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# The sediments of Lake Lögurinn – A unique proxy record of Holocene glacial meltwater variability in eastern Iceland

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ABSTRACT

The full Holocene development of the large (8100 km$^2$) Vatnajökull ice cap in Iceland with its many outlet glaciers is poorly known. The idea of an early deglaciation, leading to a glacier-free period in mid-Holocene, followed by the Neoglaciation is still the main concept for the glacial history in the North Atlantic region, including Iceland. We have examined a continuous sediment record from the glacier-fed Lake Lögurinn in eastern Iceland to infer Holocene meltwater variability of Eyjabakkajökull, which is a surge-type outlet glacier of the Vatnajökull ice cap. We focus on the early and mid-Holocene, and our data show that Eyjabakkajökull receded rapidly during the final phase of the last deglaciation, and did not deliver glacial meltwater to Lake Lögurinn by 9000 years BP, suggesting that Eyjabakkajökull was significantly smaller than today at that time. The return of glacial meltwater transport to Lake Lögurinn, and thus a return of Eyjabakkajökull is dated to ca 4400 years BP, suggesting an almost 5000 years long glacier-free period during early and mid-Holocene. During this time period, we infer that the 8.2 ka cold event did not cause a significant expansion of Eyjabakkajökull, however, we note a marked decrease in the aquatic productivity in Lake Lögurinn, which is suggested to be the result of shorter ice-free seasons of Lake Lögurinn. The Holocene Thermal Maximum is inferred by a period of maximum Holocene aquatic productivity, and dated to ca 7900–7000 years BP. Following the re-formation of Eyjabakkajökull ca 4400 years BP, we suggest that the glacier reached stable conditions ca 1700 years BP, and remained fairly stable until the later part of the Little Ice Age, when Eyjabakkajökull reached its maximum Holocene extent.



## 1. Introduction

The North Atlantic region has undergone significant climate fluctuations during the Holocene, caused by changes in the atmospheric and ocean circulation (Bond et al., 1997, 2001; Andresen et al., 2006). Iceland is the largest landmass in this region, and changes in these large-scale systems will ultimately influence the mass balance of Icelandic glaciers (Ingólfsson et al., 1997; Bradwell et al., 2006). The status of Icelandic glaciers during the Holocene is a well-studied topic (e.g. Geirsdóttir et al., 2009a), but as pointed out by Caseldine et al. (2006), most studies have been focussed on glacial activity during the later part of the Holocene and to a less extent on the glacial activity during its early part. To improve the knowledge about the early and mid-Holocene glacial activity in Iceland, a sediment sequence from Lake Lögurinn in eastern Iceland that extends back to ca 10 500 years BP (BP = calendar years before 1950 AD) have been examined. This glacier-fed lake presently receives meltwater from Eyjabakkajökull, which is a surge-type outlet glacier of the large (8100 km$^2$) Vatnajökull ice cap. In addition, Lake Lögurinn receives runoff from the catchment of River Grímsá that drains a fairly large and currently non-glaciated area. These two sources of sediment form distinct signatures in the sediment record from Lake Lögurinn, and parts of the record have previously been suggested to reveal past winter precipitation in the region and surge periodicities of Eyjabakkajökull (Striberger et al., 2011a). Here, we present new data from this unique sediment sequence to infer the glacial meltwater variability of Eyjabakkajökull throughout the Holocene, with focus on the early and mid-Holocene.

## 2. Research area and fieldwork

### 2.1. Research area

Lake Lögurinn (65°15′N, 14°25′W, 53 km$^2$, elevation 20 m a.s.l.) is situated centrally in the Fljótsdalur valley, eastern Iceland, ca

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55 km northeast of Eyjabakkajökull (Fig. 1). The lake has a mean water depth of 51 m, with maximum depths of 112, 72 and 42 m in its three sedimentary sub-basins (e.g. Hallgrímsson, 2005). The sediment input into Lake Lögurinn is mainly transported from Eyjabakkajökull via River Jökulsá í Fljótsdal that enters the southernmost and deepest sub-basin of the lake, and from the non-glaciated catchment of River Grímsá, which enters the eastern side of the lake close to a step-like sill that separates the central sub-basin from the 42-m-deep northern sub-basin. Lake Lögurinn drains towards northeast via Lagarfljót and ends up at the coast of northeast Iceland.

Eyjabakkajökull is a 10 km long and 4 km wide temperate, surge-type outlet glacier that drains the northeastern part of the Vatnajökull ice cap (Benediktssion et al., 2010). Three smaller outlets from the main ice cap merge to form Eyjabakkajökull, which descends from about 1200 to 1500 m a.s.l. and terminates at about 700 m a.s.l. Historically documented surges occurred in 1890s, 1930s and 1972–1973 (Björnsson et al., 2003) and based on the lithostratigraphy in Lake Lögurinn, Striberger et al. (2011a) suggested that surges of Eyjabakkajökull have occurred during the past ca 2200 years.

### 2.2. Fieldwork

A Uwitec fixed-piston percussion corer was used to recover sediments from the northern sub-basin of Lake Lögurinn at two core sites (L1 & L2) with water depths of 38 (L1) and 16 m (L2), respectively. To ensure complete stratigraphic recovery, two holes were cored at each site, with a starting depth offset of 1.5 m between the holes. The bulk magnetic susceptibility of the sediment cores were measured within 24 h of recovery using a Bartington Instruments MS2 meter and MS2C core logging loop sensor (80 mm diameter) to ensure that each 3-m segment overlapped. The total core lengths from the two core sites were 12 and 14 m, respectively. The sediment–water interface at L1 was captured in a 35-cm-long surface-sediment core using an LTH Kajak sediment-surface sample with 60 mm diameter.

## 3. Methods description

A range of laboratory analyses have previously been performed on the sediment sequence from Lake Lögurinn, including lamina thickness measurements, bulk magnetic susceptibility (MS), high-resolution (0.5 mm) XRF and X-radiography core scanning, $^{14}C$ dating, $^{137}Cs$ analysis and geochemical analyses of tephras (Striberger et al., 2011a, 2011b). The results from some of these analyses are presented and discussed in this study, together with new data obtained with the methods described below.

### 3.1. Lithostratigraphy

Distinct sedimentary units and numerous tephras in the sediment sequences enabled visual correlation of L1 and L2. After correlation, the characteristics of the sedimentary units in the master sequence were described, and their depths were measured. Laminated sedimentary units were examined using methods described by Striberger et al. (2011b).

### 3.2. Chronology

Striberger et al. (2011a) presented an age-depth model of the sediment sequence that was based on varve counting, $^{137}Cs$ analysis, $^{14}C$ dating of four macrofossils and 12 tephras that were identified by their geochemical fingerprints and stratigraphic positions. Here, we present a slightly revised age-depth model that has been done in OxCal 4.1 using a Poisson process deposition model (P_sequence), with the $k$ parameter set to 15 (i.e. 15 postulated sedimentary events per metre). The agreement index of the model is 80%, thus above the acceptable level of 60% (Bronk Ramsey, 2008).

### 3.3. Grain-size analysis

Grain-size analysis was performed of samples collected in 1-cm sections from each sedimentary unit in the sequence. The analysis was carried out using a SediGraph (Micromeritics SediGraph III) at

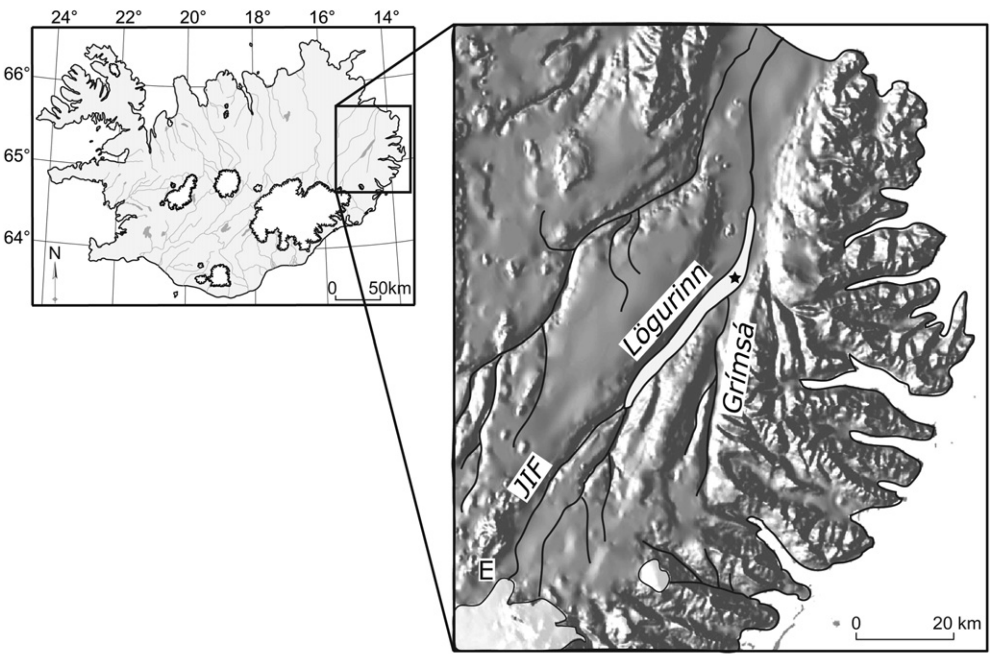


**Fig. 1.** Map of northeast Iceland showing the location of Lake Lögurinn, Eyjabakkajökull (E), River Jökulsá í Fljótsdal (JIF) and River Grímsá in the Fljótsdalur valley. The core sites in the northern part of Lake Lögurinn are marked by the black dot.

Lund University, and the results are presented as weight-% of the total mass. High-resolution samples collected every 2 cm in the upper 3.8 m of the sediment sequence were analysed using laser diffraction at the Natural History Museum in Copenhagen, Denmark. These samples are presented as volume-% of total volume.

### 3.4. Loss on ignition, carbon and nitrogen analysis

Loss on ignition (LOI) was performed on samples collected in 1-cm sections every 5 cm at 17.8–3.8 m depth, and every 2 cm in the upper 3.8 m at 550 °C according to methods described by Bengtsson and Enell (1986). The results are presented as weight-% organic matter of total dry weight.

Carbon and nitrogen concentrations were measured in freeze-dried samples collected every 0.8–1.1 m throughout the sediment sequence. Two additional samples were collected at depths of specific interest based on the organic matter content. The results are presented as weight-% carbon and nitrogen of total dry weight.

### 3.5. Biogenic silica, diatom and chironomid analysis

The concentration of biogenic silica (BSi) was measured in freeze-dried samples collected every 5 cm at 17.8–3.8 m depth using methods described by Conley and Schelske (2001). The results, expressed as weight-% $SiO_2$ of total dry weight, are presented together with the results from samples that covers the upper 3.8 m of the sediment sequence (Striberger et al., 2011b).

Samples for diatom and chironomid analysis were collected every 0.8–1.1 m throughout the sediment sequence. In addition, 13 diatom samples and four chironomid samples were collected at various depths to capture levels of specific interest based on the stratigraphy and the chronology. The freeze-dried sediment samples for diatom analyses were oxidised with 15% $H_2O_2$ for 24 h, then digested in 30% $H_2O_2$ for a minimum of 24 h, and finally heated at 90 °C for several hours. Slurries were then centrifuged and rinsed with deionised water, and then diluted to 10 ml. A known quantity of markers (plastic microspheres) was added to 200 μL aliquots of the digested slurries in order to calculate diatom concentrations (Battarbee and Kneen, 1982; Wolfe, 1997). These secondary slurries were diluted again, mixed, pipetted onto cover slips, dried at air temperature, and mounted in Naphrax® medium (refractive index = 1.65). At least 500 diatom valves per sample were counted and identified mainly using Krammer and Lange-Bertalot (1986–1991). Diatom data are expressed as relative abundances of each taxon, and as total concentrations of valves per g dry sediment, estimated by the counts of introduced markers (Battarbee and Kneen, 1982).

For chironomid analysis, sub-samples consisting of $\sim 5$ cm$^3$ sediment were used. The samples were deflocculated in warm 10% KOH for 20 min and rinsed on a 90 μm mesh sieve (Walker and Paterson, 1985). Chironomid head capsules were handpicked under a binocular microscope (40× power), dehydrated in 99% ethanol and permanently mounted in Euparal®. Fragments that consisted of more than half the mentum were counted as a whole head capsule, fragments with half the mentum were counted as half and smaller fragments were excluded. The goal was to extract a minimum of 50 head capsules from each sub-sample (Quinlan and Smol, 2001), but sub-samples from the uppermost and lowermost part of the sediment sequence were poor in head capsules and contained less than the required number. Taxonomic identification was performed under a compound microscope at 400× magnification, with reference to Wiederholm (1983) and Brooks et al. (2007). Most of the specimens were identified to species-type level. In all statistical analyses, relative abundance data (%) were used. Analysis of similarity (ANOSIM) (Clarke and Green, 1988) was performed to test the significance of the groups defined *a priori* based on other proxies. Similarity percentage analysis (SIMPER) was used to determine the contribution of each species to the observed similarity pattern within each group. Only taxa contributing to the within group similarity with >2% are shown in the stratigraphic diagram. Both of the above tests were performed using the Community Analysis Package 3.0 (Seaby and Henderson, 2004).

## 4. Results

### 4.1. Lithostratigraphy

The master sequence from Lake Lögurinn is combined by sediments from L1 and L2, and is 17.8 m long. Based on the visual characteristics of the sediments, five sedimentary units have been identified, which contain a total of 16 sedimentary sub-units (Fig. 2).

Unit 1 occurs at 17.8–15.4 m depth. It contains four sub-units (1.1–1.4) and is formed by brownish and greyish laminations that gradually fade out towards the upper boundary. Unit 2 (15.4–12.2 m) contains homogeneous, brownish sediments, and comprises three sub-units (2.1–2.3). In the next Unit 3 at 12.2–10.9 m depth, three sub-units occur (3.1–3.3), which contain brownish, homogeneous or faintly laminated sediments with thin, diffuse laminations. It is followed by Unit 4 (10.9–10.3 m), in which the laminated sediments gradually change from having a brownish hue similar to the preceding unit, to a greyish hue in its upper part. Unit 5 at 10.3–0 m depth contains five sub-units (5.1–5.5), and displays distinctly laminated greyish sediments. With the exception of sub-unit 5.1, this unit displays reoccurring 5–20 cm thick intervals that are dominated by relatively thick greyish laminae.

The laminations are most distinct in sub-unit 1.1 and in Unit 5, and they are formed by dark- and light-coloured couplets. Each couplet contains a lower, heterogeneous brownish lamina where individual grains can be observed visually. The brownish lamina is capped by a homogeneous greyish lamina where no grains can be observed.

### 4.2. Chronology

The age-depth model of the sediment sequence is constrained by the I-TOOL-1 tephra at 17.7 m depth, which has been $^{14}$C dated to ca 10 400 years BP (Björck et al., 1992) (Fig. 3). Between 17.7 m and the Hekla-4 tephra (Pilcher et al., 1995) that occurs at 12.1 m, the model is constrained by $^{14}$C dated macrofossils (water mosses) at ca 15.4 and 14.3 m depth, respectively.

In the upper 10.3 m, the age-depth model is based on a varve chronology (Striberger et al., 2011a). This varve chronology has been validated by $^{14}$C dates of two macrofossils (unidentified) at ca 8.9 and 7.9 m depth, respectively, by the $^{14}$C dated Sn-1 tephra (Steinthorsson, 1967) at ca 7.2 m depth, by eight historically documented tephras in the upper 3.8 m and by $^{137}$Cs in the upper 0.5 m. It has been corrected for a hiatus between 473 and 331 years BP, constrained by two historical tephras (Striberger et al., 2011b).

The oldest varve overlay the Hekla-3 tephra at 10.3 m depth. This varve is dated to 2813 years BP. The varve age of the Hekla-3 tephra is slightly younger than the date reported by Dugmore et al. (1995), whose combined $^{14}$C dates of peat yield an age of 3143-2883 years BP. Therefore, it cannot be excluded that an additional short hiatus may be present between the lowermost historically documented tephra at 3.8 m depth and Hekla-3, which would explain the discrepancy between our varve age and the $^{14}$C date reported by Dugmore et al. (1995) and also the slight offset between the varve age and the calibrated $^{14}$C date at 7.9 m depth.

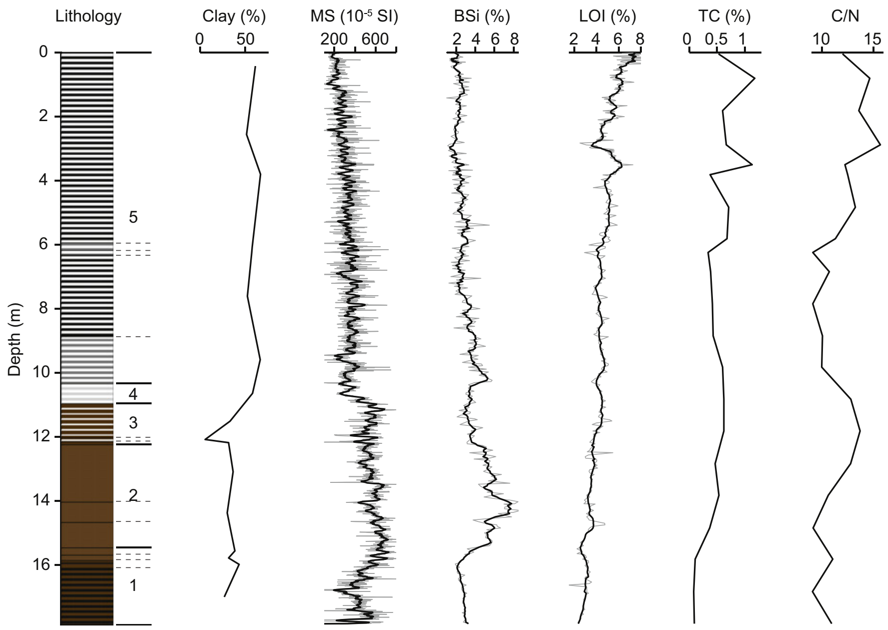


**Fig. 2.** Diagram of the sediment sequence from Lake Lögurinn showing lithology, weight percentage clay, MS, BSi, LOI, TC and C/N. Sediment units are denoted 1–5 and separated by solid lines, sub-units are marked by dashed lines.

With the age-depth model, Unit 1 is dated to have been deposited between ca 10 500 and 9000 years BP, Unit 2 between ca 9000 and 4400 years BP, Unit 3 between ca 4400 and 3300 years BP, Unit 4 between ca 3300 and 2800 years BP while the varves in Unit 5 cover the past ca 2800 years.

### 4.3. Grain-size

The sediment sequence is dominated by clay and silt with a mean combined content of 97–98%. The remainder contains fine sand, while medium and coarse sand is found in very small amounts. Units 1–3 contain about 30% clay, except in sub-unit 3.2 where the clay content drops to about 6% (Fig. 2). Units 4 and 5 contain significantly higher amounts of clay, varying between 53 and 67%.

The dense grain-size analyses in Unit 5 confirm that different grain-size distributions characterise the brownish and greyish lamina, respectively, which was also noticed during the visual observations. Grain-size samples that are dominated by brownish laminae are negatively correlated to the amount of clay ($r = -0.29$ [−0.41 to 0.16]) and positively correlated to the amount of silt ($r = 0.34$ [0.17–0.49]) (The 99% confidence interval for each correlation coefficient ($r$) determined by means of bootstrapping is herein presented within square brackets). Samples dominated by thick greyish laminae show the opposite; they are positively correlated to the amount of clay ($r = 0.32$ [0.17–0.43]) and negatively correlated to the amount of silt ($r = -0.41$ [−0.55 to 0.25]). Therefore, the 5–20 cm thick intervals that contain relatively thicker greyish laminae typically display higher clay content compared to the laminated sections in between these intervals (Fig. 4).

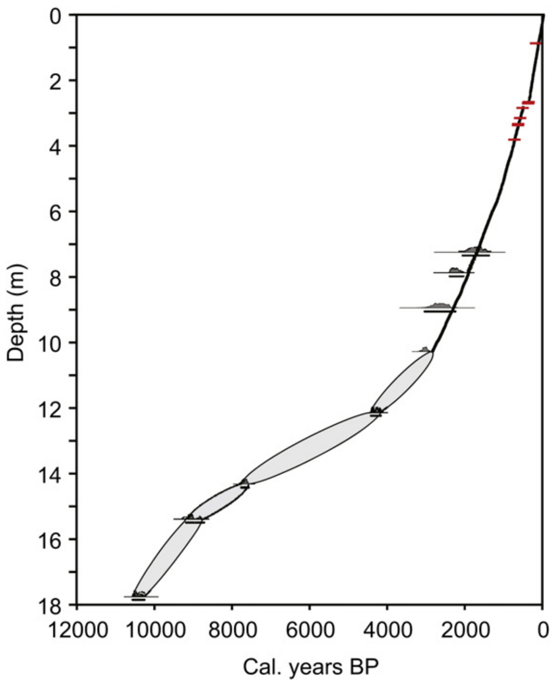


**Fig. 3.** Age-depth model. Probability distributions of $^{14}C$ dates are shown. Red lines denote historical tephras. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

### 4.4. Magnetic susceptibility

The MS data previously presented by Striberger et al. (2011a) display a mean value of ca $400 \times 10^{-5}$ SI for the whole sediment sequence (Fig. 2). Unit 1 reveals a trend of decreasing MS in the lower part of sub-unit 1.1, which is followed by a steady increase until the upper boundary of sub-unit 1.4. In Units 2 and 3, the data display the highest MS values throughout the sediment sequence, with a mean MS value of ca $570 \times 10^{-5}$ SI. Unit 4 shows a distinct decrease in the MS, which drops to ca $300 \times 10^{-5}$ SI close to its upper boundary. In Unit 5, the MS remains low with a mean value close to ca $300 \times 10^{-5}$ SI. However, in sub-unit 5.2–5.5 the MS typically decrease to ca $200 \times 10^{-5}$ SI in the reoccurring 5–20 cm thick intervals dominated by the greyish laminae, whereas outside of these intervals the MS reaches ca $400 \times 10^{-5}$ SI (Fig. 4).

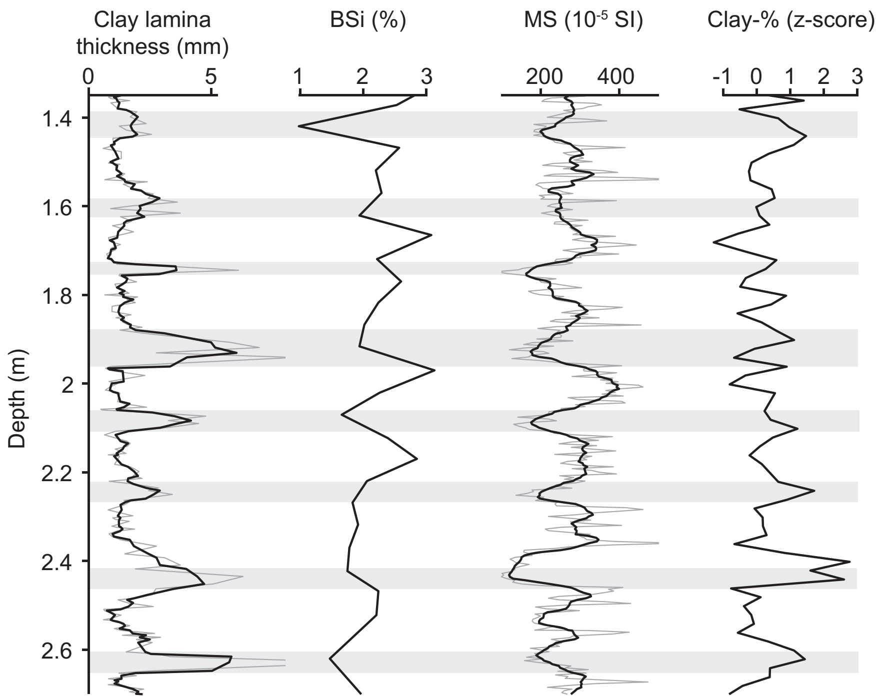


**Fig. 4.** Inferred surge intervals (shaded) in Unit 5 based on clay lamina thickness compared to BSi, MS and clay content expressed as z-score.

### 4.5. Loss on ignition, carbon and nitrogen

The amount of organic matter determined by LOI is in general low with a mean content of 4.6% (Fig. 2), and the data display an upwards increasing trend. In Unit 1, the organic matter content varies between 2 and 3.5%, which is followed by an increase in Units 2–3 where the organic matter content reaches ca 4.5% close to the upper boundary of Unit 3. In Unit 4 and in the lower part of Unit 5, the organic matter content stays relatively stable with a mean content of ca 4%, whereas in sub-unit 5.5, the organic matter content is relatively high with maximum values of 9% in its uppermost part.

The correlation between C and N concentration is high ($r = 0.95$ [0.87–0.98]), and both elements display low concentrations with a mean C concentration of 0.5% and a mean N concentration of 0.05% (Fig. 2). Unit 1 contain the lowest C concentrations in the sequence, with concentrations of 0.1% or less. The homogeneous sediments in Unit 2 show about five times higher C concentrations, with a mean value of 0.45%. Units 3 and 4 both display slightly increased C concentrations, ca 0.6%. The lower part of Unit 5 displays decreased C concentrations in sub-unit 5.1–5.3, whereas sub-unit 5.5 displays maximum C concentrations, with a mean of 0.7%.

The C/N atomic ratios in the sediment sequence vary between 9 and 16 (Fig. 2). The lower part of the sediment sequence displays C/N ratios that vary between 9 and 11. It is followed by an increase from sub-unit 2.3 until Unit 4, where the C/N ratios reach 13–14. In Unit 5, the C/N ratios return to relatively low values (9–11) in sub-units 5.1–5.4, whereas in the upper part of sub-unit 5.5, the ratios vary between 12 and 16.

### 4.6. Biogenic silica

The BSi concentrations reveal fairly large variations throughout the sediment sequence, with the main changes occurring at or close to the boundaries between the sedimentary units (Fig. 2). The lowermost unit displays relatively low BSi concentrations in sub-unit 1.1 and 1.2, which increases in its upper part and reaches 4.1% in sub-unit 1.4. Unit 2 displays a significant increase in BSi, with a mean value of 5.6%. Peak values occur in sub-unit 2.2, where the mean BSi concentration reaches 6.9% with maximum values of 8.7%. After these relatively high values, Units 3 and 4 display relatively low concentrations, with a mean value of ca 3.4%. Following a small increase in sub-unit 5.1–5.2, Unit 5 displays a trend of decreasing BSi concentrations with mean concentrations of ca 2.3% in its upper part.

### 4.7. Diatoms

The diatom concentration varies significantly in the sediment sequence (Fig. 5). The lowermost samples collected in sub-unit 1.1 display concentrations of less than $1 \times 10^7$ diatom valves per g dry sediment. This is followed by an increase in Unit 2, which displays the highest values in the sequence with a mean concentration of $33 \times 10^7$ diatom valves per g dry sediment. In Units 3–5, the diatom concentration varies between less than $1 \times 10^7$ and $22 \times 10^7$ diatom valves per g dry sediment, with a mean of $8 \times 10^7$. Sub-unit 5.5 is characterised by relatively low concentrations. Two samples were collected in the 5–20 cm thick intervals dominated by relatively thick greyish laminae at 2,4 and 2.1 m depth, respectively, and are barren in diatoms.

The diatom assemblage is dominated by the meroplanktonic *Aulacoseira subarctica*, which is present throughout the sediment sequence. It occurs in relatively low frequencies in Unit 1 and in the lower part of Unit 2. In the following units, *A. subarctica* is highly abundant until sub-unit 5.2, whereas in the upper part of Unit 5, it returns to lower abundances.

*Aulacoseira islandica* is the second-most common meroplanktonic species in the sediment sequence. However, this species is restricted to Units 1 and 2 and displays maximum abundance at the boundary between these units. *A. islandica* is present until the upper boundary of Unit 2, where it occurs in low amounts. Upwards in the sediment sequence, *A. islandica* is not present, with the

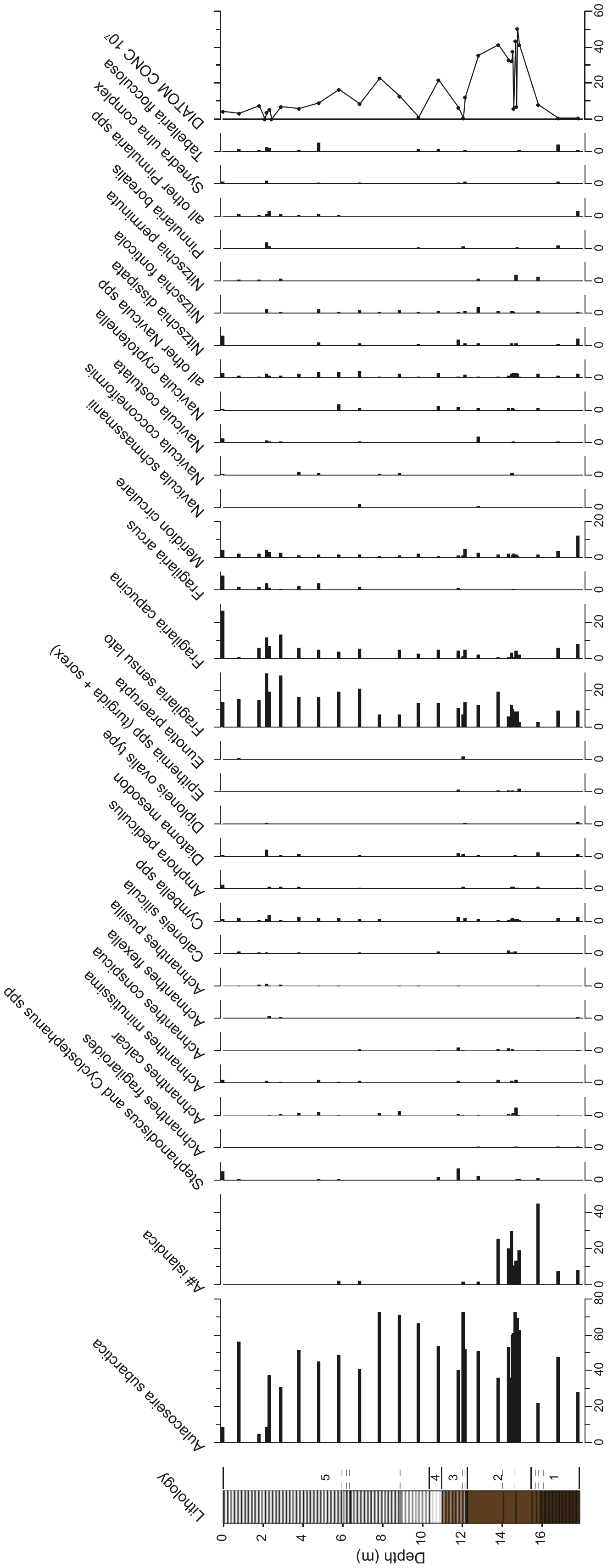


**Fig. 5.** Diatom assemblage from the Lake Lögurinn sediment sequence expressed as relative abundances of each taxon, and as total concentrations of valves per g dry sediment.

exception of three samples in Units 3 and 5, where it occurs in very low amounts.

The remainder of the diatom assemblage is to a large extent represented by benthic *Fragilaria sensu lato*. These species are present throughout the sediment sequence. They display fairly constant abundances from Unit 1 until sub-unit 5.2, although minor variations are observed. In the upper part of sub-unit 5.2 where the abundance of *A. subarctica* decreases, *Fragilaria sensu lato* increases.

### 4.8. Chironomids

A total of 31 chironomid taxa were recorded in the Lake Lögurinn sediments, and the assemblage is dominated by the cold-stenothermic *Heterotrissocladius grimshawi* type (Fig. 6). It constitutes 27% of the total abundance, and occurs throughout the whole sequence. Analysis of similarity (ANOSIM) reveals that the assemblage structure in the sediment units differs significantly from each other; Unit 2 differs both from Unit 1 ($p = 0.017$) and Unit 5 ($p = 0.003$), and Unit 1 differs from Unit 5 ($p = 0.0012$).

Unit 1 is characterised by the occurrence of *Diamesa* spp., *Orthocladius/Cricotopus* sp. and *Eukiefferiella fittkaui* type. The chironomid abundance, taxa number and diversity are low, but tend to increase. Unit 2 is characterised by the occurrence of *H. grimshawi* type, *E. fittkaui* type, *Micropsectra* spp., *Tanypodinae* and *Diamesa* spp. Also the larvae of the cold stenothermal *Oliveridia* sp. are typical for this unit. Both the abundance and diversity is high. In Units 3 and 4, the abundance and diversity remains high, and the assemblage is dominated by *H. grimshawi* type, *Psectrocladius* spp. and *Micropsectra* spp. The most common chironomids in Unit 5 are *H. grimshawi* type, *Orthocladius* (*O.*) cf. *oblidens* and *Micropsectra* spp. The abundance and diversity is initially high in this unit, but in sub-unit 5.5 both abundance and diversity drops and stays relatively low throughout the sub-unit. However, the low taxa number could be an artefact of the low abundance.

Two samples were collected from the reoccurring 5–20 cm thick intervals dominated by thicker greyish laminae in sub-unit 5.5. They did not show any significant difference in the chironomid assemblage composition compared to the rest of samples. However, the number of head capsules was strikingly low, similar to the results of the diatom analysis.

## 5. Discussion

### 5.1. Asserting the lithostratigraphy as a proxy for the presence and extent of Eyjabakkajökull

The present-day sediment transport from the two main catchments form laminated, varved sediments in Lake Lögurinn. Striberger et al. (2011b) concluded that the heterogeneous, brownish, silty laminae are formed by sediments that mainly originates from the catchment of River Grímsá, while the capping, greyish, clayey laminae are dominated by rock flour transported by meltwater from Eyjabakkajökull. Furthermore, Striberger et al. (2011a) suggested that the 5–20 cm thick intervals with thick capping clay laminae have been formed by past surges of Eyjabakkajökull. Lake Lögurinn must therefore have been highly influenced by glacial meltwater during the formation of Unit 5, and the recurrent signals of surge intervals show that rapid, short-lived changes of Eyjabakkajökull are recorded in the sediments. With this knowledge of the present processes that act on the sediment transport to Lake Lögurinn, we can conclude that laminated sediments indicate that Eyjabakkajökull is present within the catchment.

Much of the lithology in Unit 1 resembles Unit 5, but the lack of solid isochrones prevents us from characterising this laminated unit as varved. However, the similarity between sub-unit 1.1 and Unit 5 implies that these laminations were formed by processes similar to the ones that have been active since the onset of sub-unit 5.1. Therefore, we suggest that relatively large amounts of glacially derived sediments were transported to Lake Lögurinn during the formation of sub-unit 1.1. The gradual disappearance of laminations in sub-units 1.2–1.4 implies that the amount of glacial meltwater progressively decreased, indicating a gradual retreat of Eyjabakkajökull.

The homogeneous sediments in Unit 2 are similar to the sediments that occur in the brownish lamina in the laminated sediment sections. The absence of laminations implies that during the formation of this unit, no glacial meltwater was transported to the northern sub-basin of Lake Lögurinn. Therefore, Eyjabakkajökull must have been much smaller, or even totally absent at this time.

The occurrence of faintly laminated sediment in Unit 3 suggests that Eyjabakkajökull had started to deliver meltwater to Lake Lögurinn again. The clay laminae in this unit are thin and diffuse, which implies that the amount of glacial meltwater was low.

The gradual change towards more glacially derived sediments in Unit 4 indicates an increased amount of meltwater from Eyjabakkajökull, which suggests that the glacier expanded at this time. Striberger et al. (2011a) suggested that surges of Eyjabakkajökull began as a result of a continuous expansion of the glacier until it reached a certain configuration. The inferred surge intervals occur throughout sub-unit 5.2–5.5 and therefore we suggest that the expansion of Eyjabakkajökull, which intensified during the formation of Unit 4, likely continued during the formation of sub-unit 5.1, after which the extent of Eyjabakkajökull has been stable.

## 5.2. Interpretations of complementary data

### 5.2.1. Magnetic susceptibility and grain-size

The MS is relatively high in homogeneous or diffusely laminated sediments, and relatively low in distinctly laminated sediments. Furthermore, in the inferred surge intervals, MS displays minimum values. Our analyses imply that glacially derived sediments contain relatively lower concentrations of ferrimagnetic minerals, e.g. magnetite, compared to the silty sediments that occur in homogeneous or diffusely laminated units. We therefore interpret the MS data to indicate variations in the sediment source(s), ultimately, forming the different sediment units.

Unit 2 displays both high MS and low amounts of clay, which is the same "signature" as the silty lamina of the varves in Unit 5, whose sediments mainly originate from the catchment of River Grímsá (Striberger et al., 2011b). This similarity, and the absence of laminations, implies that Unit 2 mainly originate from fluvial transport, dominated by inflow from River Grímsá, and not by glaciofluvial discharge from Eyjabakkajökull. It should, however, be noted that River Jökulsá í Fljótsdal, draining the glacier today, must have turned into a non-glacial river and as such transported pure fluvial sediments to its inlet in the southern part of the lake, but possibly little of its coarser material reached the northern sub-basin. Prior to the formation of Unit 2, the MS gradually increases in sub-unit 1.2–1.4, suggesting that sediments from the catchment of River Grímsá began to dominate the sediment transport to our sites in Lake Lögurinn as the amount of glacially derived sediments decreased, concurrent with the disappearance of laminations. In Unit 3 the MS remains high until the distinct decrease in Unit 4, suggesting that the transport of glacially derived sediments were relatively low, which is verified by the thin, diffuse laminae in this unit. The distinct drop in MS and the increased clay content in Unit

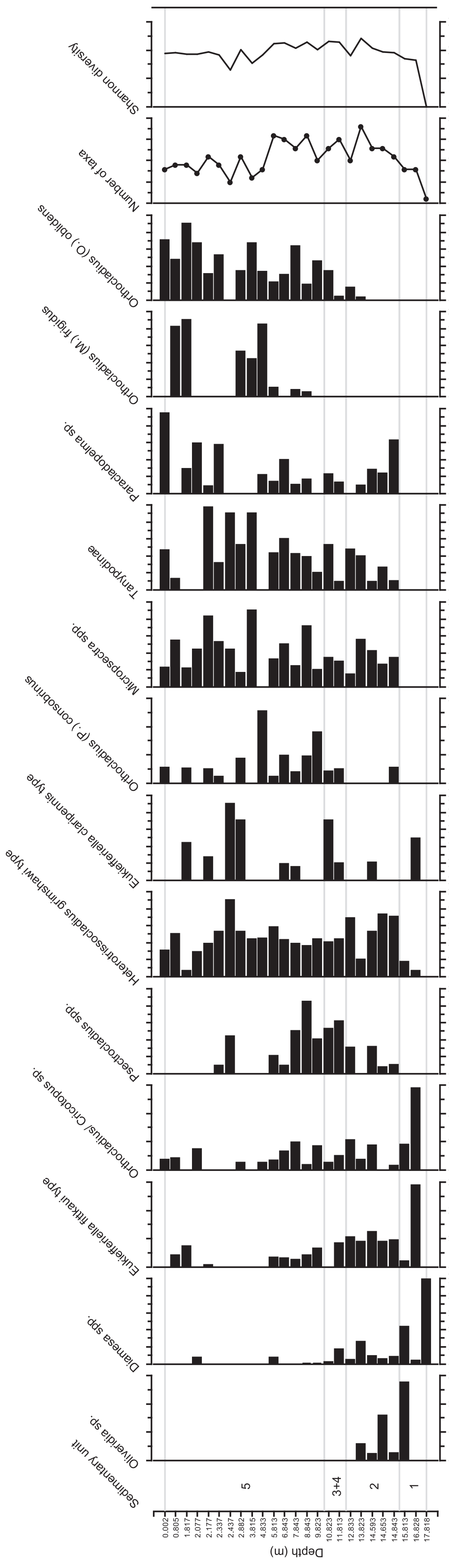


**Fig. 6.** Chironomid stratigraphy of Lake Lögurinn. Chironomid taxa are given as percentages of the total number of head capsules. Taxa are ordered according to weighed average score. Only taxa contributing to the within group similarity with >2% are shown. Thin horizontal lines mark sediment units 1–5.

4 reveal that the transport of glacially derived sediments from Eyjabakkajökull increased significantly.

### 5.2.2. Biogenic silica, diatoms and chironomids

BSi is positively correlated to MS ($r = 0.59$ [0.52–0.64]) and to the amount of silt ($r = 0.45$ [0.28–0.60]), while it is negatively correlated to the amount of clay ($r = -0.37$ [−0.52 to 0.17]). Therefore, the data display relatively high BSi concentrations in homogeneous sediments, while the BSi concentration is low in the laminated sediments. Hence, the BSi concentration is low during increased transport of glacially derived sediments to Lake Lögurinn. This is best observed in sub-units 5.2–5.5, where the BSi concentrations decrease in the clayey surge intervals, whereas relatively high concentrations occur in between these intervals (Fig. 4). As BSi concentration is a measure of the amorphous Si content of the sediments, it is typically a good proxy for diatom abundance and for other siliceous microfossils (Conley, 1988; Conley and Schelske, 2001). Therefore, the BSi concentration is a good proxy for aquatic productivity in Lake Lögurinn, which in turn is related to prevailing climate conditions, nutrients and water column characteristics including e.g. pH, light-availability and turbidity.

Because the main changes in BSi concentration occur more or less at the boundaries between sediment units (Fig. 2), the biologic productivity in Lake Lögurinn seems to be highly sensitive to changes in the amount of glacially derived sediments transported to the lake. We argue that the low BSi concentration in the laminated sediment units to a large extent is related to light-availability. When glacial sediments are transported to the lake, like today, a large portion of the fine-grained rock flour that reaches the northern basin of Lake Lögurinn stays in suspension until late in winter when the lake normally is frozen over (Hallgrímsson, 2005). This will obstruct sunlight to enter the water column and lowers the biologic productivity. This argument suggests that Unit 2, displaying the highest BSi concentrations throughout the sediment sequence, was formed during more favourable light-conditions in the water column.

Changes in local aquatic productivity are most likely not only related to variations in light-availability, but also to changes in climate. Geirsdóttir et al. (2009b) concluded that changes in BSi in Lake Haukadalsvatn in western Iceland reflect changes in primary production controlled by spring temperature, which in turn is related to the duration of ice-free seasons. We suggest that this may also be valid for the BSi concentrations in Lake Lögurinn. If light-availability is not a limiting factor, changes in biologic productivity may be related to winter and spring temperatures. For instance, warmer temperature during these seasons could cause the lake ice to break up earlier during spring, or possibly, prevent the lake from freezing over, which would enable earlier and longer algal blooms. Therefore, the peak in BSi concentrations that occurs in Unit 2 close to sub-unit 2.2 may reflect warmer conditions and thus, longer ice-free seasons. However, the changes in BSi that are accompanied with the inferred rapid, short-lived surges of Eyjabakkajökull (Fig. 4), which are not directly related to changes in climate, provide strong arguments that light-availability is the primary, but not single, factor in controlling Lake Lögurinn's aquatic productivity.

Although we think that the BSi concentrations and the diatom assemblage changes are good proxies for the biologic productivity in Lake Lögurinn, we would like to emphasis that the results of the diatom analysis should be treated with some caution due to less samples than for most of the other proxies. *A. subarctica*, which is the most abundant species in our sediments, is characterised as an acidophilus diatom, while *A. islandica*, the second-most abundance planktonic species, is considered a circumneutral and alkaliphilus taxa (Van Dam et al., 1994). *A. subarctica* is known to be a poor competitor at increasing nutrient concentrations in comparison with other *Aulacoseira* spp, which has been shown in a study in Northern Ireland where it was replaced by *A. islandica*, *Aulacoseira ambigua* and later by small *Stephanodiscus* or *Cyclostephanos* spp (Anderson, 1997). Detailed studies of the life cycle of *A. subarctica* in Lake Blelham Tarn, England, a clear-water seasonality stratified lake, revealed that insufficient turbulence during periods of thermal stratification or ice cover is unsuitable for the species, and that the combination of high light-availability, high temperatures and nutrient depletion might lead to cell death (Lund, 1971; Gibson et al., 2003). Furthermore, in Lough Neagh, a large, turbid and non-stratified lake in Northern Ireland, the low light-availability and repeated re-suspension allow *A. subarctica* to thrive (Gibson et al., 2003). Changes in the abundance of the dominating planktonic diatom species in Lake Lögurinn may therefore be related to a number of factors, including changes in pH, nutrient concentrations, turbulence, light-availability and temperature. The occurrence of small benthic *Fragilaria sensu lato* (especially *Fragilaria pinnata*, *Fragilaria construens*, *Fragilaria pseudoconstruens* and *Fragilaria brevistriata*) is consistent with Karst-Riddoch et al. (2009) results. They showed that *Fragilaria sensu lato* (19 species and varieties) is abundant in Icelandic lakes, and most likely reflect the generally cold lake water conditions in this area as it is known to be thriving in cold environments and under ice cover (Douglas and Smol, 1999; Lotter and Bigler, 2000).

The dominating chironomid, the cold-stenothermal *H. grimshawi* type that occurs throughout the sequence, indicates that Lake Lögurinn has remained cool and moderately oligotrophic during the past ca 10 500 years. This is also supported by the co-occurrence of other taxa, playing important roles in different sediment units such as *Oliveridia* sp., which is characteristic for the profundal and littoral of ultraoligotrophic lakes; *Paracladoplema* sp. living in the littoral of ultraoligotrophic and profundal of moderately oligotrophic lakes; *Orthocladius* (*P.*) *consobrinus* dwelling in the littoral of ultraoligotrophic lakes, and taxa of the *Psectrocladius* genus, characteristic for the littoral of oligo- and mesotrophic lakes (Saether, 1979). However, in the lowermost part of Unit 1, the only head capsules that were found belonged to *Diamesa* spp. Larvae of the *Diamesa* genus are cold stenothermal and primarily rheophilic; they live both in fast flowing waters and the littoral and surf zone of cold, oligotrophic lakes (Oliver, 1983). According to Lindegaard (1992) and Langdon et al. (2008), the genus inhabits proglacial rivers and lakes, but are also frequent in the surf zone of cold Icelandic lakes with low carbon content. This implies that the lake ontogenesis was in an initial phase, with strong inlet influence, and that the profundal chironomid community was not developed at that time. Dominance of *H. grimshawi* type in Unit 2, and all the following units, combined with co-occurrence of other lentic taxa, such as *Paracladopelma* sp., *Orthocladisu* (*O.*) cf. *oblidens*, *Psectrocladius* spp., *Micropsetra* spp. and taxa of the Tanypodinae subfamily confirms the change of lake status from glacio-lacustrine to lacustrine with well developed benthic community.

### 5.2.3. LOI, TC and C/N

The correlation between the organic matter content determined by LOI and total carbon (TC) is high ($r = 0.78$ [0.45–0.92]), but in contrast to most other proxies in this study, neither correlate very well to changes in the lithostratigraphy. Organic matter typically contain ca 50% carbon (Meyers and Teranes, 2001), or more accurately, 12/30 of the organic matter content $(CH_2O)_n$ (Bengtsson and Enell, 1986). This implies that the organic matter content should be about 2–2.5 times the values of TC in Lake Lögurinn as we can assume that the carbon in Lake Lögurinn explicitly is organic since $CaCO_3$ is not present in the basaltic bedrock of Iceland. However, the organic matter content determined by LOI is typically 5–10 times higher compared to the TC content. By determining a linear function between the LOI and TC results, the organic matter content reaches ca 2.5% if TC is 0%. This is exemplified in the three samples from Unit 1, in which the TC is 0.1% or less, while the organic matter content determined by LOI varies between 2.3 and 3.1%. We therefore suggest that the organic matter determined by LOI likely is overestimated by a minimum of ca 2.5–3%, possibly caused by a loss of crystal water from clay minerals during ignition (Dean, 1974). Therefore, we use the TC as a proxy for the organic matter content in the sediment sequence. If it is assumed that the organic matter in Lake Lögurinn contains about 40–50% carbon, the organic matter content in the sediment sequence is in the range of 0.1–2.4%.

The source of the organic matter originates from both aquatic and terrestrial organisms, most likely dominated by plants. The C/N ratio in the sediments varies between 9 and 16, hence, they are not within the typical limits of organic matter from aquatic sources (4–10), nor above the limit of vascular plants (>20) (Meyers and Teranes, 2001). In general, the C/N ratios indicate a dominance of aquatically derived organic matter in Lake Lögurinn. However, two sediment sections stand out from the typical ratios of 9–11; samples collected between sub-unit 2.3 and unit 4, and samples from the upper part of sub-unit 5.5 both display mean C/N ratios that exceed 13, thus indicating that the organic matter in these intervals to a larger extent contains terrestrial plant remains, indicating input from the surrounding land area.

## 6. The Holocene development of Lake Lögurinn and Eyjabakkajökull – a synthesis

### *6.1. The end of the last deglaciation of Lake Lögurinn, and the recession of Eyjabakkajökull ca 10 500–9000 years BP*

The deglaciation that followed the Last Glacial Maximum (LGM) in Iceland started about 15 000 years BP, when the Icelandic ice sheet began to retreat rapidly from its maximum position at or close to the shelf break of Iceland onto present-day dry land (Andrews et al., 2000). The initial deglaciation was followed by a period characterised by a marine environment that lasted until the first of two glacial re-advances at ca 12 000 years BP (Norðdahl and Pétursson, 2005). During this Younger Dryas re-advance, glaciers extended slightly beyond the present-day coast north of Lake Lögurinn (Norðdahl and Hjort, 1995), and well into the fjords in the Berufjörður area east of the lake (Norðdahl and Pétursson, 2005). The second re-advance occurred in Preboreal time ca 11 200 years BP, and was less extensive compared to the Younger Dryas advance (Norðdahl and Einarsson, 2001). Both these events formed sets of raised shorelines at different altitudes throughout Iceland, including in the Lake Lögurinn region, where they can be traced for about 80 km from the coast towards the southern part of Lake Lögurinn. The older set of shorelines is situated between 35 and 45 m a.s.l. and can be followed for about 20 km south of the present-day coastline, while the younger set of shorelines can be traced an additional 60 km southwards along Lake Lögurinn at increasing altitudes. At the southern end of the lake, these shorelines are situated at 63 m a.s.l.

Morphological evidence reveal that a northwards flowing outlet glacier in the Lake Lögurinn region terminated between Tjarnarland and Eiðar ca 10–20 km north of the lake, where a proglacial sandur was formed at about 30 m a.s.l. Marine shells found in sediments that are related to a relative sea-level close to 30 m have yielded an age of ca 11 130–10 415 years BP (Norðdahl and Ingólfsson, 2009). This age is interpreted as a minimum age of the Tjarnarland-Eiðar marginal zone, which indicates that Lake Lögurinn was deglaciated and emerged from the sea in Preboreal time. Therefore, the younger set of shorelines may be of Preboreal age, while the older set of shorelines likely was formed during the Younger Dryas re-advance. The occurrence of the I-TOOL-1 tephra close to the bottom of the sediment sequence from Lake Lögurinn confirms that at least the northern sub-basin of the lake was deglaciated by ca 10 400 years BP, which fits well with the interpreted minimum age of the Tjarnarland-Eiðar marginal zone. The absence of marine sediments in our cores indicate that Lake Lögurinn was not part of the sea after the deposition of the I-TOOL-1 tephra, which implies that the lake was isolated earlier in Preboreal time.

We argue that Unit 1, deposited between ca 10 500 and 9000 years BP, represent the final phase of the last deglaciation in the Lake Lögurinn region (Fig. 7). The gradual disappearance of laminated sediments during this time period implies that the former outlet glacier receded to a position where it had a low

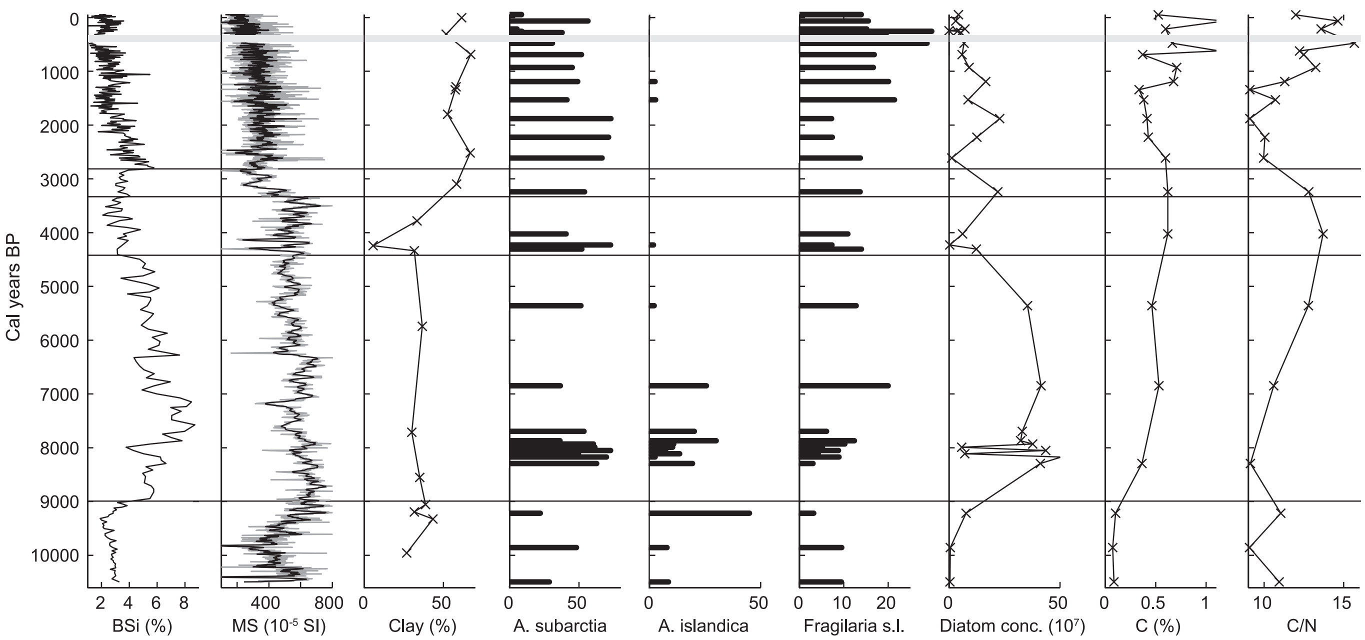


**Fig. 7.** Selected proxy records from the Lake Lögurinn sediment sequence plotted against age. Sediment units 1–5 are marked by thin horizontal lines, thick grey line marks the 473–331 years BP hiatus.

impact on the sediment transport to the northern sub-basin of Lake Lögurinn in approximately 1500 years. Therefore, the former outlet glacier, i.e. Eyjabakkajökull, was most likely smaller ca 9000 years BP compared to today. This fairly early and rapid recession of the Icelandic ice sheet around this time period has been observed elsewhere in Iceland. Stötter et al. (1999) observed the Saksunarvatn tephra (Grönvold et al., 1995) at or within Little Ice Age (LIA) glacier limits in northern Iceland, suggesting that parts of the highlands were ice free already by 10 200 years BP. The Saksunarvatn tephra has also been observed in sediment sequences from lakes along the north coast, suggesting ice-free conditions and open waters at the time of the eruption (Axford et al., 2007).

Based on chironomid and pollen data from northwest Iceland, Caseldine et al. (2006) suggest that the time period represented by Unit 1 in Lake Lögurinn is characterised complex changes in the vegetation, which is inferred to reflect a period of significant climatic change and instability. However, by 9000 years BP their chironomid data reveal a peak of higher inferred summer temperatures. Axford et al. (2007), on the other hand, infer that summer temperatures increased constantly during this time period until ca 9000 years BP. In marine records, relatively stable conditions similar to present-day scenario is inferred to have been established during the time period of Unit 1 (Eiríksson et al., 2000).

The occurrence of laminated sediments and the decreasing and low MS until about 9800 years BP suggest that Lake Lögurinn received meltwater and suspended matter from Eyjabakkajökull following the deglaciation of the lake. Therefore, Lake Lögurinn still acted as a glacio-lacustrine lake, with low biologic productivity, possibly due to large input of glacially derived sediments that minimised algal blooms. C/N ratios of 9–11 suggest that the low amount of organic matter in the lake was aquatically produced. The absence (or low input) of terrestrial organic matter at this time indicates that vegetation was sparse in the surrounding areas shortly after the deglaciation.

At 9800 years BP the MS start to increase, indicating reduced transport of glacially derived sediments to Lake Lögurinn and ca 500 years later, the aquatic productivity starts to increase, concurrent with the transition towards homogeneous sediments. 9300 years BP also corresponds to the start of a marked increase in the diatom concentrations, and to changes in the diatom assemblage. *A. islandica* increases significantly, possibly caused by the lower amount of glacially suspended matter in the water column. Concurrently *Fragilaria sensu lato* decreases, which may indicate longer seasons with ice-free conditions in Lake Lögurinn and thus, increased temperatures. The organic matter content, although still being very low, start to increase at 9300 years BP.

A glacio-lacustrine character of the lake is also supported by very low, but gradually increasing chironomid abundance and diversity in Unit 1. The low proportion of the lentic *H. grimshawi* type compared to the rheophilic *Diamesa* spp. and *E. fittkaui* type also confirms a poor lacustrine character of the lake.

Based on these observations, we propose that the lowermost unit, formed between ca 10 500 and 9000 years BP, marks the transition when Lake Lögurinn changed from being a glacio-lacustrine lake to become a non-glacially-fed lake. Our data show that the biologic productivity in Lake Lögurinn, as inferred from the BSi concentrations, seem to have responded rapidly to changes in the amount of glacially derived discharge. We therefore suggest that the change towards lacustrine conditions, with a decrease in the transport of glacial meltwater to Lake Lögurinn, intensified at 9300 years BP.

### *6.2. Lacustrine conditions in Lake Lögurinn ca 9000–4400 years BP*

By 9000 years BP, homogeneous sediments with high MS values were formed, at least in the northern part of Lake Lögurinn, and with a decreased sediment accumulation rate. In Unit 2, both BSi and diatom concentrations display the highest values throughout the sequence, indicating that the biologic productivity increased significantly. The C/N ratios indicate that most of the organic matter in this unit is aquatically produced. However, about 5400 years BP the C/N ratios increased and show that terrestrial plant remains makes up an increasing part of the organic matter. This implies that vegetation in the surrounding areas of Lake Lögurinn became denser during this time period.

The combination of absence of laminated sediments, low accumulation rates, high MS and distinct increases in BSi and diatom concentrations imply that glacial sediments were not deposited in Lake Lögurinn between ca 9000 and 4400 years BP. Therefore, we argue that Unit 2 was formed when pure lacustrine conditions prevailed in Lake Lögurinn: even with a minor glacial input the suspended fine particles would reach our coring sites in the north. The consequence of this is that Eyjabakkajökull ceased to deliver glacial meltwater to the lake between ca 9000 and 4400 years BP. Therefore we propose that the Eyjabakkajökull outlet glacier more or less disappeared for almost 5000 years during the early and mid-Holocene. From studies of the sub-aerially erupted Thjorsa Lava, it has been confirmed that parts of the central highlands were ice-free in early Holocene about 8600 years BP (Kjartansson, 1964), and reconstructions of Langjökull, the second largest ice cap in Iceland, reveal a period of nearly ice-free conditions following the 8.2 ka cold event (Alley et al., 1997), which lasted throughout the time period represented by Unit 2 (Flowers et al., 2008). This supports our interpretation that Eyjabakkajökull may have completely disappeared, or at least receded considerably during the time Unit 2 was deposited.

Caseldine et al. (2006) suggest that the Holocene Thermal Maximum (HTM) occurred between 7600 and 6800 years BP when the real development of woodlands occurred, with summer temperatures 2.5 °C higher compared to modern day observations. Axford et al. (2007), however, infer that summer temperatures gradually increased until 3500 years BP or later, which implies the warming prevailed throughout the time period represented by Unit 2. Given our interpretation that the aquatic productivity is highly influenced by changing light-conditions, which are related to the amount of suspended sediments in the water column, BSi can be seen as a proxy for glacial influence on Lake Lögurinn. However, as stated above, changes in BSi may also reflect changes in temperature, which controls the length of ice-free seasons. If higher concentrations of BSi during this time period mainly reflect generally improved light-conditions in the water column, the smaller fluctuations may reveal changes in temperature. The BSi concentrations attain peak values close to sub-unit 2.2 (Fig. 7), which is characterised by dark-coloured homogeneous sediments. This peak may be a result of more sustained algal blooms, caused by shorter, or even absence of, periods of ice-covered conditions in the lake, and therefore warmer spring temperatures. Our age-depth model yields an age of ca 7900–7000 years BP for the BSi peak. This age fits fairly well to the age of the HTM by Caseldine et al. (2006), given the uncertainty in our chronology at this depth. Thus, we infer sub-unit 2.2 to represent the HTM in the sediment sequence.

The inferred HTM is preceded by a distinct drop in the BSi concentration (Fig. 7), which correlates to a decrease in the abundance of *A. islandica*, and to an increased abundance of *Fragilaria sensu lato*, known to thrive under ice cover. Although this drop is not unique in the BSi record, it is significant and displays the lowest concentration in Unit 2. Furthermore, it occurs during a trend of increasing biologic productivity, indicating that this change was abrupt. This drop yields an age of ca 8200–8000 years BP, and may thus be a response to the 8.2 ka cold event. We do not observe any lithologic change at this time, which shows that any impact of the

8.2 ka cold event did not cause Eyjabakkajökull to re-form or expand to the extent that it contributed with meltwater and glacial sediments to Lake Lögurinn. Instead, we suggest that cooler winter-spring temperatures, which shortened the duration of ice-free conditions, may have been the main local effect of the event, resulting in decreased BSi concentrations.

The time period after the HTM is characterised by continuously high MS, relatively high BSi and diatom concentrations and homogeneous sediments, showing that lacustrine conditions continued to prevail until ca 4400 years BP. However, among the diatoms, *Fragilaria sensu lato* displays increased abundances from about 6% during the inferred HTM to 13–20% at 6800 and 5400 years BP, respectively. Concurrently, *A. islandica* remains relatively high shortly after the inferred HTM, but almost disappears at 5400 years BP. These changes may represent a period with longer duration of ice cover and thereby cooler climate. It may also have caused increased erosion in the catchment of the lake, as indicated by higher C/N ratio at 5400 years BP.

*H. grimshawi* type, a typical lacustrine chironomid taxa, became and remained dominant from the onset of Unit 2. Appearance of other lentic taxa in this unit, such as *Paracladopelma* sp. and *Micropsectra* spp. confirms the lacustrine character of the lake. The arctic ultraoligotrophic lake dweller, *Oliveridia* sp. is an important part of the assemblage, but its abundance decreases and disappears by the end of the unit. This species has been found in the coldest Icelandic lakes (Langdon et al., 2008). Axford et al. (2007) found it in the Icelandic lake Stora Viðarvatn, where it was the dominating species of the early assemblages and persisted until ca 7500 years BP. Surprisingly, however, the proportion of rheophilic taxa also remained high. The most likely reason for the high occurrence of the rheophilic *Diamesa* spp. and *E. fittkaui* type is that longer ice-free periods during Unit 2 created better light-conditions resulting in increased algal growth and a more abundant chironomid community in the littoral and surf zones of Lake Lögurinn.

### 6.3. The re-formation and expansion of Eyjabakkajökull ca 4400–2800 years BP

The first sign of a return to glacio-lacustrine conditions in Lake Lögurinn occur in Unit 3, which is characterised by irregular, thin, diffuse laminations, most likely formed by glacial discharge. Therefore, we suggest that the initial re-formation of Eyjabakkajökull into the catchment of Jökulsá í Fljótsdal occurred about 4400 years BP. The MS is still high, and the grain-size is relatively coarse, which indicate that the impact of Eyjabakkajökull on the sediment delivery to the lake was still weak. The low biologic productivity in Unit 3, as inferred by the BSi concentrations, may be an indication on how sensitive the aquatic productivity is to changing light-conditions, and/or it may imply cooler conditions with shorter seasons of ice-free conditions. We also note that the C/N ratio displays a maximum ca 4000 years BP before decreasing, possibly indicating increased erosion in the catchment, in parts perhaps caused by the re-advancing Eyjabakkajökull.

At ca 3300 years BP, marked by the start of Unit 4, the MS decreases rapidly and the clay content increases. These changes suggest that the amount of glacially derived sediments into Lake Lögurinn began to increase significantly about 3300 years BP, and by 2800 years BP the MS is down to modern day values. We therefore propose that approximately 1500 years after the initial re-formation of Eyjabakkajökull, the glacier had advanced to a position where it delivered approximately the same amount of sediments to Lake Lögurinn as it does today.

The diatom assemblages show no major changes between 4400 and 2800 years BP. *A. islandica* remains more or less absent, possibly due to the increased amount of suspended sediments in the water column. *Fragilaria sensu lato* remains relatively constant, with the exception of a small dip at 4200 years BP, concurrent with an increase in *A. subarctica* and a marked decrease in the clay content and in the diatom concentration. This may be related to the deposition of the H4 tephra, which occurs around this depth.

The chironomid assemblages of Units 3 and 4 do not differ significantly from other units and can be considered as a transition zone between Units 2 and 5. Lake inhabitants highly dominate this unit. High proportion of *Psectrocladius* spp., which is considered as a thermophilous taxon, indicates relatively mild and lacustrine conditions. *H. grimshawi* type and/or *Psectrocladius* sp. dominate the modern chironomid fauna of Icelandic lakes (Langdon et al., 2008).

All and all, we interpret that 4400–2800 years BP marks the time period when Eyjabakkajökull re-formed, which caused a return to glacio-lacustrine conditions in Lake Lögurinn. This is an unusually well defined onset of the Neoglaciation, a time period when other Icelandic glaciers are known to have advanced (e.g. Gudjónsson and Desloges, 1997; Stötter et al., 1999; Kirkbride and Dugmore, 2006).

### 6.4. The fluctuations of Eyjabakkajökull during the past ca 2800 years BP

The varved sediments in Unit 5 show that the sediment transport from Eyjabakkajökull and from the catchment of River Grímsá has been relatively stable since ca 2800 years BP. Surges of Eyjabakkajökull is suggested to have occurred since 2200 years BP, with surges at a constant periodicity since ca 1700 years BP (Striberger et al., 2011a). This inferred surge periodicity was only altered between 1619 and 1890 AD, when it is suggested that the quiescent phase shortened as a result of changes in temperature and winter precipitation at this time (Massé et al., 2008; Geirsdóttir et al., 2009a; Striberger et al., 2011b). The initiation of a surging Eyjabakkajökull is hypothesised to have been the result of an expansion of the glacier until it reached a certain mass, or geometry (Striberger et al., 2011a). The absence of inferred surge behaviour between ca 2800 and 2200 years BP suggest that Eyjabakkajökull continued to expand until ca 2200 years BP, when its configuration enabled surging, possibly caused by the return to cool conditions in northwest Europe and the North Atlantic ca 3000–2500 years BP (Van Geel et al., 1996). The inferred constant surge periodicity that followed suggests that the mass accumulation of Eyjabakkajökull was rather stable from ca 1700 years BP until the later part of the LIA, when Eyjabakkajökull reached its maximum extent during the Holocene (Sharp and Dugmore, 1985).

In the diatom assemblage, *Fragilaria sensu lato* increases after ca 1700 years BP, concurrent with a decrease of *A. subarctica*, which may be a response to the general increase of glacially derived sediments caused by the start of repeated surges. *A. islandica* is more or less absent in Unit 5, which indicates that pure lacustrine conditions have not prevailed during this time period.

Chironomid assemblages show significant differences compared to Units 1 and 2. In spite of the gradually amplified glacial influence, lotic taxa typical for Unit 1 remains rare and lentic taxa such as *H. grimshawi* type, *Micropsectra* spp. and *Procladius* sp. dominate until the end of Unit 5. However, taxa, such as the eurytopic *Orthocladius* (*O.*) cf. *oblidens*, rheophilic *O.* (*M.*) cf. *frigidus* and rheobiont *Eukiefferiella claripennis* type became an important part of the assemblages. Even though none of these taxa are primarily glacial stream inhabitants, all have been reported from glacial streams and/or glacially influenced rivers in Iceland (Hrafnsdóttir, 2005), and their presence could thus be explained by the increasing glacial influence.

The organic matter content, as shown by TC, is relatively low and stable in the lower part of this unit, in which C/N ratios also are low and indicate that most of the organic matter is aquatically produced. However, around 950 years BP, the C/N ratio increases and stays relatively high until present, concurrent with an increase in TC. We speculate that this increase may be related to the colonisation of Iceland in the late 9th century, which lasted for ca 150 years, when land use began, resulting in increased soil erosion.

## 7. Conclusions

This multi-proxy study of Lake Lögurinn's sediments has given new insights into the Holocene development of eastern Iceland, Vatnajökull and its outlet glacier Eyjabakkajökull, and lake ontogeny. Our data show that the final phase of the last deglaciation was rapid: by 10 500 years BP Lake Lögurinn was deglaciated, and ca 9000 years BP the transport of glacial meltwater from Eyjabakkajökull to Lake Lögurinn more or less ceased. During the following ca 5000 years we claim that no, or very limited amount of glacial meltwater was transported to the lake. Therefore, Eyjabakkajökull must have been much reduced in size, or even absent during the early- and mid-Holocene. This resulted in a shift to lacustrine conditions in Lake Lögurinn between ca 9000 and 4400 years BP with increased biologic productivity, possibly mainly triggered by the clear-water conditions. During this time period, we note that the 8.2 ka cold event, did not generate glacial input to the lake, but we infer that a marked decrease in the biologic productivity may be related to shorter ice-free seasons. The HTM is inferred by a period of maximum aquatic productivity, dated to ca 7900–7000 years BP. During the Neoglaciation, the re-formation of Eyjabakkajökull occurred ca 4400 years BP. This was followed by a period that we interpret as a transition from lacustrine back to glacio-lacustrine conditions, which intensified ca 3300 years BP when the transport of glacially derived sediments to Lake Lögurinn increased significantly. Based on the recurrent inferred surge periodicities of Eyjabakkajökull, we suggest that the glacier reached stable conditions ca 1700 years BP, and remained fairly stable ever since, with the exception of the later part of the Little Ice Age, when Eyjabakkajökull expanded, surged at a shorter periodicity and reached its maximum Holocene extent.

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