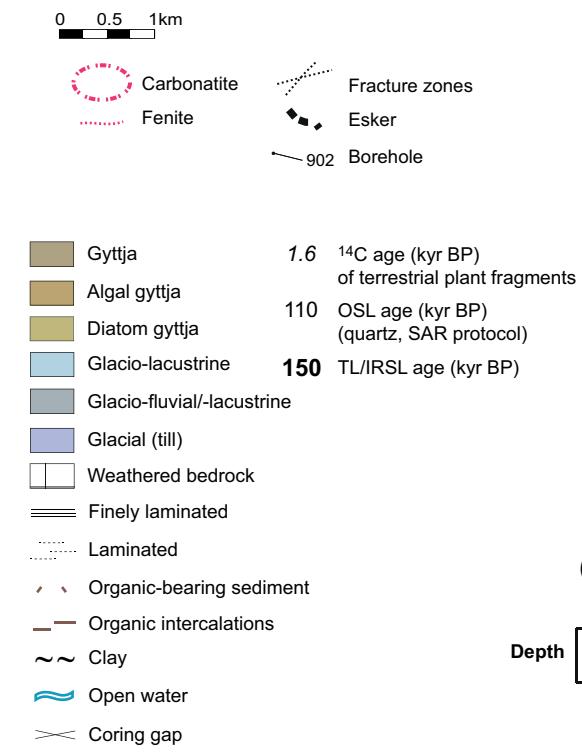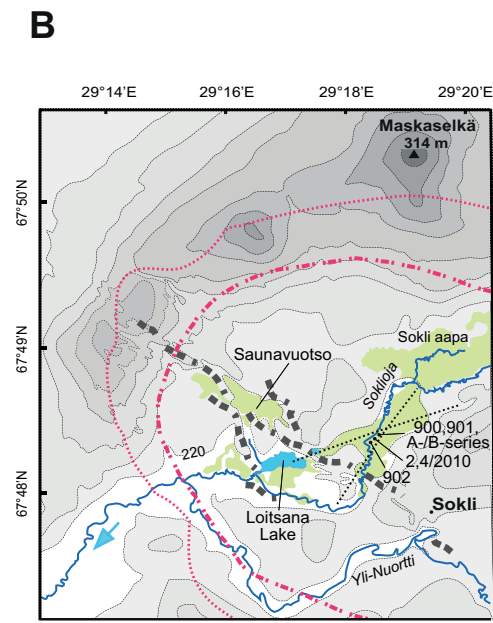
832

833 Fig. 3. Evolution of the later stages of the Sokli Ice Lake in the early Holocene; cross-sections show

834 maximum water depths in Lake Loitsana (Shala et al., 2014a). Note that elevations are modern values.

835 A similar glacial lake evolution occurred during the early MIS 3 and 5a deglaciation episodes. Lake

836 Stage 1: deglaciation of the study site. Lake Stage 2: maximum spatial extent of the glacial lake. Lake

837 Stage 3: partial drainage resulting in a smaller and more shallow glacial lake.
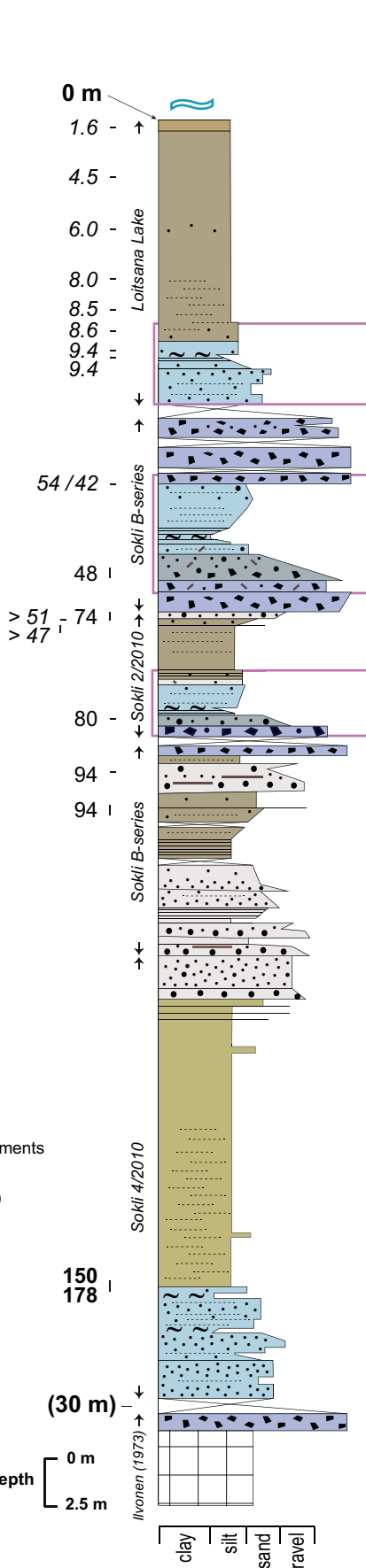
838

839   Fig. 4. Selection of proxy data for deglacial sediments in the Sokli basin dated to the early Holocene

840   (**A**), early MIS 3 (**B**) and early MIS 5a (**C**). For legends see **C**. Phytoliths and Tertiary diatoms are

841   calculated as percentages of the total sum of siliceous microfossils. Percentage values of pollen, spores

842   and NPP's are based on the total sum of pollen of terrestrial plants. Based on **A** Shala et al. (2014a,

843   2014b, 2017); **B** Engels et al. (2008), Bos et al. (2009), and Helmens et al. (2009); **C** this study.

A

Barents Sea

Norwegian Sea

Ice lakes in
Northern Finland

SOKLI ICE LAKE

White Sea basin

65°N

65°N

Central Finland
Ice Lake complex

Sotkamo
Ice Lake

Pielinen
Ice Lake

Hjørdal Ice Lake

Østerdalen
Ice Lake

Tomarus
Ice Lake

Salmaat-Saamiinki
Ice Lake

60°N

Baltic Sea basin
(Ancylus 10 kyr BP)

N

0   100   200 km

20°E

B

120°W   100°W   80°W   60°W

70°N   70°N

Hudson Bay

Glacial Lake Agassiz
(total area 8-13 kyr cal BP)

50°N

Glacial Lake Hind

50°N

Pacific Ocean

Atlantic Ocean

N

30°N   30°N

0   500   1 000 km

120°W   80°W   60°W
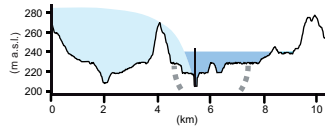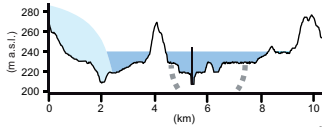
A Composite log Sokli / Loitsana

Stratigraphy Sokli basin
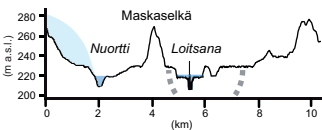
B

C Insolation July 65° N — Benthic δ18O global stack (LR04)
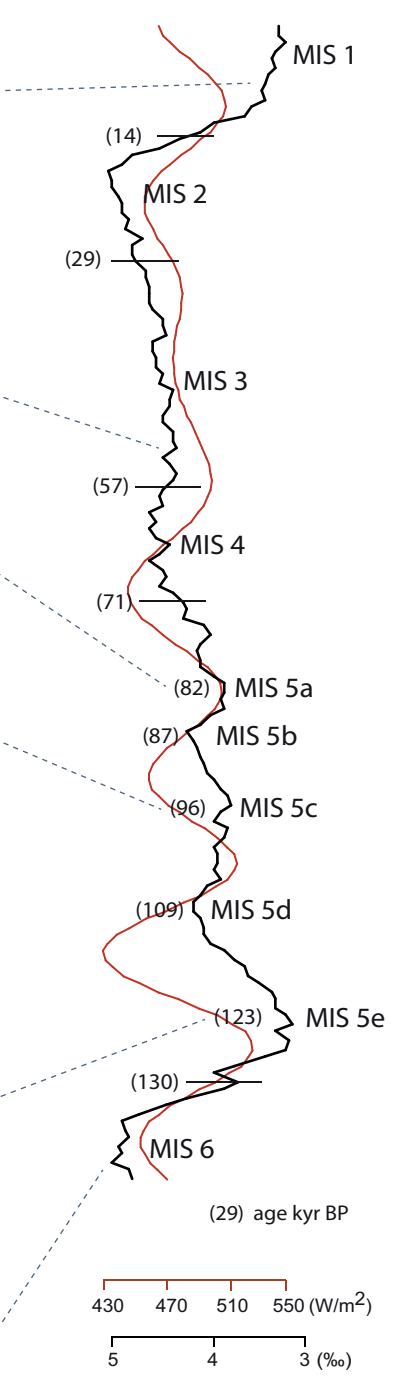
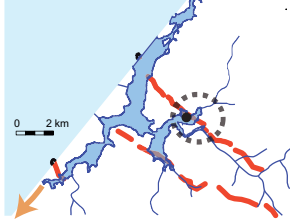Maximum extension of glacial lake
LAKE STAGE 2

Törmäoja canyon

× **240 m**

(m a.s.l.)
280
260
240
220
200
0 2 4 6 8 10
(km)

Deglaciation of coring-site
LAKE STAGE 1

Törmäoja canyon

× **240 m**

(m a.s.l.)
280
260
240
220
200
0 2 4 6 8 10
(km)

Glacial lake drainage
LAKE STAGE 3

Nuortti river canyon

× **220 m**

0 2 km

(m a.s.l.)
280
260
240
220
200

Maskaselkä

Nuortti   Loitsana

0 2 4 6 8 10
(km)
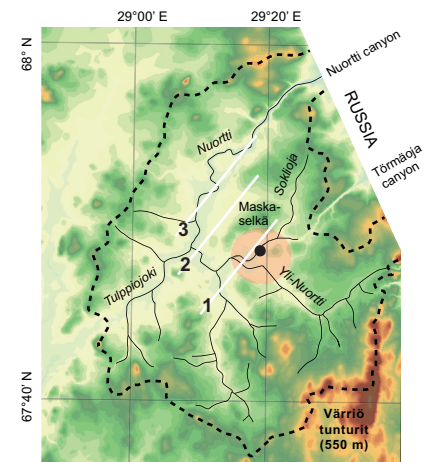
Retreating margin of the
Fennoscandian Ice Sheet

Subglacial meltwater
channel mouth
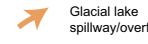
Esker
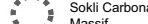
Sokli Ice Lake

Glacial lake spillway/overflow
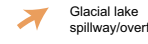
Sokli Carbonatite Massif

Study site

29°00' E   29°20' E

68° N

Nuortti canyon

RUSSIA

Törmäoja canyon

Nuortti

Soklioja

Maska-selkä

3

2

1

Tulppiojoki

Yli-Nuortti

67°40' N

Värriö tunturit
(550 m)

5   0   5 km
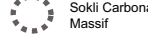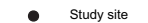
Nuortti River
drainage basin
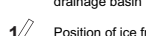
1 Position of ice front
during Lake Stage 1
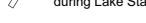
Sokli Carbonatite Massif

A (early Holocene)

Diatoms

Chironomids

Other aquatic taxa (bryozoa, cladocera, ostracods, algae, aquatic plants) / Wetland plants

Terrestrial plants

Fossil analysts:

Shyhrete Shala (siliceous micro-, macrofossils); Tomi Luoto (chironomids); Sakari Salonen (pollen, spores, NPP's)

c = macrofossil counts / 10 cc

[1] *Aulacoseira alpigena, ambigua, subarctica*

[2] *Callitriche cophocarpa/hermaphroditica*

[3] *Potamogeton spp, berchtoldii, filiformis, friesii, obtusifolius, pectinatus*

reworked   planktonic   tychoplanktonic   benthic

B (early MIS 3)

C (early MIS 5a)

Diatoms — Chironomids

CHRONOLOGY | DEPTH (M) | BOREHOLE | LITHOLOGY | LAKE STAGES

MIS 5a

MIS 5b

Sokli Lake
Glacial lake drainage (3)
Max. extent glacial lake (2)
Deglaciation (1)

reworked | planktonic | tychoplanktonic | benthic   [1] *Stephanodiscus medius, minutulus, neoastraea*

Other aquatic taxa (bryozoa, cladocera, algae, aquatic plants) / Wetland plants — Terrestrial plants

LAKE STAGES

Sokli Lake

3

2

1

Macrofossils:
ba: bark   oo: oogonia
bd: bud scale   pr: perigynia
car: caryopses   sb: statoblast
ck: catkin scale sd: seed
ep: ephippia   st: stem
f: fruit   t: tissue
fc: frontoclypeus tw: twig
l: leave   vr: vegetative remain
lv: leavy stem
nt: nutlet

ls: leave spike (microfossil analysis)

Fossil analysts:
Christos Katrantsiotis (siliceous microfossils);
Tomi Luoto (chironomids);
Niina Kuosmanen (pollen, spores, NPP's);
Minna Väliranta (macrofossils)

c = macrofossil counts / 10-15 cc   [2] *Callitriche cophocarpa, hermaphroditica*   [3] *Potamogeton spp, compressus, berchtoldii*

> 47000 ^{14}C age (yr BP)
74000   OSL age (yr BP)
(in-between brackest): from other borehole

Gyttja
Organic matter
Distinct clay laminae
Laminated
Till