Holocene development of Lake Lögurinn and Eyjabakkajökull : a multi-proxy approach

Striberger, Johan

2011

LUNDQUA Thesis 65

Holocene development of Lake Lögurinn and Eyjabakkajökull in eastern Iceland – a multi-proxy approach

Johan Striberger

Avhandling

Att med tillstånd från Naturvetenskapliga Fakulteten vid Lunds Universitet för avläggande av filosofie doktorsexamen, offentligen försvaras i Geocentrum IIs föreläsningssal Pangea, Sölvegatan 12, lördagen den 1 oktober 2011 kl. 14.15.

Lund 2011
Lund University, Department of Earth and Ecosystem Sciences
Division of Geology, Quaternary Sciences

Organization LUND UNIVERSITY Department of Earth and Ecosystem Sciences, Division of Geology, Quaternary Sciences	Document name DOCTORAL DISSERTATION
	Date of issue 6 September 2011
	Sponsoring organization
Author(s) Johan Striberger	

Title and subtitle

Holocene development of Lake Lögurinn and Eyjabakkajökull in eastern Iceland – a multi-proxy approach

Abstract

The North Atlantic region has experienced significant climate fluctuations during the Holocene. It has been shown that these fluctuations affected the terrestrial environment in Iceland, including its glaciers and ice caps. However, the full Holocene development of Icelandic glaciers, including the large Vatnajökull ice cap and its outlet glaciers, is not fully known. In this thesis, a sediment sequence covering the past 10 500 years from Lake Lögurinn in eastern Iceland has been analysed. This glacier-fed lake currently receives meltwater and sediments from Eyjabakkajökull, which is a surging outlet glacier that drains the northeastern part of Vatnajökull. Using a multi-proxy approach, proxies for glacial meltwater variability and surge periodicities of Eyjabakkajökull have been examined to infer its Holocene development. In addition, changes in sediment transport from a non-glaciated catchment adjacent to Lake Lögurinn have been analysed to reconstruct winter precipitation in the Lake Lögurinn region during the past ca. 750 years. The sediments and proxy records show a dynamic development of Eyjabakkajökull during the current interglacial. After the final phase of the last deglaciation in eastern Iceland, glacially derived sediments more or less ceased to be deposit in Lake Lögurinn between ca. 9000 and 4400 years BP (BP = calendar years before 1950 AD), which suggests that Eyjabakkajökull was much reduced in size or possibly non-existing in early and mid-Holocene. During this time, the biologic productivity in Lake Lögurinn increased. This increase is inferred to reflect a switch from glacio-lacustrine to lacustrine conditions in the lake, which likely was caused by higher temperatures both in the lake and in the ambient atmosphere. The Holocene Thermal Maximum is inferred by a period of maximum Holocene aquatic productivity, and dated to ca. 7900-7000 years BP. By 4400 years BP, glacial meltwater and sediments were again transported to Lake Lögurinn, thus marking the return of the Eyjabakkajökull glacier and the onset of Neoglaciation in eastern Iceland. The Neoglacial expansion of Eyjabakkajökull caused the glacier to begin to surge ca. 2200 years BP. During the last 1700 years, the glacier has surged at a fairly constant periodicity except for the later part of the Little Ice Age (ca. 1600-1900 AD), when the surge periodicity almost halved. This increased surge activity was likely caused by increased mass accumulation of Eyjabakkajökull, which eventually caused the glacier to reach its maximum Holocene extent since the last deglaciation. This expansion and increased surge activity may to a large extent be related to increased winter precipitation, in combination with lower annual temperatures.

Key words: Iceland, the Holocene, lake sediments, varves, glacial meltwater variability, surge periodicity, palaeoclimate

Classification system and/or index termes (if any):

Supplementary bibliographical information: 200 copies		Language English
ISSN and key title: 0281-3033 LUNDQUA THESIS		ISBN 978-91-86746-71-1
Recipient's notes	Number of pages 29 + 4 app.	Price 120 SEK
	Security classification	

DOKUMENTDATABLAD enl SIS 61 41 21

Distribution by (name and address)

Signature ____________________ Date 23 August 2011

Holocene development of Lake Lögurinn and Eyjabakkajökull in eastern Iceland – a multi-proxy approach

Johan Striberger

Department of Earth and Ecosystem Sciences, Division of Geology, Quaternary Sciences, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden

This thesis is based on three papers listed below as Appendices I-III. Paper I and II are reprinted with the permission of John Wiley and Sons, Ltd. Paper III has been submitted to the journal indicated and is under consideration. Appendix IV presents photographs of selected diatom species and chironomid type from Lake Lögurinn.

Appendix I: Striberger, J., Björck, S., Ingólfsson, Ó., Kjær, K.H., Snowball, I. and Uvo, C.B., 2011. Climate variability and glacial processes in eastern Iceland during the past 700 years based on varved lake sediments. Boreas 40, 28-45.

Appendix II: Striberger, J., Björck, S., Benediktsson, Í.Ö., Snowball, I., Uvo, C.B., Ingólfsson, Ó. and Kjær, K.H., 2011. Climatic control of the surge periodicity of an Icelandic outlet glacier. Journal of Quaternary Science 26, 561-565.

Appendix III: Striberger, J., Björck, S., Holmgren, S. and Hamerlík, L. The sediments of Lake Lögurinn – a unique proxy record of Holocene glacial meltwater variability in eastern Iceland. Manuscript submitted to Quaternary Science Reviews.

Appendix IV: Photographs of selected diatom species and chironomid type from Lake Lögurinn.

Contents

1. Introduction

1.1 Background

The North Atlantic region has undergone significant climate fluctuations during the present interglacial, the Holocene, associated with both millennial scale and abrupt, decadal to centennial scale variations in the atmospheric and ocean circulation (e.g. Bond et al., 1997; Bond et al., 2001; Andresen et al., 2006). Parts of these variations may be related to changes in the thermohaline circulation, which brings warm saline surface waters to the region. These waters provide northwest Europe with relatively warm air masses. In addition, the formation of North Atlantic deep water in the Norwegian and Greenland Seas drives the thermohaline circulation, which in turn partly drives global ocean currents. As such, alterations of the thermohaline circulation, for instance through buoyancy forcing caused by fluxes of freshwater input from melting glaciers, may have global effects on climate (Lozier, 2010).

Iceland constitutes the largest landmass in the North Atlantic, and provides an ideal setting for palaeoclimatic studies, and for studies of glacier fluctuations (Gudmundsson, 1997). The North Atlantic Polar Front, defined as the boundary where northwardly flowing, warm, saline Atlantic surface waters converge with cold, low-salinity water from the Arctic, currently form just north of Iceland (Lowe and Walker, 1997). Studies of marine sediments from the north shelf of Iceland have provided information about complex temperature changes in the waters during the Holocene (e.g. Andrews et al., 2000; Eiríksson et al., 2000), which likely have influenced the terrestrial environment in Iceland, and thus, Icelandic glaciers.

Today, Icelandic glaciers are melting at a fast rate (Gudmundsson et al., 2011), and with the presently warming global climate there is a concern that changes in the freshwater input into the North Atlantic may alter the thermohaline circulation and thereby impact on society on a global scale. Therefore, it is important to understand how glaciers in this region have responded to past climate forcing, which may have influenced deep water formation sites in the North Atlantic and the convective strength of the thermohaline circulation.

One approach to track past climatic change is to examine fluctuations of glaciers and ice caps as they respond to changes in temperature and precipitation, thus providing important palaeoclimate information (Gudmundsson, 1997). Due to the closely situated large-scale atmospheric and oceanographic boundaries, the mass balance of Icelandic glaciers and ice caps are affected by changes in these systems, which will cause fluctuations in the frontal positions of the glaciers and consequently alter the amount of meltwater discharged from the glaciers (e.g. Ingólfsson et al., 1997; Bradwell et al., 2006). The idea of a progressive early Holocene deglaciation, leading to a relatively glacier-free period in Iceland and Fennoscandia, followed by the Neoglaciation in mid-Holocene when glaciers started to advance has been the main concept for the Holocene glacial history in the North Atlantic region. Although several publications have reported Holocene glacier variations in the region (e.g. Karlén, 1988; Nesje et al., 2001; Kirkbride and Dugmore, 2006), the glacial history of the Vatnajökull glacial system, with its many large outlet glaciers, is poorly known. Vatnajökull constitutes one of the largest (>8000 km^2) ice caps outside Antarctica and Greenland, and is positioned centrally in this climatically sensitive region. It is influenced by changes in the convective strength of thermohaline circulation and by moisture-bearing cyclones from the southwest. Therefore, Vatnajökull may be regarded as a sensor for a combination of regional climatic driving processes.

While the approach of examining glacier fluctuations to track past climatic change may seem straightforward, there are challenges that have to be overcome; local effects on glacier fluctuations, e.g. volcanism, have to be considered and non-climatic influences that may affect a glacier need to be resolved before using glaciers for palaeoclimatic reconstructions (Gudmundsson, 1997). In addition, a common challenge when examining past glacier fluctuations is the lack of continuous records and chronological constraints. Terrestrial evidence of past glacier fluctuations are by nature often overridden by later advances and, therefore, evidence of glacier activity in Iceland prior to recent glacial advances is patchy (Geirsdóttir et al., 2009a).

One way to overcome these challenges is to examine sediment deposition in lakes that receive glacial meltwater, so-called glacier-fed lakes. Glacier-fed lakes are, in contrast to proglacial lakes, located further from the glacier front and therefore, fluctuations of the glacier front do not disturb the sediments that are being deposited in the lake. If a sediment sequence from a glacier-fed lake can be well dated, it provides an opportunity to examine glacial meltwater fluctuations, which may be related to glacier advances and retreats. By using a multi-proxy approach it may be possible to decipher these fluctuations to a combination of climatic changes and internal glacial processes.

1.2 Project objectives

The glacier-fed Lake Lögurinn is situated in eastern Iceland, northeast of the large Vatnajökull ice cap. It is part of the drainage system of Eyjabakkajökull, which is a conspicuous surging outlet glacier of the ice cap. The lake forms a sediment trap for meltwater and suspended matter from the glacier and also for sediments from the large River Grímsá that drains a currently non-glaciated catchment. This mix of glacial and non-glacial suspensions in the sediments of Lake Lögurinn provides an opportunity to examine how these different regimes have varied during the Holocene and how these variations relate to glacial meltwater discharge, fluvial discharge, glacial processes and changes in climate. The specific aims of this thesis were:

- To reconstruct past climate in eastern Iceland with focus on the last millennia by examining the properties of varved sediments recovered from Lake Lögurinn.

- To construct a palaeo-surge record of Eyjabakkajökull based on "surge-fingerprints" in the sediments from Lake Lögurinn that formed during historically documented surges, and explore the relationship between surge periodicity and climate over longer time periods.

- To obtain a general glaciation history of Vatnajökull throughout the Holocene, expressed as meltwater variations from Eyjabakkajökull, by distinguishing glacial and non-glacial periods in the sediments from Lake Lögurinn.

To clarify the concept of varves and glacier surges, which constitute a large part of the discussion in this thesis and in the appendices, a short introduction to varves and surges is provided in the following sections.

1.3 Varves

Variations in the properties of suspended matter transported to sedimentary basins may give rise to laminated sediments, if no mixing occurs at the basin floor after deposition, e.g. through bioturbation. Laminated sediments have been observed globally, but typically occur in regions where climate is characterised by strong seasonal contrasts, such as high-latitude regions. If laminae are deposited in annual cycles, they are referred to as varves. Hence, a varve consists of sediments deposited during one annual cycle, and in its simplest form, it consists of two laminae. In these varves, a lower lamina is formed from early spring until late autumn, and a capping upper lamina is formed during winter. However, varves are often more complex, and may contain inter-annual laminae (sub-laminae) (Kaufman et al., 2011), formed by periodic input of suspended (mineral) matter, settling of biogenic matter and chemical precipitates.

Depending on the specific basin and region, different types of varves may form. Biogenic-clastic varves contain alternating lamina of autochthonous organic matter (e.g. algae and diatoms) and allochthonous mineral matter, but varves may also form by settling of calcium carbonates and iron hydroxides/sulphides (O´Sullivan, 1983). In glacial regions, clastic varves commonly form in proglacial or glacier-fed lakes as a consequence of strong seasonal variations in discharge from glacier melt. These varves typically contain different grain-sizes in their laminae, with relatively coarse-grained sediments in the lower lamina, and fine-grained sediments in the upper lamina formed by suspended matter that settles to the lake floor during winter.

The annual nature of varves provides a possibility to construct high-resolution chronologies in lake sediments. Since the pioneering works on the deglacial varves in Sweden by G. De Geer in the late 1800s and early 1900s (De Geer, 1912), varves have been used as a tool for dating sediments (e.g. Ojala and Saarinen, 2002; Zillén et al., 2002), and properties of varves, typically varve thickness, have been used to reconstruct a wide range of climatic and environmental parameters. In Arctic environments, where lake basins often are ice-covered during most parts of the year, varve thickness, which yields annual sediment accumulation rates, have been widely used for climate reconstruction purposes. Several studies have found relationships between melt-season temperature and varve thickness (Hughen et al., 2000; Moore et al., 2001; Besonen et al., 2008; Menounos and Clague, 2008; Bird et al., 2009; Cook et al., 2009; Loso, 2009; Thomas and Briner, 2009), but also relationships between varve thickness and discharge and precipitation have been observed (Itkonen and Salonen, 1994; Sander et al., 2002; Tomkins et al., 2010).

Even though varves have successfully been used for palaeoenvironmental reconstructions and dating purposes, varve formation has complex relationships to the lake basin, its catchment and within-lake productivity as a range of parameters affect varve formation (Gälman et al., 2006; Hodder et al., 2007). Therefore, it is essential to fully understand the key processes forming varves in a specific lake and verify that the laminations are indeed of annual nature (Jones et al., 2009) by independent isochrones, e.g. historical tephras or radiometric dating methods.

1.4 Glacier surges

Surging glaciers exhibit short periods of relatively fast motion, followed by longer periods of slower flow. During the active phase, commonly referred to as the surge, ice is transferred rapidly from the upper part of a glacier (the accumulation area) towards the lower part (the ablation area). This results in a marked advance of the glacier front of up to several kilometres, which may occur at velocities up to 10 times the velocity during periods of slower flow (Raymond, 1987). Eventually, thinning of the upper accumulation area and thickening of the lower ablation area causes a reduction in the overall gradient of the glacier, which possibly triggers a shift to slower flow. The period of slow flow is referred to as the quiescent phase, and typically has a duration of 10-100 years (Kamb et al., 1985). During the quiescent phase, increase of mass in the accumulation area and loss in the ablation area will cause a steepening of the glacier gradient, and eventually, cause a shift back to the active phase, and trigger the next surge (Benn and Evans, 1998). Therefore, one of the main characteristics of surge-type glaciers is that they surge repeatedly in so-called surge cycles.

Surge-type glaciers are found globally, but are more common in certain areas (Harrison and Post, 2003), such as northwest North America (Alaska, British Columbia and Yukon), in the North Atlantic region (Iceland and Svalbard) and in western Asia (Pamirs). However, surge-type glaciers have also been observed in e.g. Greenland, in parts of Arctic Canada, in the Caucasus, Tien Shan and Karakoram Mountains in Asia and in the Andes (Benn and Evans, 1998), while there are currently no surging glaciers in e.g. the Alps.

One of the early ideas for the mechanism behind glacier surges was that they were triggered as a result of a switch from a glacier frozen to its bed to a water-lubricated base (Van der Veen, 1999). However, as it is now known that temperate glaciers surge, which remain well-lubricated at their beds during the quiescent phase, e.g. Eyjabakkajökull and all of the Icelandic surge-type glaciers (Björnsson et al., 2003), this is not the only explanation for why surges occur. Today, the processes behind surges are still much debated, as highlighted by Harrison and Post (2003). However, it has been recognised that surges are probably related to changes in the subglacial conditions and their relationship with the hydraulic system (e.g. Kamb et al., 1985).

Despite detailed observations of recent surges (Kamb et al., 1985) and suggestions of their indirect link to climate (e.g. Dowdeswell et al., 1995) the long term perspective on surge activity is fairly unknown as the available data of historically documented surges are restricted to the last couple of centuries, at most. Studies of the internal processes of surging glaciers are practically difficult and the lack of palaeo-surge records prevents any

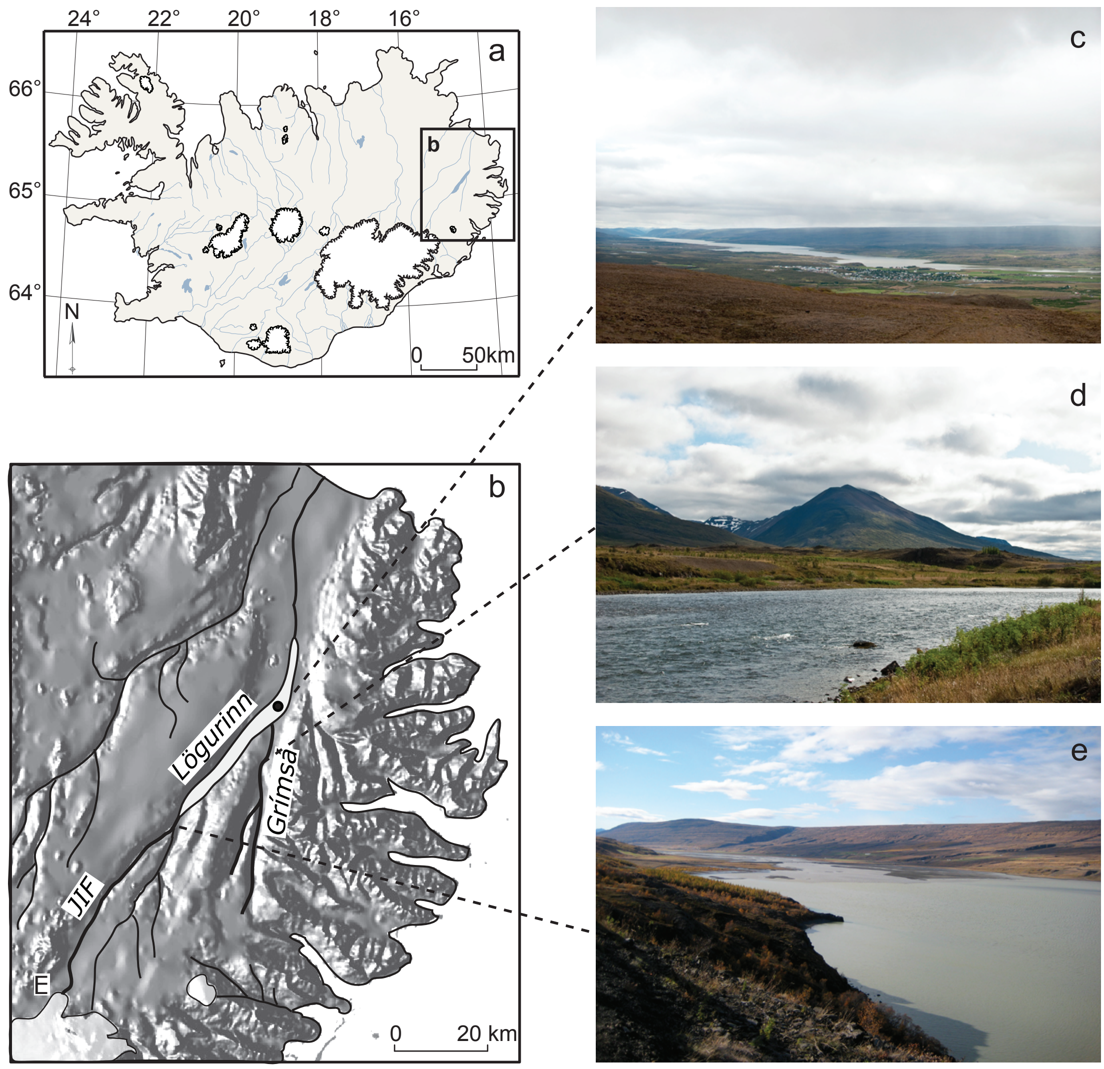

Figure 1. (a) Map of Iceland. (b) Detailed view of the study area in eastern Iceland showing the location of Lake Lögurinn, Eyjabakkajökull (E), River Jökulsá í Fljótsdal (JIF) and River Grímsá in the Fljótsdalur valley. The core sites in the northern sub-basin of Lake Lögurinn are marked by the black dot. (c) View towards the southwest of Lake Lögurinn. (d) View towards the south of River Grímsá. (e) View towards the south of the inlet of River Jökulsá í Fljótsdal.

comparison between surge activity and climate. Therefore, current understanding is restricted to the past century (Dowdeswell et al., 1995).

2. Site description

The Fljótsdalur valley runs in a SW-NE direction about 40-50 km inside the coast of eastern Iceland. The valley is glacially sculptured and has served as a conduit of ice during previous glaciations in Iceland. The bedrock consists of a ca. 1500 m thick sequence of basaltic lava flows, with consolidated sedimentary interbeds of sandstone and siltstone, and was formed during the last 6.5 million years (Pálmason, 1992).

2.1 Lake Lögurinn

Lake Lögurinn (Lagarfljót) is situated centrally in Fljótsdalur valley (65°15´N, 14°25´W), (Fig. 1). The lake is approximately 30 km long with a maximum width of 2.8 km and covers 53 km^2, which makes it one of the largest lakes in Iceland. The bottom topography is rather variable as the lake consists of three sub-basins of different depths, which are separated by sills. The southern sub-basin is deepest with a maximum depth of 112 m and sediment thicknesses that average ca. 80 m (Gudjónsson and Desloges, 1997). The central and northern sub-basins both have sediment thicknesses of ca. 40-80 m, with maximum water depths of 72 and 42 m, respectively. The mean water depth of the lake is 51 m (Hallgrímsson, 2005). Because the mean water surface of the lake is situated at ca. 20 m a.s.l. the Lake Lögurinn bedrock floor reaches down to ca. 90 m below present sea level in the southern sub-basin. The lake drains northward via River Lagarfljót, which flows into a wide delta on the coast of northeast Iceland.

2.2 River Jökulsá í Fljótsdal and River Grímsá

Lake Lögurinn receives discharge from a number of smaller streams and rivers, but the main part is transported to the lake by two major rivers. River Jökulsá í Fljótsdal is the largest river to enter Lake Lögurinn. This glacial river drains Eyjabakkajökull and delivers sediment via a braided system and a large delta in the southernmost part of Lake Lögurinn. The catchment of River Jökulsá í Fljótsdal mainly consists of heath, grassland, cultivated land and wetlands, while the area closest to Eyjabakkajökull is very sparsely vegetated (Kardjilov et al., 2006). The 1963-2005 daily average discharge of River Jökulsá í Fljótsdal was 37.5 $m^3 s^{-1}$ (Orkustofnun, 2006).

River Grímsá is the second largest river that delivers suspended matter to Lake Lögurinn, and enters the lake at its northeastern shore close to the sill that separates the central and northern sub-basin. River Grímsá is a direct run-off river and its discharge increases almost instantly during heavy rain events. It can dry out during frost and dry conditions (Einarsson, 1994). It drains a currently non-glaciated catchment that contains heath, grassland and cultivated land (Kardjilov et al., 2006) and its 1963-2005 daily average discharge was 24 $m^3 s^{-1}$ (Orkustofnun, 2006).

On average, the discharge in both rivers starts to increase in early May during the spring snow melt (Orkustofnun, 2006). The discharge in River Grímsá peaks in June, while the discharge in River Jökulsá í Fljótsdal remains high until early September. The longer period of higher discharge rates in the glacial river is caused by an initial snow melt, followed by summer melting of Eyjabakkajökull, while the shorter discharge peak in River Grímsá mainly results from snow melt during spring and early summer. During autumns and winters, River Grímsá often shows distinct discharge peaks, caused by heavy rainstorms or early winter snowfalls that melt rapidly. However, except for 1972, the mean annual discharge since the early 1960s in the two rivers has always been highest in River Jökulsá í Fljótsdal.

2.3 Eyjabakkajökull

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. It is formed by three smaller outlets, which descends from ca. 1200-1500 m a.s.l. and terminates in the highlands at ca. 700 m a.s.l., about 55 km southwest of Lake Lögurinn, where River Jökulsá í Fljótsdal transports its meltwater to Lake Lögurinn. The equilibrium line altitude of Eyjabakkajökull varied between 1040-1240 m a.s.l. during the 1990s (Björnsson et al., 2002) and its surface slope of ca. 2.7° falls in the average range of 1.6-4° for surge-type glaciers in Iceland (Björnsson et al., 2003).

Owing to the remoteness of Eyjabakkajökull, historical evidence of its fluctuations is rather sparse and exists only from events after 1890, when the first documented surge occurred (Björnsson et al., 2003). Historically documented surges also occurred in 1931, 1938 and 1972-1973. In addition, a less reliably documented surge may have taken place in 1894 (Björnsson et al., 2003). The known surges of Eyjabakkajökull have resulted in ice front advances of ca. 2-4 km (Benediktsson et al., 2010). During the most recent surge the ice front of Eyjabakkajökull advanced ca. 2 km (Sigurðsson, 1998), which resulted in an addition 2 km^3 of ice to the ablation area (Magnússon et al., 2004) and a significant increase of suspended matter in River Jökulsá í Fljótsdal. During this surge the amount of clay in the suspended matter exceeded 90%, far above the mean observed value of 35% between 1965 and 1995 (Pálsson and Vigfússon, 1996).

The three smaller outlets that form Eyjabakkajökull do not always advance simultaneously during surges (Benediktsson et al., 2010), which may explain the possible surge in 1894 shortly after the well-known surge in 1890 and also the short time interval between the surges in the 1930s when the western and central outlets advanced, respectively (Sharp, 1985). With the assumption that the surges in the 1890s and 1930s were part of the same surge cycle, documented surges have occurred about every 35-40 years.

2.4 Climate

Because of the Vatnajökull ice cap, the Fljótsdalur valley and Lake Lögurinn are partly in precipitation shadow from the moisture-bearing southerly winds that typically generate rain and snow in Iceland. Southerly winds often cause föhn-winds in the region, which combined with the distance from the cool coastal waters causes the present climate to be more continental than other regions in Iceland, with relatively warm summers. It is for instance one of few Icelandic regions with birch forest (Hallormsstaðaskógur). Mean annual 1961-1989 temperature in the surroundings of Lake Lögurinn was 3.4 °C with January being the coldest month when mean temperature was -1.6 °C (Veðurstofa Íslands, http://www.vedur.is). Mean annual precipitation for the same time period was 766 mm year^{-1}. Most of the precipitation falls during autumns and winters.

Lake Lögurinn is normally ice-covered by February-March, but the central parts have been ice-free about every 3-5 years during the past 50 years (Hallgrímsson, 2005). When the lake freezes over ice first starts to form over the less deep northern parts of the lake and later spreads southwards. On average, the lake ice starts to disintegrate in the beginning of April.

3. Methods

3.1 Fieldwork, coring and subsampling

Fieldwork was carried out in September 2006 and 2007. Prior to the first fieldwork, a seismic survey was carried out in the northern sub-basin of Lake Lögurinn using a C-Phone hydrophone steamer connected to a C-Boom system. Based on eleven seismic profiles obtained during this survey two core sites were chosen at 38 and 16 m water depth (L1 & L2) (Fig. 1).

A steel-cable operated Uwitec "Niederreiter 60" piston corer, mounted on an anchored Uwitec floating platform (Fig. 2), was used to collect sediments in overlapping 3 m segments in transparent PVC liners with an internal diameter of 60 mm. Coring at L1 resulted in a 12 m long sediment sequence, and at the L2 core site, 14 m of sediments were recovered. The undisturbed sediment-water interface was captured at L1 in a complementary 0.35 m long surface-sediment core using a LTH Kajak sediment-surface sampler. The PVC liners were split lengthwise into "D" sections, wrapped in plastic and kept cool during transport back to Lund. The sediment cores were then stored in a cold room in Lund until the analyses were carried out.

Figure 2. Uwitec floating platform used during core collection in Lake Lögurinn.

The cores from L1 and L2 were correlated visually in the laboratory using tephra layers and distinct sediment units. Later, the correlation was refined with the aid of magnetic susceptibility measurements. Subsampling was carried out on the correlated cores.

3.2 Radiometric dating

The sediments from Lake Lögurinn are extremely poor in organic material and, therefore, the use of radiocarbon dating, which is probably the most commonly used method for dating lake sediment sequences (Lowe and Walker, 1997) was limited. The plant remains (macrofossils) that were found in the sediments were dated by accelerator mass spectrometry (AMS) ^{14}C dating at Lund University and the radiocarbon ages were calibrated with OxCal 4.1 (Bronk Ramsey, 1995, 2001) using the calibration dataset IntCal09 (Reimer et al., 2009).

^{137}Cs analyses were carried out to estimate the age of the recent sediments from Lake Lögurinn. Significant levels of ^{137}Cs were detected in the atmosphere in 1954 (Pennington et al., 1973) due to tests of nuclear weapons and measurements of ^{137}Cs in Icelandic soils began in 1958 (Sigurgeirsson et al., 2005). Samples of recent sediments, which were assumed to cover the Northern Hemisphere fall-out peak in 1963 (Pennington et al., 1973) and the Chernobyl accident in 1986, were measured with gamma spectrometry in a calibrated geometry over two days using a well-type HpGE detector.

3.3 Tephra analysis

Owing to the frequent volcanic eruptions in Iceland, tephras are commonly found in Icelandic soils and sediments. Since the settlement of Iceland ca. 870 AD, volcanic eruptions are often mentioned in historical records with quite accurate dates, while pre-historical tephras often rely on ^{14}C dating of overlying and underlying peat and soil (e.g. Dugmore et al., 1995). Previous work has resulted in a detailed tephrochronology of Icelandic tephras throughout the Holocene (Haflidason et al., 2000; Larsen and Eiríksson, 2008).

Major element geochemical analysis of volcanic glass shards from selected tephras were determined by standard wavelength dispersal techniques on a JEOL JXA-8200 microprobe at the GeoCenter, University of Copenhagen, operating at 15 kV with a beam current of 8 nA and a beam size of 7 µm. By comparing their geochemical fingerprints and stratigraphic positions with those of independently identified and dated tephras elsewhere eight historically documented tephras and four pre-historic tephras were identified, which were used for dating the sediments.

3.4 Magnetic susceptibility

Magnetic susceptibility is a measure of the degree to which sediments can be magnetised and it is strongly dependant of the amount of ferro/ferrimagnetic particles in a sample (Thompson and Oldfield, 1986). Two techniques were used during the measurements. Within 24 h of sediment recovery the sediment cores were measured using a Bartington Instruments MS2 meter and MS2C core logging loop sensor (80 mm diameter) at 2 cm intervals. In the laboratory, the sediment surfaces of split cores were covered with thin (<0.01 mm) plastic film and the magnetic susceptibility of the cleaned surface were measured with the MS2 meter coupled to a MS2E core logging sensor at 4 mm intervals, operated by an automatic TAMISCAN core logging conveyor. Magnetic susceptibility of the sediments was measured to aid the correlation of the sediment cores, and to examine the dominating sediment source(s) in different sediment units.

3.5 Loss on ignition

Loss on ignition (LOI) was used to estimate the amount of organic matter in the sediments (Bengtsson and Enell, 1986). Samples from the sediment sequence were dried at 105°C for 24 h and then combusted at 550°C for 2 h.

3.6 X-radiography and X-ray fluorescence scanning

X-radiography and X-ray fluorescence (XRF) scanning was carried out of the sediments using an ITRAX Core Scanner (Croudace et al., 2006) at the Core Processing Laboratory in the Department of Geological Sciences at Stockholm University. The ITRAX Core Scanner is non-destructive and provides element profiles and radiographic images of the sediments, which were used mainly to aid the interpretation of laminated sections in the Lake Lögurinn sediments (Guyard et al., 2007).

The element profiles display peak areas of counts per second (cps), and were obtained using a molybdenum anode X-ray tube. The sediments were covered with a thin plastic film to protect the sediments from drying out during the scans and the measurements were carried out on split-core surfaces from a 4 mm wide and 0.1 mm thick area in 0.5 mm steps, with an exposure time of 10 s per measurement. For the analyses of the XRF derived data, light elements (e.g. Al and Si) were excluded as they have been shown to attain strongly reduced intensities caused by the water content of sediment surfaces (Tjallingii et al., 2007). Furthermore, elements with intensities <40 cps were discarded. The final elements used were K, Ca, Ti, Mn, Fe, Co, Zn, Sr and Zr. Caution was taken in the interpretation of extreme values in the data, which typically were observed at cracks in the sediments, or in tephras.

Radiographic images produced by the ITRAX Core Scanner display bulk density variations in the sediments, which may reflect changes in grain-size, mineral and/or organic content. The images are so-called "radiographic positives", which means that low-density areas appear light and high-density areas appear dark. To facilitate the interpretation of these images they were converted into greyscale values using IMAGEJ 1.38X (http://rsb.info.nih.gov/ij/index.html).

3.7 Grain-size analysis

Grain-size analyses were performed mainly to estimate whether the grain-size distribution was different between laminated and non-laminated sediment units, as well as between lower and upper laminae in laminated units. The analyses were carried out using two different techniques. High-resolution samples from recent sediments were analysed by laser diffraction (Mastersizer 2000) at the Natural History Museum in Copenhagen, Denmark, which showed volume-% of the total volume. In the second case, samples covering the full sediment sequence were analysed using a SediGraph (Micrometrics SediGraph III) at Lund University, which showed weight-% clay and silt of the total mass.

3.8 Biogenic silica

Biogenic silica concentration (BSi), expressed as weight-% SiO_2, was measured using methods described by Conley & Schelske (2001). BSi is a measure of the amorphous Si content in sediments, and typically a good proxy for diatom abundance and for other siliceous microfossils (Conley, 1988; Conley and Schelske, 2001). BSi was, therefore, measured to estimate the within-lake biologic productivity in Lake Lögurinn, which in turn may be related to changes in climate, nutrients and water column characteristics such as pH, light-conditions and turbidity.

3.9 Element analysis

Analyses of carbon (C) and nitrogen (N) in the sediments were carried out to estimate the amount of organic matter in the sediments and to provide information about the source of the organic matter. Organic matter typically contains about 50% carbon (Meyers and Teranes, 2001), or more accurately, 12/30 carbon $(CH_2O)_n$) (Bengtsson and Enell, 1986). Because the basaltic bedrock in Iceland does not contain $CaCO_3$, the carbon in the Lake Lögurinn sediments is exclusively organic. By multiplying the carbon content by 2-2.5, a rough indication of the amount of organic matter may be obtained.

The atomic C/N ratio was calculated by multiplying C/N by 1.167, and was used to infer the source(s) of the organic matter in Lake Lögurinn. Terrestrial organic matter typically has C/N ratios that exceed 20 (Meyers and Teranes, 2001), while aquatically produced organic matter often is dominated by algae, which contain relatively higher amounts of nitrogen. Therefore, C/N ratios of aquatically produced organic matter are lower, typically in the range between 4 and 10 (Meyers and Teranes, 2001).

3.10 Diatom analysis

Diatoms are unicellular algae with siliceous shells (frustules) and are commonly used as a proxy for changes in the environmental conditions in lakes because they are sensitive to changes in e.g. nutrients and pH (Lowe and Walker, 1997). The sediments in Lake Lögurinn were analysed for diatoms to provide information about within-lake biologic productivity, and to examine whether lithologic changes are related to changes in the diatom assemblage. Samples were collected from the sediments, freeze-dried, and oxidised with 15% H_2O_2 for 24 h, then digested in 30% H_2O_2 for at least 24 h, and finally heated at 90°C for several hours. Slurries were then centrifuged and rinsed with deionised water and finally diluted to 10 ml. A known quantity of 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 results were expressed as relative abundances of each taxon, and as total concentrations of valves per g dry sediment (Battarbee and Kneen, 1982).

3.11 Chironomid analysis

Adult chironomids are non-biting midges and remains of their aquatic larvae are often used for palaeoenvironmental reconstructions. Similar to diatoms, chironomids may indicate changes in e.g. nutrient availability and pH in lakes. However, they have also shown to be good indicators of past summer surface water temperatures, and therefore, chironomids are commonly used to infer past summer temperatures (Caseldine et al., 2006; Axford et al., 2007; Axford et al., 2009). Chironomids from the sediments were mainly analysed to infer changes in the glacial influence of Lake Lögurinn, and to some extent, to infer past temperatures.

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 (40x 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). Taxonomic identification was performed under a compound microscope at 400x 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.

3.12 Lamina and varve measurements

Laminated sediments were analysed to examine whether the laminations were of annual nature (i.e. varved), and the thickness of each lamina (lower and upper) was measured to determine sediment accumulation.

The laminations were mainly examined with a Wild Heerbrugg M420 macroscope equipped with a polarizing filter, which was coupled to an Aniol electric tree-ring measuring system in the Laboratory for Wood Anatomy and Dendrochronology at Lund University. This equipment enabled measurements of the lamina thickness at micrometre precision. The sediments were cleaned and polished before the measurements, and extra lights were used to obtain a satisfying view of the sediment surfaces. The measurements were taken along the central axis of the sediments, within the inner undisturbed 18 mm of the sediments, which equals the scanning width of the X-radiography and XRF measurements.

The lamina measurements were carried out during at least three separate occasions, and to compensate for minor horizontal variations in the lamina, the mean thickness of these measurements was used. To avoid cumulative errors in the core depth, the measurements were carried out between fixed intervals determined by marker horizons (e.g. tephras), so that each set of measurements started with a "clean sheet" at correct depth. To keep track of the measurements and counts, the sediments were photographed with an AF-S Micro Nikkor 60-mm f/2.8G ED lens at close range. The photos were mounted in Adobe Illustrator CS2, where the measured laminations were marked and counted.

Lamina and varve identification is often subjective, because the identification normally relies on visual interpretations, either from images or through a macroscope. To minimise the subjectivity during the measurements, a "model" was constructed for interpretation of the laminae and the varves in the Lake Lögurinn sequence, which included data from the x-radiography and XRF scans (see section 5.1).

4. Summary of papers

4.1 Appendix I

Striberger, J., Björck, S., Ingólfsson, Ó., Kjær, K.H., Snowball, I. and Uvo, C.B., 2011. Climate variability and glacial processes in eastern Iceland during the past 700 years based on varved lake sediments. Boreas 40, 28-45.

In this paper, properties of varved sediments from Lake Lögurinn were examined to infer past climate in the region, and glacial processes of Eyjabakkajökull, since 1262 AD. The aim of the study was two-fold. First, we examined whether laminated sediments in Lake Lögurinn have been formed in annual cycles (i.e. varved) during the past ca. 750 years, and then different varve properties were correlated to meteorological records and compared to glaciological observations.

With the aid of visual observations, close-up photographs, X-ray density and geochemical properties determined by X-radiography and X-ray fluorescence scanning, a varve chronology covering 1262-1477 AD and 1619-2005 AD was constructed. This chronology was verified by independent dating provided by ^{137}Cs and eight historically documented tephras. The sediment section that represents 1477-1619 AD, which is constrained by two historically documented tephras, only contains 18 inferred varves and thus reveals a well-defined hiatus in the sediment record from Lake Lögurinn. This part was, therefore, excluded in the analyses.

Lower lamina thickness, mainly controlled by the amount of suspended matter from the non-glacial River Grímsá, was significantly correlated to autumn and winter precipitation in the Lake Lögurinn region (r=0.57 [0.19 0.76]) between 1961 and 1989, with the highest correlation between lower lamina thickness and winter (Dec-Feb) precipitation (r=0.70 [0.27 0.86]) (The 99% confidence interval for each correlation coefficient (r) determined by means of bootstrapping is herein presented within square brackets). Late season precipitation causes the discharge in River Grímsá to increase, which results in additional sediment transport to Lake Lögurinn. This late season sediment transport forms inter-annual lamina (sub-lamina) in the lower laminae prior to ice coverage of Lake Lögurinn, when the upper laminae are formed.

Based on the correlation, winter precipitation in the Lake Lögurinn region was reconstructed for the past ca. 750 years. The reconstruction shows that winter precipitation was higher and more variable from the early 1600s until the late 1800s, when compared to the precipitation that prevailed in the early part of the record and during the 1900s. The period of inferred higher winter precipitation corroborates the later part of the Little Ice Age (LIA) when Icelandic glaciers expanded, including Eyjabakkajökull (Sharp and Dugmore, 1985; Bradwell et al., 2006; Kirkbride and Dugmore, 2006). It is, therefore, suggested that increased winter precipitation could have been an important parameter, along with reduced summer temperatures, for the enhanced glacier growth at this time. This interpretation is similar to what has been suggested for glacier advances in western Scandinavia during the 1700s (Nesje et al., 2008).

Upper lamina thickness, controlled by the amount of suspended matter from the glacial River Jökulsá í Fljótsdal, increased significantly during the 1972 surge of Eyjabakkajökull. Similar increases were observed in the 1930s and 1890s, when the other historically documented surges occurred. These increases of upper lamina thickness form a recurring cyclic pattern of intervals dominated by relatively thick upper laminae in the sediment sequence that covers the past ca. 750 years. Based on these observations it is suggested that Eyjabakkajökull has surged repeatedly since at least 1262 AD. It is also noticed that these intervals occur more frequently during the latter part of the LIA. Therefore, it is suggested that the quiescent phase of Eyjabakkajökull shortened as a response to the colder temperatures that prevailed during this time period (Jiang et al., 2005; Massé et al., 2008) and, possibly, also as a response of increased winter precipitation as inferred by the lower lamina thickness in the sediment sequence.

4.2 Appendix II

Striberger, J., Björck, S., Benediktsson, Í.Ö., Snowball, I., Uvo, C.B., Ingólfsson, Ó. and Kjær, K.H., 2011. Climatic control of the surge periodicity of an Icelandic outlet glacier. Journal of Quaternary Science 26, 561-565.

Surge-type glaciers affect a large part of the ice covered area in Iceland and occur in all of the major ice caps, including the large (>8000 km^2) Vatnajökull ice cap. Despite their widespread occurrence, little is known about their Holocene surge history. Historical surge records only extend a couple of centuries back in time at most (Björnsson et al., 2003) and, therefore, studies of the relationship between surge periodicity and climate have been limited to recent observations. In this paper, we used varved sediments from Lake Lögurinn covering the past ca. 2800 years to construct a palaeo-surge record of Eyjabakkajökull. This record of inferred surges of Eyjabakkajökull is used to assess when the glacier began to surge, and to examine whether its surge periodicity is related to climate.

By applying the methods presented in Appendix I the varve chronology from Lake Lögurinn was extended to 2813 years BP. In the varved sediment section, intervals dominated by relatively thick upper laminae were formed during the historically known surges since 1890 AD. Similar intervals occur in most parts of the varved sequence and they are inferred to represent past glacier surges of Eyjabakkajökull.

These "surge intervals" began to form ca. 2200 years BP, suggesting that Eyjabakkajökull shifted to a "surge mode" at that time. This time period follows the late Holocene return to cool conditions (Neoglaciation) in northwest Europe and the North Atlantic (Van Geel et al., 1996; Bond et al., 1997), when glaciers in Iceland expanded. It is speculated that this expansion caused the profile of Eyjabakkajökull to steepen until the basal stress, which is a key parameter in changing the basal motion of glaciers (Boulton and Jones, 1979), passed a critical point and triggered surging. The surging restored the glacier profile to near-equilibrium conditions (see section 5.4 for further discussion).

The surge intervals occur irregularly between ca. 2200 and 1700 years BP. However, based on Fourier and wavelet analyses of the upper lamina thickness record, the record shows that surge intervals following 1700 years BP occurred at a periodicity of ca. 34-38 years until the early 1600s, when the periodicity almost halved to 21-23 years. This shorter surge periodicity lasted until the late 1800s, when the wavelet analysis indicate a return to a longer periodicity of ca. 35-40 years, which corroborates the historically known surge periodicity, given that the multiple surges in the 1890s and 1930s were part of the same surge cycles.

The marked shift in the surge periodicity from 34-38 to 21-23 years occurred when Iceland is considered to have experienced its coldest climate during the past 8000 years; a period when glaciers in Iceland had their largest extent since the last deglaciation (Geirsdóttir et al., 2009a), including Eyjabakkajökull (Sharp and Dugmore, 1985) and when the reconstruction presented in Appendix I suggests that winter precipitation increased. Following this cold period, Eyjabakkajökull returned to a longer surge periodicity, which implies that the warming climate during the 1900s caused Eyjabakkajökull to behave in the same way as it did prior to the LIA. Therefore, the results presented in this paper suggest that climatically driven mass balance changes have altered the surge periodicity since Eyjabakkajökull began to surge ca. 2200 years BP. If current warming continues to cause the mass balance of Eyjabakkajökull to be negative the glacier may fail to re-enter the active surge phase and switch back to a non-surge mode, concurrent with observations from Svalbard during the 1900s (Dowdeswell et al., 1995).

4.3 Appendix III

Striberger, J., Björck, S., Holmgren, S. and Hamerlík, L. The sediments of Lake Lögurinn – a unique proxy record of Holocene glacial meltwater variability in eastern Iceland. Manuscript submitted to Quaternary Science Reviews.

The North Atlantic region has undergone significant climate fluctuations during the Holocene (Bond et al., 1997; Andresen et al., 2006), caused by changes in large-scale atmospheric and ocean circulation patterns that dominate this region. Changes in these systems will ultimately influence the mass balance of Icelandic glaciers by making them advance or retreat (Ingólfsson et al., 1997; Norðdahl and Einarsson, 2001; Bradwell et al., 2006). The status of Icelandic glaciers during the Holocene has been a fairly well studied topic (Geirsdóttir et al., 2009a), but most studies have been focussed on

Table 1. Contributors to the research results presented in Appendices I-III.

	Appendix I	Appendix II	Appendix III
Fieldwork	*J. Striberger* *S. Björck* *I. Snowball* *Ó. Ingólfsson*	*J. Striberger* *S. Björck* *I. Snowball* *Ó. Ingólfsson* *Í.Ö. Benediktsson*	-
Core correlation and sampling	*J. Striberger* *I. Snowball*	*J. Striberger*	*J. Striberger*
Sediment description	*J. Striberger*	*J. Striberger*	*J. Striberger*
Lamina measurements	*J. Striberger* *S. Björck* *I. Snowball*	*J. Striberger*	*J. Striberger*
Magnetic susceptibility	*I. Snowball*	*J. Striberger* *I. Snowball*	-
X-radiography and X-ray fluorescence scanning	*J. Striberger*	*J. Striberger*	-
Loss on ignition	*J. Striberger*	-	*J. Striberger*
Grain-size analysis	*J. Striberger*	-	*K.H. Kjær* *J. Striberger*
Tephra analysis	*K.H. Kjær*	*K.H. Kjær*	-
Biogenic silica	*H. Lindvall*	-	*H. Lindvall*
Diatom analysis	-	-	*S. Holmgren*
Chironomid analysis	-	-	*L. Hamerlík*
Statistics	*C.B. Uvo* *J. Striberger*	*C.B. Uvo* *J. Striberger*	-
Data interpretation	*J. Striberger* *S. Björck* *Ó. Ingólfsson* *I. Snowball* *C.B. Uvo* *K.H. Kjær*	*J. Striberger* *S. Björck* *Í.Ö. Benediktsson* *I. Snowball* *C.B. Uvo* *Ó. Ingólfsson* *K.H. Kjær*	*J. Striberger* *S. Björck* *S. Holmgren* *L. Hamerlík*

glacial activity during the latter part of the Holocene, presumably because continuous Holocene records of glacier fluctuations are sparse. In this manuscript, a multi-proxy approach of the sediments in the glacier-fed Lake Lögurinn was used to infer meltwater variability of Eyjabakkajökull during the past ca. 10 500 years, which is related to fluctuations of the glacier throughout the Holocene.

The data reveal that the final phase of the last deglaciation in the Lake Lögurinn region was rapid. The lake was deglaciated by 10 500 years BP and by ca. 9000 years BP the discharge of glacial meltwater from Eyjabakkajökull to Lake Lögurinn more or less ceased. During the following ca. 5000 years it is suggested that no, or very limited amounts of glacial meltwater entered Lake Lögurinn. Therefore, Eyjabakkajökull must have been significantly smaller, or even non-existing during the early and mid-Holocene. This resulted in a shift to pure lacustrine conditions in Lake Lögurinn between ca. 9000 and 4400 years BP with increased biologic productivity, possibly mainly triggered by clear water conditions caused by the absence of suspended glacial rock flour. During this time period, we note that the 8.2 ka cold event (Alley et al., 1997) 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 caused by cooler winter conditions. The Holocene Thermal Maximum (HTM) (Snowball et al., 2004) is inferred by a period of maximum aquatic productivity, and dated to ca. 7900-7000 years BP.

During the Neoglaciation, Eyjabakkajökull began to reform ca. 4400 years BP. This was followed by a period inferred as a transition from lacustrine back to glacio-lacustrine conditions in Lake Lögurinn, which intensified ca. 3300 years BP when the transport of glacially derived sediments to the lake increased significantly. Based on recurrent surge periodicities of Eyjabakkajökull presented in Appendix II it is suggested that the glacier reached conditions that enabled periodic surges starting ca. 1700 years BP, which prevailed until the later part of the LIA when Eyjabakkajökull expanded and surged more often, reaching its maximum Holocene extent.

This manuscript therefore gives new insights into the Holocene development of eastern Iceland, Vatnajökull and its outlet glacier Eyjabakkajökull, and the development of Lake Lögurinn.

5. Discussion

5.1 Towards objective varve identification

Varves display different characteristics depending on the regional settings in which they are formed, and therefore, a standard method for identifying, counting and measuring varves does not exist, but there are a number of methods that are commonly used (Lamoureux, 2002). Thin sections and image analysis are two approaches that both aim to provide a better view of the sedimentary structures of varves, especially for varves with low sediment accumulation rates. The varves in Lake Lögurinn are on an average 3.7 mm thick (1σ: 2.7 mm), and thus typically thick enough to be observed with the naked eye. However, to obtain a satisfying view of the sedimentary structures, the varves were mainly observed through a macroscope.

During the construction of the varve chronology, one of the aims was to minimise the subjectivity of varve identification by using an objective method to identify the lower and upper laminae in the varves. The main differences between the two types of lamina are their colour and grain-size composition, and ideally, image and grain-size analysis would be suitable. Grain-size analysis was carried out, but at a too coarse resolution to obtain results from each individual lamina. To obtain grain-size distributions for each lamina using standard methods would have required an enormous amount of sub-samples, and was not practical. Image analysis, on the other hand, was tested. Photographs of the sediments at close range were taken in a controlled environment where external light sources and water reflections from the sediment surfaces were removed (e.g. Christensen and Björck, 2001). The photos were then converted into grey-scale images, and different threshold values for grey-scale levels were tested in order to separate the lower and upper laminae. However, the heterogeneous appearance of the lower laminae typically resulted in them being identified as several

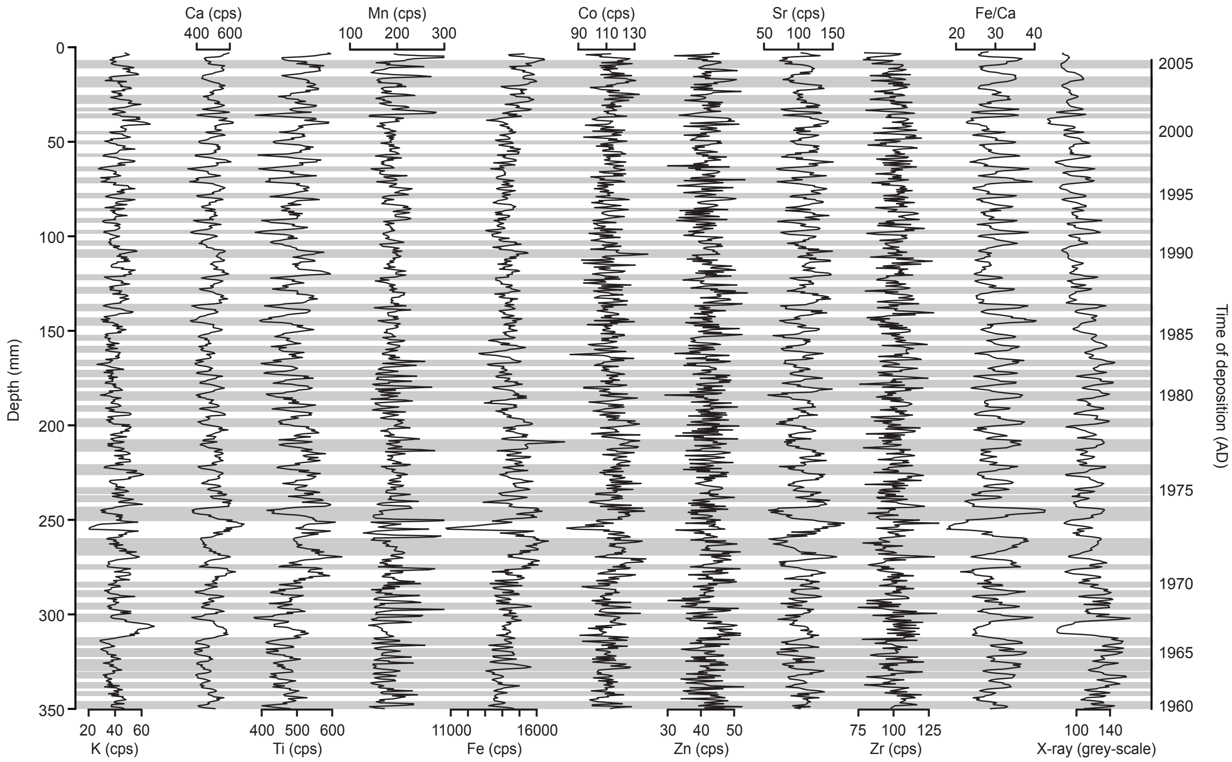

Figure 3. XRF-derived element profiles and grey-scale values obtained from radiographic images, which were used to aid the interpretation of varves in the sediment sequence. Fe/Ca display high ratios in upper laminae (grey bars) and low ratios in lower laminae (white bars).

laminae. Hence, image analysis did not provide better results compared to visual observations through the macroscope. For image analysis to work properly, high contrast between the laminae is required, and in addition, the laminae need to be more or less homogeneous.

Another approach that was tested, with greater success, was X-radiography and X-ray fluorescence (XRF) scanning. The high-resolution of the scans captured specific data from all but 4% of the laminae in the sediment sequence. The working hypothesis was that the X-radiography would enable separation of lower and upper laminae due to different bulk densities, related to grain-size variations or possibly, to different mineral composition as the sediments forming the laminae mainly originate from two different catchments (see section 5.2). Furthermore, element profiles from the XRF scans were believed to reveal different chemical compositions of the laminae.

Neither the resulting radiographic images or the XRF data enabled a straightforward separation of the laminae, but the analyses turned out to be useful as a complement to the visual observations (Fig. 3). The radiographic images revealed that, in general, the bulk densities are significantly different in the lower and upper laminae, respectively. Similar to the results from the image analysis of the photos, the heterogeneity of the lower laminae prevented automatic separation of the two types of laminae by e.g. grey-scale analysis. However, using the XRF data, it was noticed that Fe showed relatively lower intensities in the lower laminae. A trend of relatively higher Ca intensities was also observed in these laminae, while the upper laminae corresponded to relatively higher Fe and relatively lower Ca intensity. Therefore, Fe was normalised to Ca to test whether the Fe/Ca ratio varied in accordance with lower and upper laminae (Fig. 3). Although the variations do not correspond perfectly to changes in the lithology, the lower laminae generally revealed relatively lower Fe/Ca ratio compared to the upper laminae, which in general corresponded to peak ratios. Neither Fe nor Ca correlate to backscatter measurements from the analysis and these intensities are, therefore, likely not biased by e.g. variations in the water content (Tjallingii et al., 2007).

It cannot be concluded what causes the significantly different Fe/Ca ratios in the lower and upper laminae, respectively; both laminae show a rather typical basaltic composition (John Boyle, personal communication). However, the anti-correlation between Fe intensity and magnetic susceptibility shown in Appendix I likely implies that the bulk of the Fe in the sediment is not associated with magnetite. The glacier surge intervals discussed in Appendix II display peak Fe intensities (and thus, low magnetic susceptibility), and increased clay content. Furthermore, Fe/Ca is significantly, although moderately, correlated to bulk density (r=0.44 [0.41 0.46]). Therefore, it is possible that changes in Fe/Ca are related to grain-size, but the lack of a better correlation between Fe/Ca and bulk density shows that changes in mineral composition between the two types of laminae possibly explain part of the Fe/Ca variation.

A model for identifying varves in the laminated sediments was developed using these approaches. The upper laminae are more distinct compared to the lower laminae, and therefore, this difference formed the basis for identifying each varve. In the first stage, lower and upper laminae were identified visually using a macroscope, and their thicknesses were measured. This identification was done during at least three different occasions until a consensus was reached. The results from the visual observations were then compared to the grey-scale values obtained from the radiographic images and to the Fe/Ca ratios. In the case where a lamina had been observed during the visual observations that did not show up in the radiographic image, nor in the Fe/Ca ratios, the lamina was re-examined, and possibly, the interpretation was changed if the visual observations were equivocal (Fig. 4). In many cases, discrepancies between the visual observations and the radiographic images and Fe/Ca ratios could be related to tephras or cracks in the sediments.

Even though this varve identification method still relied on subjective visual observations, the use of radiographic images and XRF derived Fe/Ca ratios provided certain objectivity to the varve identification. The model was first tested in the topmost sediments, which covered the past 60 years according to the varve counts. Using ^{137}Cs, it was found that the varve chronology matched the 1963 bomb peak (Pennington et al., 1973) and the 1986 increase related to the Chernobyl nuclear accident. These results showed that recent varves were accurately identified using the model and, therefore, the model was used for sediments further down in the sequence. Owing to the large number of historical tephras, the varves were continuously re-examined if they did not corroborate the ages of the tephras. Typically, the offsets between initial counts and final counts, based on the historical tephras, were in the order of 0-5%. Below the oldest historical tephra (Katla, 1262 AD) and the Hekla-3 tephra (Dugmore et al., 1995) the age offset based on the ^{14}C date of Hekla-3 is 3-12%. This offset may be related to a hiatus in the Lake Lögurinn sediments, similar to the hiatus observed between 1477 and 1619 AD, presumably in the older part

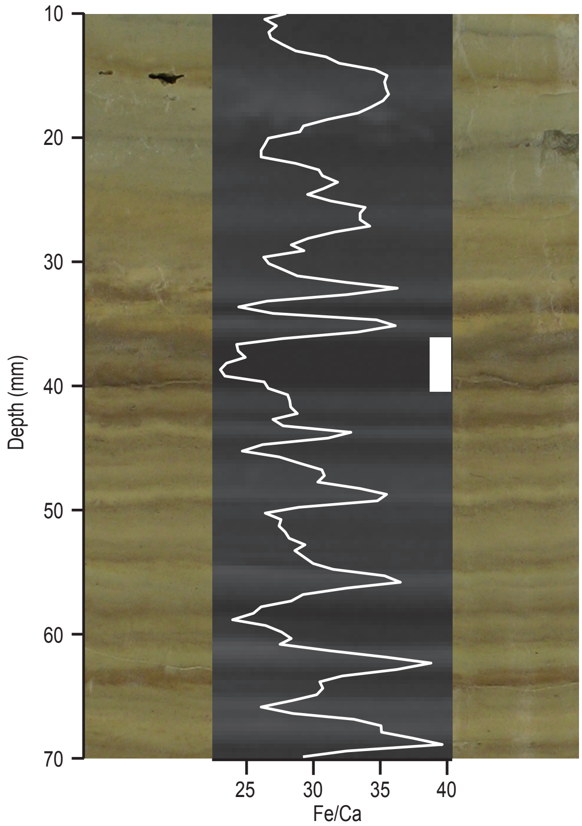

Figure 4. An example of how radiographic images and XRF-derived Fe/Ca were used to aid varve identification in the sediment sequence. At ca. 35-40 mm depth (marked by white bar) three laminae were identified visually and interpreted as two dark-coloured lower laminae, separated by a light-coloured upper lamina. However, Fe/Ca display relatively low ratios and no bulk density changes are observed in the radiographic image. Therefore, the initial interpretation was changed, and instead the interval was interpreted as a lower lamina formed by three sub-laminae.

of the record as the varve ages display an offset to the ^{14}C dated macrofossil at 7.87 m depth, whereas the varve ages corroborate the ^{14}C date of the Sn-1 tephra at 7.24 m depth. The more or less complete absence of macrofossils in the sediments prevents further ^{14}C dating of organic matter for resolving the discrepancy between the accepted age of the Hekla-3 tephra and its varve age.

5.2 Varve formation in Lake Lögurinn

Based on the visual appearance of the laminations and the seasonal discharge (and thus sediment transport) to Lake Lögurinn, the highly minerogenic laminated sediments were at an early stage hypothesised to form clastic varves. Clastic varves are characterised by different grain-size compositions in their laminae, with a relatively coarse-grained lower lamina, formed during spring/summer, and a relatively fine-grained upper lamina formed in autumn and winter. The lower lamina is normally formed by sediments that enter a lake during spring/summer, which settle shortly after being transported into the lake, while the upper lamina is formed by suspended matter that is able to settle only during calm conditions in the water column. Therefore, the upper lamina is typically formed during winters, when discharge is low, and when varve-forming lakes typically often are ice-covered. This is also how the varves in Lake Lögurinn are hypothesised to be formed. However, there are a number of specific factors that need to be considered for the interpretation of the varve formation in Lake Lögurinn: (i) the lake drains towards the sea via a large outlet in the north, which allows a substantial amount of the annual sediment delivery to be transported from Lake Lögurinn, (ii) the lake has two main inlets from which sediments enter the lake and these inlets are located at significantly different distances from the northern sub-basin where the sediments were collected, and (iii), the rivers that enter the lake are of different types (glacial and fluvial) and probably by different climatic parameters.

Owing to the general complexity of varves, which is further enhanced in Lake Lögurinn by the factors listed above, the main parameters controlling the varve formation need to be established. The distance between the inlets of River Grímsá and River Jökulsá í Fljótsdal is considered to play a key role for the varve formation in Lake Lögurinn. Sediments derived from the catchment of River Grímsá are transported ca. 5 km before reaching the northern sub-basin in the lake, while sediments that originate from Eyjabakkajökull are transported ca. 55 km in River Jökulsá í Fljótsdal and an additional 30 km before reaching the northern sub-basin. Thus, glacially derived sediments need to stay in suspension for about 85 km in order to reach the northern sub-basin. Therefore, it is hypothesised that only the most fine-grained sediments from Eyjabakkajökull reach the northern sub-basin, while coarser sediments are deposited in the southern, and possibly, central sub-basin, respectively. Sediments from River Grímsá, on the other hand, enter the lake close to the core sites, and therefore, relatively coarse-grained sediments from its catchments are deposited in the northern sub-basin.

The coarse-grained lower laminae in the varves from Lake Lögurinn frequently contain inter-annual laminae (sub-laminae), which often occur in the bottom and in the top of the lower laminae. In between these sub-laminae, relatively fine-grained sediments occur. The fine-grained upper laminae, on the other hand, are homogeneous and do not contain any sub-laminae (Fig. 5). These observations have resulted in an interpretation of how varves are formed in Lake Lögurinn.

Relatively coarse-grained sediments from the catchment of River Grímsá mainly enter the lake in spring/summer, and start to form the lower laminae. Owing to the short distance between the inlet of River Grímsá and the northern sub-basin, significant changes in the transport of sediments in River Grímsá most likely affect the sediment deposition at the core sites. It is suggested, therefore, that the sub-laminae in the lower lamina represent periods of increased discharge and are a signal of increased transport of relatively coarse-grained sediments by River Grímsá.

Concurrent with increased discharge rates in River Grímsá, the discharge rates in River Jökulsá í Fljótsdal begins to increase and thus, the transport of glacially derived sediments to Lake Lögurinn. However, the long distance between the inlet of

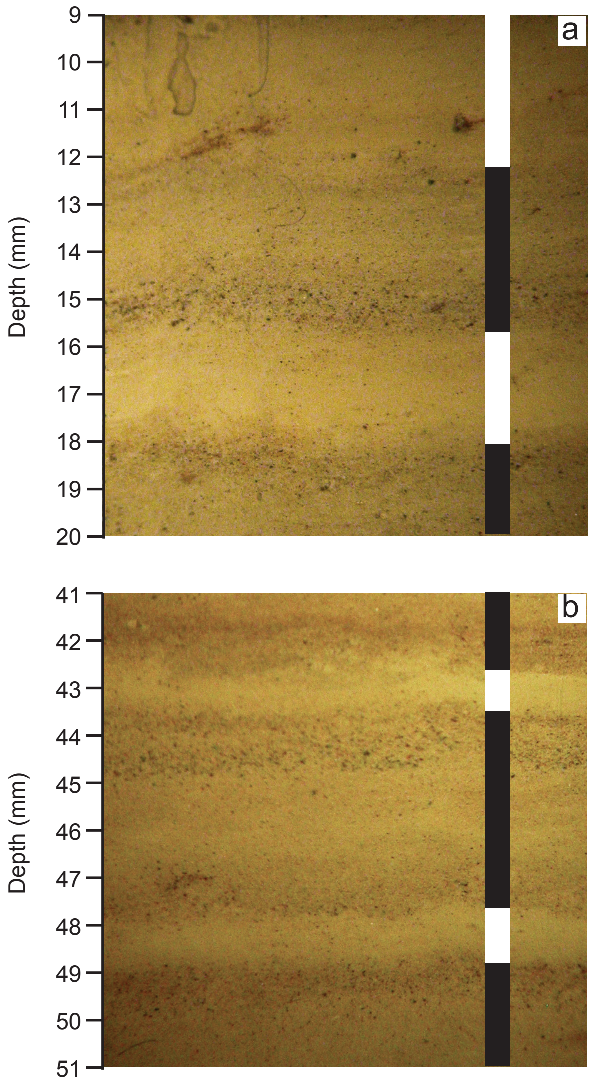

Figure 5. Photos of lower (marked in black) and upper laminae (marked in white) in the sediment sequence, which highlight the two types of lower lamina that are observed in the sediment sequence. The lower lamina between 12-15.5 mm in (a) do not display any sub-laminae, while the lower lamina between 43.5-48 mm in (b) displays two relatively coarse sub-lamina in its lower and upper part at ca. 46.8-48 and 43.5-45 mm, respectively. The lower sub-lamina is formed by sediments transported to the lake during spring/summer, and the upper sub-lamina is hypothesised to form by additional sediment transport from River Grímsá during autumn and winter prior to ice coverage.

River Jökulsá í Fljótsdal and the northern sub-basin prevents glacial coarse-grained sediments from entering the northern sub-basin. Therefore, significant fluctuations in the discharge rates of River Jökulsá í Fljótsdal will likely only affect sediment deposition in the southern sub-basin, and possibly, the central sub-basin. The only glacially derived sediment that reaches the northern sub-basin is the fine-grained rock flour, which stays in suspension until winter, when the lake normally is ice-covered by the end of February until April, and when the settling of the fine-grained suspended matter intensifies. Therefore, variations in upper lamina thickness are altered by the amount of fine-grained sediments that settles during winters, and are thus mainly related to the amount of fine-grained sediments delivered from Eyjabakkajökull and the duration of ice-coverage of Lake Lögurinn.

5.3 Varve properties: a proxy for autumn and winter precipitation in the Lake Lögurinn region?

Clastic varve thickness is commonly used as a proxy for past climatic change, with the assumption that changes in climate (temperature or precipitation) affect the sediment transport to lake basins, and thus, sediment accumulation. In Appendix I, this approach was used to infer past climate in the Lake Lögurinn region since 1262 AD. As described in section 5.2, varve thickness in Lake Lögurinn is related to the sediment transport in both River Grímsá and River Jökulsá í Fljótsdal, whose discharge rates are controlled by different climatic parameters. Therefore, the relationship between varve thickness in Lake Lögurinn and climate is difficult to resolve. Using the thickness of lower and upper laminae, respectively, is in this case a better approach as they are formed predominantly by sediments from the two different catchments.

Certain assumptions need to be made in order to reconstruct climatic change based on sediment accumulation. The most important assumption for the Lake Lögurinn sediments, and for other lake sediments, based on a restricted number of cores, is that the location of the sampling site is representative for the whole lake basin, or in this case, at least for the northern sub-basin. Ideally, multiple cores should have been collected and cross-correlated (Lamoureux, 2002; Kaufman et al., 2011), but this was not practically possible in Lake Lögurinn. However, a confined section in L1 and L2, constrained by two historically documented tephras, revealed the same number of varves. The varves were thinner in L2 due to its location closer to the shore and stronger currents, but the two cores revealed the same relative thickness changes. Therefore, it was assumed that the varves used for the reconstruction are representative for at least the whole northern sub-basin.

Discharge rates in River Grímsá from 1963-2005 are highly correlated to the amount of precipitation in its catchment (r=0.82 [0.59 0.83]), which shows that the rate of discharge increases when precipitation is high, and vice versa. With the assumption that sediment transport increases with increasing discharge rates, the thickness of lower laminae should be at least partly related to precipitation. Because most of the precipitation in this region falls during autumn and winter, correlation between lower lamina thickness and autumn/winter precipitation was calculated. The results presented in Appendix I reveal a fairly high correlation between lower lamina thickness and winter precipitation (r=0.70 [0.27 0.86]). However, it is important to emphasise that the correlation reveals that only part of the variability of the lower lamina thickness is related to precipitation. If the correlation between lower lamina thickness and autumn/winter (September-February) precipitation is used, which may be more correct since this period is associated with the period of highest precipitation in the catchment of River Grímsá, the correlation decreases (r=0.57 [0.19 0.76]). Snowmelt in the catchment of River Grímsá, which causes peak discharge rates in May-June when most of the sediments from the catchment are transported to Lake Lögurinn, is one explanation of why autumn/winter or winter precipitation is not better correlated to lower lamina thickness. Furthermore, it is probably fair to assume that a certain amount of the fine-grained rock flour transported from Eyjabakkajökull starts to settle prior to winter, thereby increasing the lower lamina thickness. In essence, caution should be taken to single out one specific process to explain varve/lamina thickness, as it most likely ignores the numerous variables in the processes leading to formation of varves in Lake Lögurinn.

The lower lamina thickness record covering the past ca. 750 years displays increased thicknesses between the 1600s and the late 1800s, i.e. the late LIA, and implies that erosion in the River Grímsá catchment increased at this time. Based on the correlation between lower lamina thickness and precipitation (see Appendix I) is that wetter autumns and winters prevailed in the region during this time period and that the higher precipitation increased soil erosion. The lower lamina thickness record was extended to cover the past ca. 2800 years in Appendix II and no prolonged period revealed lower laminae that were thicker than those that formed during the late LIA (Fig. 6). During the LIA, the coldest conditions are inferred to have prevailed between the 1600s and the late 1800s (Jiang et al., 2005; Massé et al., 2008). Therefore, it is striking that the inferred increase in winter precipitation occurred concurrently with the expansion of glaciers in Iceland, when Eyjabakkajökull likely reached its largest extent since the last deglaciation (Sharp and Dugmore, 1985; Bradwell et al., 2006; Kirkbride and Dugmore, 2006). The data suggest, therefore, that the expansion of Eyjabakkajökull at this time was caused not only by reduced summer temperatures that shortened the melt-seasons, but also by increased winter precipitation. On the other hand, the reconstruction is based on observational data from the catchment of River Grímsá between 1961-1990 and the reconstruction assumes that similar run-off conditions prevailed in the catchment since the mid-1200s. During the cold conditions in the late LIA vegetation cover may have decreased, thus exposing more easily eroded soils. Therefore it cannot be ruled out that the increased thicknesses of lower laminae may reflect lower temperatures that prevailed at this time.

5.4 Is changing surge periodicity indicative of mass balance changes of Eyjabakkajökull, and ultimately, climatic changes?

The recent surge of Eyjabakkajökull caused the sediment load in River Jökulsá í Fljótsdal to increase significantly (Pálsson and Vigfússon, 1996). Although no instrumental data exist, it is fair to assume that similar increases occurred during the historic surges. As shown in Appendix I, upper laminae formed during periods of known surges display increased thicknesses, which supports other conclusions that sedimentation rates increases in proglacial/glacier-fed lakes during glacial surges due

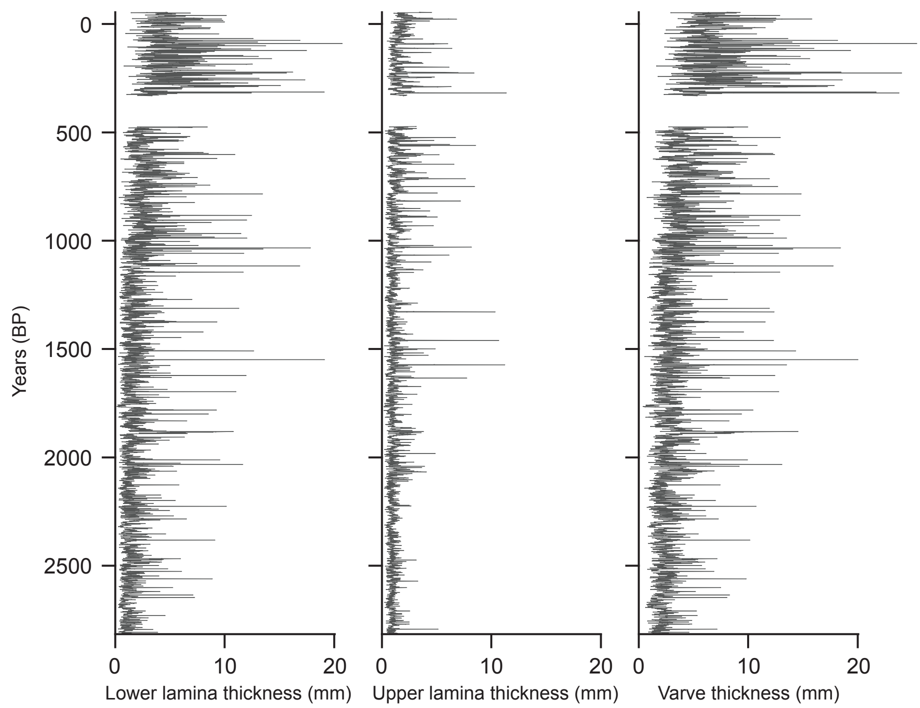

Figure 6. Lower laminae, upper laminae and varve thickness records for Lake Lögurinn for the time period 2813 to -55 years BP. Note the hiatus between 473 and 331 years BP.

to increased erosion rates and the melting of dead ice in the ablation area (Sharp, 1988; Humphrey and Raymond, 1994; Gilbert et al., 2002).

One of the aims of this project was to reconstruct regional atmospheric temperature based on meltwater discharge from Eyjabakkajökull, with the hypothesis that meltwater discharge, and thus, sediment transport from the glacier, would increase with increased melt-season temperatures. As shown in Appendix I, the positive correlation between discharge rates in River Jökulsá í Fljótsdal and summer temperatures (r=0.72 [0.47 0.87]) suggests that accumulation rates of glacially derived sediments may potentially be related to melt-season temperatures. However, the observations of increased upper laminae thicknesses associated with surges of Eyjabakkajökull reveal that surges of the glacier have a large impact on the sediment accumulation in Lake Lögurinn, and therefore, the aim of reconstructing atmospheric temperature based on sediment accumulation rates of glacially derived sediments was abandoned. In addition, unlike the relatively coarse-grained sediments that form the lower laminae, much of the fine-grained glacial rock flour stays in suspension for a fairly long time. Even if no data exist, it is reasonable to suggest that part of the annual sediment delivery from Eyjabakkajökull may stay in suspension throughout winters, and a large part is definitely transported past the northern sub-basin of Lake Lögurinn and out into the sea.

The mechanisms behind a glacial surge are not fully understood. However, changes in the subglacial conditions and their relationship with the hydraulic system are considered key components for the shift from an active to a quiescent phase of a surge cycle (Harrison and Post, 2003), either due to a disruption of a deforming (till) bed and the hydraulic system (e.g. Fowler et al., 2001), or the hydraulic system alone if the glacier overlies bedrock (Kamb, 1987). By emphasising the latter process, a surge cycle of Eyjabakkajökull can be explained as follows. Depending on the rate of accumulation, Eyjabakkajökull gain mass during the quiescent phase with increased thickness in the accumulation area, that is larger than the melt loss and retreat in the ablation area. This will increase the overall steepness of the glacier profile. The rate of build-up is thus related to melt-season temperatures and winter precipitation. As the glacier profile of Eyjabakkajökull steepens, the driving stress for glacier flow will gradually increase. When a certain critical value of the basal drag is reached, which balances the driving stress at the glacier-bed, the sliding velocity may become too large for discrete subglacial tunnels to be maintained and, instead, a linked-cavity system develops. A linked-cavity system is associated with lower effective stresses, as compared to the effective stresses that prevail when a glacier is drained by large subglacial tunnels (Fowler, 1987). This reduction in effective stress will increase the velocity further and might trigger a surge. When Eyjabakkajökull is in its active surge phase, mass transfer from the upper accumulation area to the lower ablation area will result in a lowering of the glacier profile. This will in turn decrease the driving stress and, therefore, the velocity of Eyjabakkajökull until sliding is too slow to maintain a linked-cavity system. This then collapses, and a discrete subglacial tunnel system is reformed that brings Eyjabakkajökull to a halt; hence, a return to a quiescent phase (Kamb, 1987).

In Appendix II a palaeo-surge record of Eyjabakkajökull is presented, which is based on recurring sediment intervals that contain abnormally thick upper laminae. The record reveals that the length of the quiescent phase of Eyjabakkajökull has been fairly stable since ca. 1700 years BP, with the exception of one excursion during the late LIA, when it shortened from ca. 34-38 to ca. 21-23 years. The model presented above implies that the length of the quiescent phase of Eyjabakkajökull is related to the time it takes for the glacier to build up its mass until the critical value of the basal drag is reached, which enables a switch to the active phase. Therefore, changes in the surge periodicity of Eyjabakkajökull suggest that the rate of net mass accumulation must have changed as well. The 21-23 year surge periodicity between the 1600s and the late 1800s implies that the build-up of Eyjabakkajökull until the surge-triggering critical value was breached occurred in almost half the time compared to prior to the LIA and during the 1900s. This timing is reasonable given that this period represents the coldest centuries of the LIA (Jiang et al., 2005; Massé et al., 2008) and possibly since ca. 8000 years BP (Geirsdóttir et al., 2009a). Furthermore, it corroborates the period when Eyjabakkajökull reached its largest extent since the last deglaciation (Sharp and Dugmore, 1985), and when the reconstruction presented in Appendix I displays increased winter precipitation. It has previously been put forward that climate does not trigger surges *per se*, but these results show that climatic changes causing significant changes in glacier mass balance may facilitate surges, and thus, alter the surge periodicity as suggested by Dowdeswell (1995). Therefore, palaeo-surge records, although difficult to obtain, provide the opportunity to infer past glacial mass balance fluctuations, which may be related to long-term climatic changes. These arguments suggest that the current quiescent phase of Eyjabakkajökull may be prolonged, as the glacier is currently receding. Although highly speculative, it is interesting to note that Eyjabakkajökull has not switched to a surge mode since 1972, which is closing in on the maximum duration of the documented quiescent phase.

5.5 The deposition of non-laminated sediments in early and mid-Holocene: evidence for the disappearance of Eyjabakkajökull?

The occurrence of the Saksunarvatn tephra (10 200 years BP) in Icelandic lake sediments (e.g. Caseldine et al., 2006; Axford et al., 2007) and inferred ice-free conditions in the Icelandic highlands by ca. 8600 years BP (Hjartarson and Ingólfsson, 1988) suggest that the final phase of the last deglaciation of Iceland was rapid. Results of a model simulation show that Langjökull, the second largest ice cap in Iceland, more or less disappeared following the 8.2 ka cold event, and did not reform until ca. 5000-3000 years BP (Flowers et al., 2008), concurrent with other observations of Neoglacial advances in Iceland (Gudmundsson, 1997; Kirkbride and Dugmore, 2006). As put forward by Caseldine et al. (2006), most studies of terrestrial records of climate change in Iceland have been focussed on the later part of the Holocene. Although continuous Holocene records exist and have been used to infer Holocene glacial fluctuations (Black, 2008), little is known of the status of Icelandic ice caps during the early part of the Holocene (Geirsdóttir et al., 2009a) and the full Holocene history of Vatnajökull and its outlet glaciers remains fairly unknown. Lake Lögurinn constitutes one of few sediment traps for suspended matter transported by meltwater from the ice cap, and therefore, provides an opportunity to study how meltwater production has varied through time. Appendix III therefore focuses on the Holocene history of Eyjabakkajökull, with the aim of resolving whether the glacier was continuously present or not in the catchment of River Jökulsá í Fljótsdal since the last deglaciation.

Based on the results and discussions presented above and in Appendices I & II, formation of laminated sediments in Lake Lögurinn constitutes compelling evidence for transport of glacially derived sediments from Eyjabakkajökull to the lake. As part of the sediment sequence contains non-laminated sediments and poorly developed laminations, the lithology implies that the transport of glacial meltwater to Lake Lögurinn was not continuous since the last deglaciation. Five distinct sedimentary units were observed, based on the lithology. One of these units, dated to have accumulated between ca. 9000 and 4400 years BP, is strikingly different compared to the other units by containing dark-coloured, homogeneous sediments.

The physical proxies presented in Appendix III more or less follow changes in the lithology; high magnetic susceptibility is associated with homogeneous, or poorly developed laminated sediment units and relatively low clay content, and low magnetic susceptibility is associated with distinctly laminated sediments where the clay content is relatively high. The change towards increased clay content in laminated sediments and the concurrent decrease in magnetic susceptibility after the homogeneous sediment section shows that changes in magnetic susceptibility most likely are associated with changes in grain-size (Björck et al., 1982). Therefore, despite relatively few grain-size analyses from the homogeneous sediment section, the high magnetic susceptibility together with the absence of laminated sediments imply that the transport of glacial meltwater and suspended matter were significantly lower at this time. However, discharge from River Jökulsá í Fljótsdal must still have existed even if Eyjabakkajökull did not contribute meltwater. However, it is very likely that the discharge rates in the river decreased at this time due to the lack of glacial meltwater input. Therefore, the source area of the sediments formed between ca. 9000 and 4400 years BP is inferred to be dominated by the catchment of River Grímsá.

Because the physical proxies are related to each other, a number of biological proxies were employed to examine their relation to changes in the lithology during the time period represented by the homogeneous sediment section. BSi was analysed to infer the within-lake biologic productivity, with the working hypothesis that shifts in the influence between glacial and fluvial systems would be reflected in the primary production. In addition, samples were taken for diatom and chironomid analyses to infer what may have caused changes in the biologic productivity and furthermore, element analyses were carried out to estimate the amount of organic matter and its source(s). However, except for BSi, all biological proxies were sampled at a lower resolution and can therefore only be considered as indicator-proxies and complements to the high-resolution BSi samples.

Changes in the biologic productivity in Lake Lögurinn are likely related to two main parameters: changes in climate and/or changing conditions in the water column. These are difficult to separate, as they are partly related; when glacial meltwater is transported to lakes, water temperatures decrease and suspended matter in the surface water will prevent light from penetrating the water column (Black, 2008). Both of these effects may possibly lead to a reduction in aquatic productivity. This interpretation is supported by the observations of decreased BSi in the inferred surge intervals and the positive correlation to magnetic susceptibility, which indicates that BSi in general increases with increasing grain-size composition. However, climate/ambient air temperature is another parameter that controls glacier activity and directly also the biologic productivity, as has been seen elsewhere in Iceland (Geirsdóttir et al., 2009b). For the Lake Lögurinn system, changing climatic conditions may have altered the glacial influence, but also the duration of ice-free seasons, which would enable earlier and prolonged algal blooms.

The physical proxies suggest that no glacial meltwater entered Lake Lögurinn between ca. 9000 and 4400 years BP, and this sediment section reveals the highest BSi (and diatom) concentrations throughout the sediment sequence. Based on the observations of changing BSi during surges, it is suggested that the primary reason for this increase is due to the lack of suspended glacially derived sediments in the water column, and thus, increased light conditions, but possibly also increased water temperatures. However, during this time period fairly large fluctuations in the BSi record occur, and as suggested in Appendix III, if light conditions were not a limiting factor for the biologic productivity at this time, changes in the biologic productivity may be related to changes in climate. Although the chronology in this part of the sediment sections is not well constrained, except for its upper and lower boundaries, maximum biologic productivity occurred between ca. 7900 and 7000 years BP. As this age corresponds closely to the age of the HTM presented by Caseldine et al. (2006), it is hypothesised that this increased productivity is related to the warm conditions that prevailed during this time period, when temperatures possibly reached 2-4°C higher than modern observations (Caseldine et al., 2006; Flowers et al., 2008). In Lake Lögurinn this was possibly a result of a minimum in glacial influence and a maximum in air and water temperatures.

The above inferred HTM is preceded by a BSi drop, which yields an age of ca. 8200-8000 years BP. This drop may therefore be a response to the 8.2 ka cold event, possibly caused by cooler temperatures and a temporary return to shorter ice-free seasons in Lake Lögurinn. Clearly, a better constrained chronology is needed to verify if this drop indeed is related to the 8.2 ka event. There are no changes in the physical proxy records that can be related to the inferred 8.2 ka event, and therefore Eyjabakkajökull, if it at all existed, does not seem to have responded to this cold spell, at least not to the extent that it began to contribute with meltwater and sediments to the northern sub-basin of Lake Lögurinn.

Despite poor age-control within the homogeneous sediment section, its duration is fairly well constrained by the ^{14}C dated water mosses close to its lower boundary, and the occurrence of the Hekla-4 tephra slightly above its upper boundary. Therefore, given the absence of glacially derived sediments between ca. 9000 and 4400 years BP, the data presented in Appendix III reveal that Eyjabakkajökull most likely disappeared for nearly 5000 years in early and mid-Holocene, and its reappearance provides a well-constrained signal for the onset of Neoglaciation in eastern Iceland.

6. Conclusions

This thesis presents proxy based records from the unique sediment sequence from the glacier-fed Lake Lögurinn. They have been used to infer past glacial fluctuations of Eyjabakkajökull and climatic change in eastern Iceland during the Holocene. The results and discussion in this thesis lead to the following main conclusions:

- The proxy records show that glacial meltwater transport to Lake Lögurinn has varied significantly during the Holocene. These variations are inferred to be directly associated with changes in the extent of Eyjabakkajökull, which has responded to the ambient climate conditions.

- Lake Lögurinn was deglaciated ca. 10 500 years BP. By ca. 9000 years BP, Eyjabakkajökull had little or no impact on the sediment transport to the lake, implying a rapid ice retreat in eastern Iceland during the final phase of the last deglaciation.

- No or limited amounts of glacial meltwater were transported to Lake Lögurinn in the early and mid-Holocene. This implies that Eyjabakkajökull more or less disappeared 9000 years BP, and did not return until the onset of Neoglaciation in eastern Iceland, ca. 4400 years BP.

- The Holocene Thermal Maximum in Iceland, as inferred by maximum Holocene biologic productivity in Lake Lögurinn, is dated to ca. 7900-7000 years BP.

- Glacier surges of Eyjabakkajökull began ca. 2200 years BP, possibly as a response to its expansion during the Neoglaciation.

- Glacier surge periodicities of Eyjabakkajökull during the past 1700 years were altered by climatic changes, likely related to mass balance changes of Eyjabakkajökull.

- The expansion of Eyjabakkajökull during the coldest phase of the Little Ice Age is likely associated with not only colder summer temperatures, but also increased winter precipitation.

7. Potential future projects

The results presented in Appendices I-III show the potential that lies in using a multi-proxy approach to assess glacial history, ice dynamics and past climatic changes. Given the strategic location of Iceland for palaeoclimatic studies, Lake Lögurinn is ideal for further studies in the sense that a wide range of processes affects sediment transport to the lake. Below, a number of suggestions for future projects are provided.

To date, this work is likely the first to extend a surge record beyond the historical record. The novel approach of using lacustrine sediments to track past surges has shown that palaeo-surge records may reveal long-term climatic changes, and therefore, hold potential for palaeoclimatic studies. However, the results from this work should be tested by further studies of other surge-type glaciers.

A key finding in Appendix I is the hiatus that occurs in the varved section between the Veidivötn 1477 AD tephra and the Grimsvötn 1619 AD tephra, where only 18 couplets (most likely varves) are observed. This hiatus occurs in both sediment cores and it is thus likely that this lack of sedimentation is valid for large parts of the northern sub-basin of Lake Lögurinn. This is an unusually well-defined hiatus, but the reason for its occurrence remains unknown and should be examined.

The sediment sequence from Lake Lögurinn contains numerous tephras; for instance more than 50 tephras occur in the varved section covering the past ca. 2800 years. In this work, only selected tephras were analysed and identified. The annual nature of the varved sediments provides an excellent opportunity to refine the current Icelandic tephrochronology (Haflidason et al., 2000; Larsen and Eiríksson, 2008). In addition, identification of known well dated tephras deposited in the early and mid-Holocene would improve the current chronology in the Lake Lögurinn sediment record.

Parts of the proxy records presented in Appendices I-III were too coarsely sampled to provide unequivocal evidence of the Holocene development of the Lake Lögurinn system. A high-resolution study of the biologic proxies presented in Appendix III would provide further knowledge of the lake history, and possible causes for the fluctuations of Eyjabakkajökull.

Acknowledgements

First, I would like to thank my main supervisor Svante Björck for introducing me to this project, and for his continuous support during these four years. Svante has always been helpful and enthusiastic about my work, and I am thankful for all the interesting discussions we have had. During my time in Lund, Svante has continuously encouraged me to broaden my knowledge within the world of Quaternary science. Therefore, I've had the pleasure to visit many interesting places all over the world during fieldworks, conferences and excursions where I have met many new friends and colleagues. For this, I am deeply grateful.

To my co-supervisors Ólafur Ingólfsson, Ian Snowball and Cintia Uvo, I'm deeply thankful. Thanks to Ian for all his support during fieldwork, for interesting discussions and for the many nice memories from fieldworks and workshops. Thanks to Cintia for all the help with numbers and statistics, and for the fulfilling discussions we have had over the years. Thanks to Ólafur for all encouragement and support during these years. Ólafur has always reminded me of the importance of our project, which has inspired me to continuously try and improve my work. A big thank you is also given to Ólafur's family for letting me stay at their home during my visits to Iceland.

I would like to thank co-authors Kurt Kjær, Ívar Örn Benediktsson, Sofia Holmgren and Ladislav Hamerlík for their analyses, and for their contributions to the papers. Hanna Lindvall and Åsa Wallin are also acknowledged for their work with BSi, grain-size and element analyses.

Obtaining sediments from Lake Lögurinn is tricky, and fieldwork was carried out by a large number of people. To those I am very thankful. Special thanks go to Anna Broström for attending fieldwork during her vacation, and to the Icelanders who helped out during the hard work, and who introduced me to some interesting Icelandic dishes.

Financial support by the Swedish Research Council (VR), the Icelandic Research Council (Rannís), The Royal Swedish Academy of Sciences (KVA), Letterstedtska föreningen, Helge Ax:son Jonssons stiftelse and the Royal Physiographical Society in Lund is gratefully acknowledged.

I would also like to thank the people in Quaternary Sciences at the Geobiosphere Science Centre in Lund for all their assistance during these years, and for providing a friendly and inspiring environment. I have learnt a lot thanks to you. Thanks to my PhD colleagues for all the fun times. Special thanks are addressed to Andreas Nilsson with whom I have spent many days during these years, both at the department but also during fieldworks and conferences.

Finally, but most importantly, I would like to thank Rebecka and Daniel for all their support and encouragement, especially during the final phase of this work.

Svensk sammanfattning

Under den nuvarande värmeperioden (holocen) som inleddes för ca 11 600 år sedan, har klimatet i den nordatlantiska regionen varierat på både korta och långa tidsskalor. Orsaken till dessa variationer är många och komplexa, men kan till viss del relateras till temporära förändringar i havsströmmar och den atmosfäriska cirkulationen. Den termohalina cirkulationen, som delvis driver de globala havsströmmarna, har en stor inverkan på klimatet i regionen, då den transporterar varmt, hög-salint ytvatten till Nordatlanten. Denna transport är bl.a. anledningen till att delar av Europa har ett förhållandevis milt klimat, trots dess nordliga läge. När det varma ytvattnet når Nordatlanten kyls det ner, och får en högre densitet än omgivande vattenmassor p.g.a. dess höga salthalt. Det leder i sin tur till att vattnet sjunker, för att bilda djupvatten som transporteras söderut. Denna process är därför delvis styrd av densitetsskillnader mellan olika vattenmassor i djupvattenbildande områden. En utjämning av detta förhållande, t.ex. genom ett ökat tillskott av glacialt smältvatten, skulle försvaga transporten av varmt ytvatten till Nordatlanten.

Island utgör den största landmassan i Nordatlanten. Den nordatlantiska polarfronten, som utgör gränsen där varmt vatten från sydliga breddgrader möter kallt vatten från Arktis, ligger för närvarande strax norr om Island. Studier av marina sediment från detta område har visat på komplexa temperaturförändringar under holocen, vilket troligtvis även påverkat den terrestra miljön på Island, och därmed även de isländska glaciärerna. Idag smälter dessa glaciärer snabbt, och för att förstå vilka följder detta kan komma att få är det viktigt att känna till hur glaciärer i regionen har reagerat på tidigare förändringar i klimatet under den nuvarande värmeperioden.

I denna studie har sjösediment från Lögurinn på östra Island undersökts för att kartlägga holocena förändringar av den svämmande utloppsglaciären Eyjabakkajökull, som dränerar den nordöstra delen av den stora (>8000 km^2) Vatnajökull-glaciären. Lögurinn utgör en sedimentfälla för material som transporteras med smältvattnet från Eyjabakka-jökull, och för sediment som transporteras från ett icke-nedisat avrinningsområde som dräneras av floden Grímsá, vars flöde huvudsakligen styrs av mängden nederbörd som faller i området.

Med hjälp av årligt avsatta sedimentlager, s.k. varv, har en kronologi för sediment som avsatts de senaste 2800 åren i Lögurinn kunnat konstrueras. Denna varvkronologi har gjort det möjligt att undersöka hur mycket sediment som årligen transporterats från Eyjabakkajökull och från floden Grímsás dräneringsområde till Lögurinn. Resultaten visar på ett positivt samband mellan sedimenttransport via Grímsá och mängden neder-börd som faller i dess upptagningsområde under hösten och framförallt under vintern. Med hjälp av detta samband har den årliga vinternederbörden sedan 1262 rekonstruerats. Rekonstruktionen visar att nederbörden ökade markant från 1600-talets början fram till 1800-talets slut. Denna period utgör den senare, och kallare delen av den lilla istiden, då isländska glaciärer, inklusive

Eyjabakkajökull, expanderade. En av slutsatserna i denna studie är därför att expansionen av Eyjabakkajökull, och troligtvis även av andra isländska glaciärer under den här perioden, inte enbart var ett resultat av lägre temperaturer utan även av en ökad vinternederbörd.

Kortlivade svämningar av Eyjabakkajökull, då dess glaciärfront avancerar 2-4 km relativt snabbt för att sedan stagnera och smälta av, har dokumenterats sedan 1890 då den första kända svämningen skedde. Sedan dess har glaciären svämmat på 1930-talet och senast 1972. Vid dessa svämningar transporterades stora mängder finkornigt glacialt sediment till Lögurinn, vilket bildade sektioner med tjocka lager av glacialt material i sedimentsekvensen. Liknande sektioner återfinns i stora delar av varvkronologin, vilka tolkas ha avsatts vid tidigare svämningar. Dessa sektioner började deponeras i Lögurinn för ca 2200 år sedan, vilket tolkas utgöra tidpunkten då Eyjabakkajökull började svämma. 500 år senare började glaciären att svämma med en relativt konstant periodicitet fram till den kallare delen av den lilla istiden, då tiden mellan svämningar nästan halverades. Sedan denna köldperiod, då klimatet troligen var som kallast på Island under de senaste 8000 åren, har svämningar av Eyjabakkajökull skett ungefär varje 35-40:e år, vilket är i stort sett samma periodicitet som rådde före den lilla istiden. Dessa resultat visar därför att perioder då klimatet tillåter en snabbare expansion av Eyjabakkajökull, genom en ökad ackumulationshastighet, leder till mer frekventa svämningar. Därför bör den konstanta svämningsperiodiciteten som inleddes för ca 1700 år sedan och som avslutades i samband med den lilla istiden innebära att Eyjabakkajökull hade en relativt konstant ackumulationshastighet under den här tiden, och således var klimatet relativt stabilt.

Den del av sedimentsekvensen som är äldre än 2800 år har åldersbestämts med hjälp av ^{14}C-datering av växtrester (makrofossil), och genom geokemisk identifikation av tidigare åldersbestämda asklager (tephror) som deponerats vid vulkanutbrott. Med dessa metoder har det kunnat fastställas att sedimentsekvensen täcker de senaste 10 500 åren, d v s nästan hela holocen. Under denna period har Eyjabakkajökull varierat kraftigt i sin utbredning. En tydlig indikation för att glaciären har försett Lögurinn med smältvatten och sediment är bildandet av laminerade sediment, medan homogena sediment indikerar att mängden glacialt smältvatten som dräneras till sjön varit låg, eller obefintlig.

Resultaten visar att den senaste deglaciationen av östra Island var snabb. Den forna utloppsglaciären som under sin maximala utbredning nådde kusten norr om Lögurinn smälte av tidigt i holocen, och för ca 10 500 år sedan hade åtminstone den norra delen av sjön frilagts. Ca 1500 år senare hade resterna av den forna utloppsglaciären, d.v.s. Eyjabakkajökull, minskat så pass att den inte längre bidrog med sediment till den norra delen av Lögurinn. Sedimentsekvensen visar därefter på en nästan 5000 år lång period då inget glacialt sediment avsattes i Lögurinn. Avsaknaden av glaciala sediment under denna period leder till slutsatsen att Eyjabakkajökull var betydligt mindre, eller möjligtvis helt bortsmält för 9000 år sedan fram till ca 4400 år sedan, då glaciala sediment återigen transporterades till sjön. Under denna period ökade den biologiska produktionen i Lögurinn. Detta berodde troligtvis på en kombination av förbättrade ljusförhållande i vattenkolumnen p.g.a. avsaknaden av suspenderat glacialt sediment i ytvattnet, och högre vattentemperaturer, både p.g.a. avsaknaden av kallt glacialt smältvatten, men troligtvis även p.g.a. högre lufttemperaturer. Denna period inkluderar det holocena värmeoptimat (*The Holocene Thermal Maximum*), då temperaturrekonstruktioner från Island indikerar på ett klimat ca 2-4°C varmare än idag. Baserat på ett intervall i sekvensen då den biologiska produktiviteten i Lögurinn nådde ett maximum under de senaste 10 500 åren dateras detta värmeoptimum till ca 7900-7000 år före nutid.

För ca 4400 år sedan började Eyjabakkajökull att expandera, vilket sammanfaller med den s.k. Neoglaciationen då flertalet glaciärer på Island växte till. Denna expansion pågick under drygt 2000 år, då dess konfiguration ledde till att glaciären började svämma. Under de senaste 1700 åren tolkas Eyjabakkajökulls utbredning ha varit relativt stabil, bortsett från den senare delen av den lilla istiden, då glaciären nådde sin maximala utbredning.

References

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U., 1997. Holocene climatic instability; a prominent, widespread event 8200 yr ago. Geology 25, 483-486.

Andresen, C., Björck, S., Rundgren, M., Conley, D., Jessen, C., 2006. Rapid Holocene climate changes in the North Atlantic: evidence from lake sediments from the Faroe Islands. Boreas 35, 23-34.

Andrews, J.T., Hardardóttir, J., Helgadóttir, G., Jennings, A.E., Geirsdóttir, Á., Sveinbjörnsdóttir, Á.E., Schoolfield, S., Kristjánsdóttir, G.B., Micaela Smith, L., Thors, K., Syvitski, J.P.M., 2000. The N and W Iceland Shelf: insights into Last Glacial Maximum ice extent and deglaciation based on acoustic stratigraphy and basal radiocarbon AMS dates. Quaternary Science Reviews 19, 619-631.

Axford, Y., Geirsdóttir, Á., Miller, G., Langdon, P., 2009. Climate of the Little Ice Age and the past 2000 years in northeast Iceland inferred from chironomids and other lake sediment proxies. Journal of Paleolimnology 41, 7-24.

Axford, Y., Miller, G.H., Geirsdóttir, A., Langdon, P.G., 2007. Holocene temperature history of northern Iceland inferred from subfossil midges. Quaternary Science Reviews 26, 3344-3358.

Battarbee, R.W., Kneen, M.J., 1982. The Use of Electronically Counted Microspheres in Absolute Diatom Analysis. Limnology and Oceanography 27, 184-188.

Benediktsson, Í.Ö., Schomacker, A., Lokrantz, H., Ingólfsson, Ó., 2010. The 1890 surge end moraine at Eyjabakkajökull, Iceland: a re-assessment of a classic glaciotectonic locality. Quaternary Science Reviews 29, 484-506.

Bengtsson, L., Enell, M., 1986. Chemical analysis, In: Berglund, B.E. (Ed.), Handbook of Holocene Palaeoecology and Palaeohydrology. John Wiley & Sons Ldt., Chichester, pp. 423–451.

Benn, D.I., Evans, D.J.A., 1998. Glaciers and glaciation. Arnold, London.

Besonen, M.R., Patridge, W., Bradley, R.S., Francus, P., Stoner, J.S., Abbott, M.B., 2008. A record of climate over the last millennium based on varved lake sediments from the Canadian High Arctic. The Holocene 18, 169-180.

Bird, B., Abbott, M., Finney, B., Kutchko, B., 2009. A 2000 year varve-based climate record from the central Brooks Range, Alaska. Journal of Paleolimnology 41, 25-41.

Björck, S., Dearing, J.A., Jonsson, A., 1982. Magnetic susceptibility of Late Weichselian deposits in southeastern Sweden. Boreas 11, 99-111.

Björnsson, H., Pálsson, F., Haraldsson, H.H., 2002. Mass balance of Vatnajökull (1991-2001) and Langjökull (1996-2001), Iceland. Jökull 51, 75-78.

Björnsson, H., Pálsson, F., Sigurðsson, O., Flowers, G.E., 2003. Surges of glaciers in Iceland. Annals of Glaciology 36, 82-90.

Black, J.L., 2008. Holocene climate change in south-central Iceland: A multi-proxy lacustrine record from glacial lake Hvitarvatn, In: Miller, G.H.G.A. (Ed.), ProQuest Dissertations and Theses. Geology, United States -- Colorado.

Bond, G., Kromer, B., Beer, J., Muscheler, R., Evans, M.N., Showers, W., Hoffmann, S., Lotti-Bond, R., Hajdas, I., Bonani, G., 2001. Persistent Solar Influence on North Atlantic Climate During the Holocene. Science 294, 2130-2136.

Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G., 1997. A Pervasive Millennial-Scale Cycle in North Atlantic Holocene and Glacial Climates. Science 278, 1257-1266.

Boulton, G.S., Jones, A.S., 1979. Stability of temperate ice caps and ice sheets resting on beds of deformable sediments. Journal of Glaciology 24, 29-43.

Bradwell, T., Dugmore, A.J., Sugden, D.E., 2006. The Little Ice Age glacier maximum in Iceland and the North Atlantic Oscillation: evidence from Lambatungnajökull, southeast Iceland. Boreas 35, 61-80.

Bronk Ramsey, C., 1995. Radiocarbon calibration and analysis of stratigraphy: The OxCal program. Radiocarbon 37, 425-430.

Bronk Ramsey, C., 2001. Development of the radiocarbon program OxCal. Radiocarbon 43, 381-389.

Brooks, S.J., Langdon, P.G., Heiri, O., 2007. The identification and use of Palaearctic Chironomidae larvae in palaeoecology. QRA Technical Guide No. 10. Quaternary Research Association, London.

Caseldine, C., Langdon, P., Holmes, N., 2006. Early Holocene climate variability and the timing and extent of the Holocene thermal maximum (HTM) in northern Iceland. Quaternary Science Reviews 25, 2314-2331.

Christensen, J., Björck, S., 2001. Digital sediment colour analyses, DSCA, of lake sediments - pitfalls and potentials. Journal of Paleolimnology 25, 531-538.

Conley, D., 1988. Biogenic silica as an estimate of siliceous microfossil abundance in Great Lakes sediments. Biogeochemistry 6, 161-179.

Conley, D.J., Schelske, C.L., 2001. Biogenic silica, In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Press, Dordrecht, pp. 281-293.

Cook, T., Bradley, R., Stoner, J., Francus, P., 2009. Five thousand years of sediment transfer in a high arctic watershed recorded in annually laminated sediments from Lower Murray Lake, Ellesmere Island, Nunavut, Canada. Journal of Paleolimnology.

Croudace, I.W., Rindby, A., Rothwell, R.G., 2006. ITRAX: description and evaluation of a new multi-function X-ray core scanner. Geological Society, London, Special Publications 267, 51-63.

De Geer, G., 1912. A Geochronology of the Last 12 000 Years. Proceedings of the International Geological Congress, Stockholm, 241–253.

Dowdeswell, J.A., Hodgkins, R., Nuttall, A.M., Hagen, J.O., Hamilton, G.S., 1995. Mass balance change as a control on the frequency and occurrence of glacier surges in Svalbard, Norwegian High Arctic. Geophys. Res. Lett. 22, 2909-2912.

Dugmore, A.J., Cook, G.T., Shore, J.S., Newton, A.J., Edwards, K.J., Larsen, G., 1995. Radiocarbon dating tephra layers in Britan and Iceland. Radiocarbon 37, 379-388.

Einarsson, T., 1994. Geology of Iceland, Rocks and Landscapes. Mál og menning, Reykjavik.

Eiríksson, J., Knudsen, K.L., Haflidason, H., Henriksen, P., 2000. Late-glacial and Holocene palaeoceanography of the North Icelandic shelf. Journal of Quaternary Science 15, 23-42.

Flowers, G.E., Björnsson, H., Geirsdóttir, Á., Miller, G.H., Black, J.L., Clarke, G.K.C., 2008. Holocene climate conditions and glacier variation in central Iceland from physical modelling and empirical evidence. Quaternary Science Reviews 27, 797-813.

Fowler, A.C., 1987. A theory of glacier surges. Journal of Geophysical Research 92, 9111-9120.

Fowler, A.C., Murray, T., Ng, F.S.L., 2001. Thermally controlled glacier surging. Journal of Glaciology 47, 527-538.

Geirsdóttir, Á., Miller, G.H., Axford, Y., Ólafsdóttir, S., 2009a. Holocene and latest Pleistocene climate and glacier fluctuations in Iceland. Quaternary Science Reviews 28, 2107-2118.

Geirsdóttir, Á., Miller, G., Thordarson, T., Ólafsdóttir, K., 2009b. A 2000 year record of climate variations reconstructed from Haukadalsvatn, West Iceland. Journal of Paleolimnology 41, 95-115.

Gilbert, R., Nielsen, N., Möller, H., Desloges, J.R., Rasch, M., 2002. Glacimarine sedimentation in Kangerdluk (Disko Fjord), West Greenland, in response to a surging glacier. Marine Geology 191, 1-18.

Gudjónsson, K.A., Desloges, J.R., 1997. Late glacial and Holocene sediment infill of Lagarfljót NE Iceland, In: Lewkowicz, A.G., Kokelj, S.V. (Eds.), 27th Arctic Workshop Program and Abstracts, Department of Geography, University of Ottawa, pp. 98-102.

Gudmundsson, H.J., 1997. A review of the holocene environmental history of Iceland. Quaternary Science Reviews 16, 81-92.

Gudmundsson, S., Björnsson, H., Magnússon, E., Berthier, E., Pálsson, F., Gudmundsson, M.T., Högnadóttir, T., Dall, J., 2011. Response of Eyjafjallajökull, Torfajökull and Tindfjallajökull ice caps in Iceland to regional warming, deduced by remote sensing. Polar Research 30.

Guyard, H., Chapron, E., St-Onge, G., Anselmetti, F.S., Arnaud, F., Magand, O., Francus, P., Mélières, M.-A., 2007. High-altitude varve records of abrupt environmental changes and mining activity over the last 4000 years in the Western French Alps (Lake Bramant, Grandes Rousses Massif). Quaternary Science Reviews 26, 2644-2660.

Gälman, V., Petterson, G., Renberg, I., 2006. A Comparison of Sediment Varves (1950–2003 AD) in Two Adjacent Lakes in Northern Sweden. Journal of Paleolimnology 35, 837-853.

Haflidason, H., Eiríksson, J., Van Kreveld, S., 2000. The tephrochronology of Iceland and the North Atlantic region during the Middle and Late Quaternary: a review. Journal of Quaternary Science 15, 3-22.

Hallgrímsson, H., 2005. Lagarfljót - Mesta vatnsfall Íslands. Skrudda, Reykjavik.

Harrison, W.D., Post, A.S., 2003. How much do we really know about glacier surging? Annals of Glaciology 36, 1-6.

Hjartarson, Á., Ingólfsson, O., 1988. Preboreal Glaciation of Southern Iceland. Jökull 38, 1-15.

Hodder, K.R., Gilbert, R., Desloges, J.R., 2007. Glaciolacustrine varved sediment as an alpine hydroclimatic proxy. Journal of Paleolimnology 38, 365-394.

Hughen, K.A., Overpeck, J.T., Anderson, R.F., 2000. Recent warming in a 500-year palaeotemperature record from varved sediments, Upper Soper Lake, Baffin Island, Canada. The Holocene 10, 9-19.

Humphrey, N.F., Raymond, C.F., 1994. Hydrology, erosion and sediment production in a surging glacier: Variegated Glacier, Alaska, 1982-83. Journal of Glaciology 40, 539-552.

Ingólfsson, O., Björck, S., Haflidason, H., Rundgren, M., 1997. Glacial and climatic events in Iceland reflecting regional North Atlantic climatic shifts during the Pleistocene-Holocene transition. Quaternary Science Reviews 16, 1135-1144.

Itkonen, A., Salonen, V.-P., 1994. The response of sedimentation in three varved lacustrine sequences to air temperature, precipitation and human impact. Journal of Paleolimnology 11, 323-332.

Jiang, H., Eiríksson, J., Schulz, M., Knudsen, K.-L., Seidenkrantz, M.-S., 2005. Evidence for solar forcing of sea-surface temperature on the North Icelandic Shelf during the late Holocene. Geology 33, 73-76.

Jones, P.D., Briffa, K.R., Osborn, T.J., Lough, J.M., van Ommen, T.D., Vinther, B.M., Luterbacher, J., Wahl, E.R., Zwiers, F.W., Mann, M.E., Schmidt, G.A., Ammann, C.M., Buckley, B.M., Cobb, K.M., Esper, J., Goosse, H., Graham, N., Jansen, E., Kiefer, T., Kull, C., Kuttel, M., Mosley-Thompson, E., Overpeck, J.T., Riedwyl, N., Schulz, M., Tudhope, A.W., Villalba, R., Wanner, H., Wolff, E., Xoplaki, E., 2009. High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. The Holocene 19, 3-49.

Kamb, B., 1987. Glacier Surge Mechanism Based on Linked Cavity Configuration of the Basal Water Conduit System. J. Geophys. Res. 92, 9083-9100.

Kamb, B., Raymond, C.F., Harrison, W.D., Engelhardt, H., Echelmeyer, K.A., Humphrey, N., Brugman, M.M., Pfeffer, T., 1985. Glacier Surge Mechanism: 1982-1983 Surge of Variegated Glacier, Alaska. Science 227, 469-479.

Kardjilov, M.I., Gíslason, S.R., Gísladóttir, G., 2006. The effect of gross primary production, net primary production and net ecosystem exchange on the carbon fixation by chemical weathering of basalt in northeastern Iceland. Journal of Geochemical Exploration 88, 292-295.

Karlén, W., 1988. Scandinavian glacial and climatic fluctuations during the Holocene. Quaternary Science Reviews 7, 199-209.

Kaufman, C.A., Lamoureux, S.F., Kaufman, D.S., 2011. Long-term river discharge and multidecadal climate variability inferred from varved sediments, southwest Alaska. Quaternary Research 76, 1-9.

Kirkbride, M.P., Dugmore, A.J., 2006. Responses of mountain ice caps in central Iceland to Holocene climate change. Quaternary Science Reviews 25, 1692-1707.

Krammer, K., Lange-Bertalot, H., 1986-1991. Bacillariophyceae. 1–4 Teil. Süsswasserflora Von Mitteleuropa. Gustav Fischer Verlag, Stuttgart.

Lamoureux, S., 2002. Varve Chronology Techniques, In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments. Springer Netherlands, pp. 247-260.

Larsen, G., Eiríksson, J., 2008. Holocene tephra archives and tephrochronology in Iceland – a brief overview. Jökull, 229-250.

Loso, M., 2009. Summer temperatures during the Medieval Warm Period and Little Ice Age inferred from varved proglacial lake sediments in southern Alaska. Journal of Paleolimnology 41, 117-128.

Lowe, J.J., Walker, M.J., 1997. Reconstructing Quaternary Environments, 2nd edition. Prentice Hall, Harlow.

Lozier, M.S., 2010. Deconstructing the Conveyor Belt. Science 328, 1507-1511.

Magnússon, E., Pálsson, F., Björnsson, H., 2004. Yfirborð Brúar- og Eyjabakkajökuls og vatnasvið Jökulsár á Brú, Kreppu, Kverkár og Jökulsár í Fljótsdal 1946-2000. Raunvísindastofnun Háskólans RH-10-2004, 1-32.

Massé, G., Rowland, S.J., Sicre, M.-A., Jacob, J., Jansen, E., Belt, S.T., 2008. Abrupt climate changes for Iceland during the last millennium: Evidence from high resolution sea ice reconstructions. Earth and Planetary Science Letters 269, 565-569.

Menounos, B., Clague, J.C., 2008. Reconstructing hydro-climatic events and glacier fluctuations over the past millennium from annually laminated sediments of Cheakamus Lake, southern Coast Mountains, British Columbia, Canada. Quaternary Science Reviews 27, 701-713.

Meyers, P.A., Teranes, J.L., 2001. Sediment Organic Matter, In: Last, W.M., Smol, J.P. (Eds.), Tracking Environmental Change Using Lake Sediments. Springer Netherlands, pp. 239-269.

Moore, J.J., Hughen, K.A., Miller, G.H., Overpeck, J.T., 2001. Little Ice Age recorded in summer temperature reconstruction from vared sediments of Donard Lake, Baffin Island, Canada. Journal of Paleolimnology 25, 503-517.

Nesje, A., Dahl, S., Thun, T., Nordli, Ø., 2008. The 'Little Ice Age' glacial expansion in western Scandinavia: summer temperature or winter precipitation? Climate Dynamics 30, 789-801.

Nesje, A., Matthews, J.A., Dahl, S.O., Berrisford, M.S., Andersson, C., 2001. Holocene glacier fluctuations of Flatebreen and winter-precipitation changes in the Jostedalsbreen region, western Norvay, based on glaciolacustrine sediment records. The Holocene 11, 267-280.

Norðdahl, H., Einarsson, T., 2001. Concurrent changes of relative sea-level and glacier extent at the Weichselian-Holocene boundary in Berufjordur, Eastern Iceland. Quaternary Science Reviews 20, 1607-1622.

Ojala, A.E.K., Saarinen, T., 2002. Palaeosecular variation of the Earth's magnetic field during the last 10000 years based on the annually laminated sediment of Lake Nautajarvi, central Finland. The Holocene 12, 391-400.

Orkustofnun, 2006. Gagnabanki Vatnamælinga, afgreiðsla nr. 2006/53.

O'Sullivan, P.E., 1983. Annually-laminated lake sediments and the study of Quaternary environmental changes – a review. Quaternary Science Reviews 1, 245-313.

Pálmason, P.R., 1992. On the selection of the rock support system for the powerhouse area of the Fljótsdalur hydroelectric project. Tunnelling and Underground Space Technology 7, 177-188.

Pálsson, S., Vigfússon, H., 1996. Gagnasafn Aurburdarmælinga 1963-1995. Orkustofnun OS-96032/VOD-05, 1-270.

Pennington, W., Tutin, T.G., Cambray, R.S., Fisher, E.M., 1973. Observations on Lake Sediments using Fallout ^{137}Cs as a Tracer. Nature 242, 324-326.

Quinlan, R., Smol, J.P., 2001. Setting minimum head capsule abundance and taxa deletion criteria in chironomid-based inference models. Journal of Paleolimnology 26, 327-342.

Raymond, C.F., 1987. How Do Glaciers Surge? A Reviews. J. Geophys. Res. 92, 9121-9134.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., T.J., H., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal04 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal BP. 51, 1111-1150.

Sander, M., Bengtsson, L., Holmquist, B., Wohlfarth, B., Cato, I., 2002. The relationship between annual varve thickness and maximum annual discharge (1909-1971). Journal of Hydrology 263, 23-35.

Sharp, M., 1985. Sedimentation and stratigraphy at Eyjabakkajökull - An Icelandic surging glacier. Quaternary Research 24, 268-284.

Sharp, M., 1988. Surging glaciers: geomorphic effects. Progress in Physical Geography 12, 533-559.

Sharp, M., Dugmore, A., 1985. Holocene glacier fluctuations in eastern Iceland. Zeitschrift für Gletscherkunde und Glazialgeologie 21, 341-349.

Sigurðsson, O., 1998. Glacier variations in Iceland 1930-1995. Jökull 45, 3-26.

Sigurgeirsson, M.A., Arnalds, O., Palsson, S.E., Howard, B.J., Gudnason, K., 2005. Radiocaesium fallout behaviour in volcanic soils in Iceland. Journal of Environmental Radioactivity 79, 39-53.

Snowball, I., Korhola, A., Briffa, K.R., Koç, N., 2004. Holocene climate dynamics in Fennoscandia and the North Atlantic, In: Battarbee, R.W., Gasse, F., Stickley, C.E. (Eds.), Past Climate Variability through Europe and Africa. Springer, Dordrecht, pp. 465-494.

Thomas, E.K., Briner, J.P., 2009. Climate of the past millennium inferred from varved proglacial lake sediments on northeast Baffin Island, Arctic Canada. Journal of Paleolimnology 41, 209-224.

Thompson, R., Oldfield, F., 1986. Environmental Magnetism. Allen & Unwin, London.

Tjallingii, R., Röhl, U., Kölling, M., Bickert, T., 2007. Influence of the water content on X-ray fluorescence core-scanning measurements in soft marine sediments. Geochem. Geophys. Geosyst. 8.

Tomkins, J.D., Lamoureux, S.F., Antoniades, D., Vincent, W.F., 2010. Autumn snowfall and hydroclimatic variability during the past millennium inferred from the varved sediments of meromictic Lake A, northern Ellesmere Island, Canada. Quaternary Research 74, 188-198.

Van der Veen, C.J., 1999. Fundamentals of Glacier Dynamics. A.A. Balkema, Rotterdam.

Van Geel, B., Buurman, J., Waterbolk, H.T., 1996. Archaeological and palaeoecological indications of an abrupt climate change in The Netherlands, and evidence for climatological teleconnections around 2650 BP. Journal of Quaternary Science 11, 451-460.

Walker, I.R., Paterson, C.G., 1985. Efficient separation of subfossil Chironomidae from lake sediments. Hydrobiologia 122, 189-192.

Wiederholm, T.e., 1983. Chironomidae of the Holarctic region. Keys and diagnoses. Part 1 - Larvae. Entomologica Scandinavica Suppl. 19, 1-457.

Wolfe, A.P., 1997. On diatom concentrations in lake sediments: results from an inter-laboratory comparison and other tests performed on a uniform sample. Journal of Paleolimnology 18, 261-268.

Zillén, L.M., Wastegard, S., Snowball, I.F., 2002. Calendar year ages of three mid-Holocene tephra layers identified in varved lake sediments in west central Sweden. Quaternary Science Reviews 21, 1583-1591.