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Past dynamics of a marine-terminating glacier in lower Borgarfjörður, west Iceland - Analyses of glaciotectonic sediments and landforms

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Past dynamics of a marine-terminating glacier in lower Borgarfjörður, west Iceland

Analyses of glaciotectonic sediments and landforms

THORBJÖRG SIGFÚSDÓTTIR

QUATERNARY SCIENCES | DEPARTMENT OF GEOLOGY | LUND UNIVERSITY 2019





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Past dynamics of a marine-terminating glacier in lower Borgarfjörður, west Iceland

Analyses of glaciotectonic sediments and landforms

Thorbjörg Sigfúsdóttir



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Quaternary Sciences
Department of Geology

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Front cover: Deformed glaciomarine sediments in the Melabakkar-Ásbakkar coastal cliffs.
Photo by Ivar Örn Benediktsson

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Title and subtitle: Past dynamics of a marine-terminating glacier in lower Borgarfjörður, west Iceland - Analyses of glacioteconic sediments and landforms		
Abstract <p>Large and complete sections through glacial landforms formed in subaqueous environments are rare, impeding our knowledge of their internal composition and the processes responsible for their formation. Following the last deglaciation of the Icelandic Ice Sheet (IIS), a marine-terminating outlet glacier advanced out of the fjord of Borgarfjörður resulting in large-scale glacioteconic deformation of glaciomarine sediments. Due to isostatic uplift and erosion, these glacioteconic formations are now extensively exposed in the region and provide an opportunity to study a glacioteconised marine sequence on land. The aim of this study is to investigate the inter-relationship between ice-marginal deformation and deposition in a glaciomarine setting, increase the understanding of glacioteconic processes at the margins of marine-terminating glaciers, and elucidate past glacier dynamics and the regional glacial history.</p> <p>The main focus of the sedimentological and structural work was on the coastal cliffs of Belgsholt, Melabakkar-Ásbakkar and Skipanes. The sediments and glacioteconic structures were analysed on a range of scales using sedimentological and structural field methods, high resolution LiDAR scans and micromorphological thin sections. Shells of marine molluscs were sampled for radiocarbon dating and interpreted in the context of the stratigraphy and glacioteconics to constrain the timeline of the regional glacial history.</p> <p>The study revealed a series of glacioteconic moraines in the Melabakkar-Ásbakkar and Belgsholt coastal cliffs. The southernmost moraine is the largest and structurally most complex and is interpreted to indicate the maximum extent of the Borgarfjörður glacier. Other moraines in the series record repeated re-advances of the glacier during its active northward retreat. The moraines were mainly formed by large-scale thrusting and folding of glaciomarine sediments and subsequent deposition of ice-marginal sand and gravel. During the active retreat, glaciomarine sediments accumulated in front of the glacier providing source material for the formation of subsequent moraines.</p> <p>Detailed analysis of micro- and macroscale structures developed within décollements show that the detachment and transport of un lithified and unfrozen sediment blocks was enabled by overpressurisation of subglacial/ice-marginal porewater. This implies that hydrogeology played a key role in the construction of the moraines.</p> <p>The advances and subsequent active retreat of the Borgarfjörður glacier occurred between c. 13.0 -11.7 cal. ka BP indicating that it coincided with widespread glacier advances in Iceland and in the North Atlantic region during the Younger Dryas (c. 12.7-11.5 cal. ka BP). In the Early Holocene, after c. 11.3 cal. ka BP, the glacier re-expanded to a position around 5 km inside the Younger Dryas ice limit, indicating more extensive glaciation in the region than previously thought.</p> <p>The results of this thesis highlight the diversity of sedimentological and glacioteconic processes involved in the construction of large glacioteconic moraines at the margins of marine-terminating glaciers, and indicate that such glaciers were more dynamic during the deglaciation than previously thought.</p>		
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List of papers

This thesis is based on the three papers below.

Paper I

Active retreat of a Late Weichselian marine-terminating glacier: an example from Melasveit, western Iceland. Sigfúsdóttir, T., Benediktsson, Í. Ö., and Phillips, E: 2018, *Boreas* 47, 813-836. <https://doi.org/10.1111/bor.12306>. Reprinted with permission from John Wiley & Sons

Paper II

Micromorphological evidence for the role of pressurised water in the formation of large-scale thrust-block moraines in Melasveit, western Iceland. Sigfúsdóttir, T., Phillips, E., and Benediktsson, Í. Ö. *Quaternary Research*, in press. doi:10.1017/qua.2019.48

Paper III

Refining the history of Younger Dryas and Early Holocene glacier advances in the Borgarfjörður region, western Iceland. Sigfúsdóttir, T., and Benediktsson, Í. Ö., Submitted to *Boreas*.

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1. Introduction

Glaciers are effective in shaping the landscape and as they retreat they commonly leave behind complex landforms and sediments which can be studied to learn about past glacier fluctuations and climate change (Benn & Evans 2010).

Glaciotectonism has been defined as deformation of bedrock or sediments due to glacier overriding or pushing (Aber & Ber 2007; Phillips 2017). In areas that have undergone deformation by glaciers, resolving glacioteconic formations is an essential part of stratigraphic work and environmental reconstructions (McCarroll & Rijdsdijk 2003; Rijdsdijk *et al.* 2010). Glaciotectonic structures and landforms occur on a wide range of scales. The largest can be many kilometers in lengths and width (Aber & Ber 2007; Phillips 2017), and include large blocks of sediments/bedrock that have been transported and pushed at the ice margins to form extensive end moraines (van der Wateren 1995; Bennett 2001; Vaughan-Hirsch & Phillips 2017). At the other end of the spectrum are features so small that they need to be analysed under a microscope (van der Meer 1993; Menzies 2000; van der Meer & Menzies 2011). Many different types of deformation structures exist and they are often divided into two broad categories; brittle and ductile. Ductile deformation takes place by internal flow of material typically forming various types of folds. Brittle deformation occurs when the material breaks along sharp planes, whereas the internal fabric of the material remains intact (Phillips & Lee 2011). The type and size of glacioteconic structures and landforms depends on variety of factors such as; intensity and rate of the applied glacier stress, type of sediments that are deformed, and whether the deformation takes place below (subglacially), at the margins, or in front of the glacier (proglacially) (van der Wateren 1995; Bennett 2001). Another important component in glacioteconics is the presence of pressurised groundwater. High water pressures often contribute to reduced sediment strengths, which can both enhance deformation and increased flow rates of glaciers (Boulton & Caban 1995; Kjær *et al.* 2006; Benediktsson *et al.* 2008; Evans 2018). Due to the inter-relationship between the movements of glaciers and glacioteconics, analysing such sediments and landforms can provide important information about past glacier dynamics and glaciation history.

Glaciotectonic landforms are widespread in past glaciated regions, both in terrestrial and marine environments (Aber and Ber, 2007; Rütther *et al.*, 2013; Vaughan-Hirsch and Phillips, 2017; Kurjanski *et al.* 2019). Submarine landforms, including large thrust-block moraines, have been extensively mapped using geophysical methods both on continental shelves and in fjords (Andreassen *et al.* 2007; Rütther *et al.* 2013; Vaughan-Hirsch & Phillips 2017). However, large and complete open sections

through such landform associations are rare, impeding knowledge on their internal composition and the processes that formed them.

During the deglaciation of Iceland, a marine-terminating glacier advanced from Borgarfjörður, W-Iceland, into the Melasveit/Leirársveit district in the lower Borgarfjörður region, which was below sea level at that time (Fig. 1). This resulted in deformation of pre-existing sediments and the construction of a series of large, glacioteconic end-moraines. Due to isostatic uplift after the deglaciation, these glaciomarine sediments and landforms are now exposed on land. Extensive coastal cliffs provide insight into the stratigraphy and internal architecture of these moraines and provide an opportunity to study in detail the inter-relationship between deformation and sedimentation in a subaquatic setting (Fig. 2). The lower Borgarfjörður region has been central for reconstructing the glacier history of Iceland, especially on dynamics following the collapse of the Icelandic Ice Sheet (IIS) (Ingólfsson & Norðdahl 2001; Ingólfsson *et al.* 2010; Norðdahl & Ingólfsson 2015). The sedimentology and stratigraphy in the area has previously been described by (Ingólfsson 1987, 1988). Nevertheless, there are still stratigraphical and chronological problems that remain unsolved, which partly stem from overprinted deformation and the stratigraphic complexity of the area.

2. Aim of the thesis

The primary aim of this thesis is to improve the current knowledge on glacioteconic processes and the interplay between deposition, deformation and glacier dynamics, particularly in marine settings, as recorded in the coastal cliffs in Melasveit/Leirársveit. Furthermore, the study aims to increase the understanding of the Late-Weichselian to Early Holocene environmental history and past glacier dynamics in this part of Iceland. Extensive and detailed, multi-scale analyses of glacioteconic sediments and landforms are combined with new and pre-existing data of the stratigraphy and geomorphology to re-assess the regional glacial history. Specific research questions include:

- How many glacier advances can be identified the region and when did they occur? Were all of the glacioteconic landforms in the region formed by advances of the Borgarfjörður glacier (from the north) or did other glaciers also advance into the area during the Late Weichselian and/or Early Holocene?
- Is there any evidence of oscillating glacier margins during the deglaciation? Where the glacier advances climate driven or where they a result of glaciodynamic instability (e.g. surges induced by ice-shelf collapse) during the deglaciation?

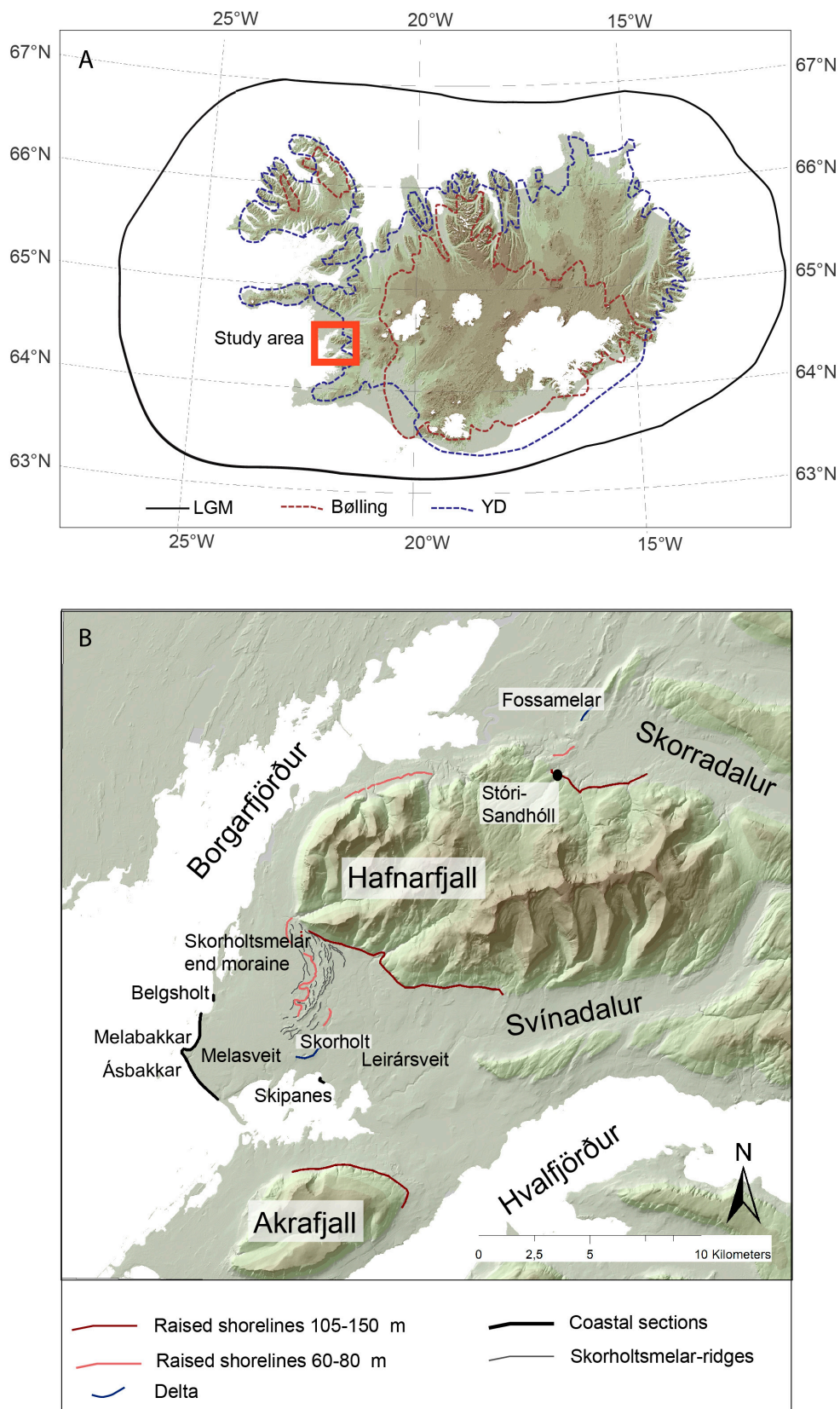


Figure 1. A: The evolution of the Icelandic Ice Sheet (IIS) during the Late Weichselian. The Last Glacial Maximum (LGM: c. 25-20 cal. ka BP) limit is drawn according to Patton et al. (2017) and is based mainly on submarine geomorphology. The suggested minimum ice extent at the end of the Bølling interstadial (c. 14.0 cal. ka BP) and the Younger Dryas maximum extent (YD: c. 12.7-11.5 cal. ka BP) is based on Norðdahl et al. (2008). It is, however, worth noting that the extent of IIS in many parts of Iceland, including western Iceland, is both temporally and spatially poorly constrained. B: A topographic map of the lower Borgarfjörður region, showing localities and the main geological features referred to in the text. The 60-80 m raised shorelines are drawn according to a reconstruction in Ingólfsson (1988), the 105-150 shorelines are drawn according to Magnúsdóttir and Norðdahl (2000) and Ingólfsson & Norðdahl (2001). The map excludes younger shorelines at lower levels. Basemaps from the National Land Survey of Iceland (Landmælingar Íslands).

- What are the styles of deformation observed in the coastal cliffs and what controlled them?
- What was the role of pressurised water in glaciotectonics and construction of thrust-block moraines? Did the subaquatic setting contribute to the style and magnitude of deformation

3. Overview of the Late Weichselian to Early Holocene glacial history of Iceland

The Iceland Ice Sheet (IIS) reached its maximum size during the Last Glacial Maximum (LGM) around 20-25 thousand years ago when it extended out to the shelf break around Iceland (Fig. 1A). It was mostly grounded below sea level and as a result it was sensitive to oceanic forcings such as changes in sea level and temperature (Hubbard *et al.* 2006; Norðdahl *et al.* 2008; Ingólfsson *et al.* 2010; Patton *et al.* 2017). Between c. 15.0 cal. ka BP and 14.7 cal. ka BP the western sector of the IIS retreated rapidly from Jökuldjúp to the lower Borgarfjörður region (a distance of ~100 km) (Syvitski *et al.* 1999; Andrews *et al.* 2000; Jennings *et al.* 2000; Norðdahl & Ingólfsson 2015). This extremely rapid recession indicates that marine-based parts of the ice sheet collapsed, possibly in response to the rising global sea levels linked with the melting of Laurentide and Eurasian ice sheets (Norðdahl & Ingólfsson 2015; Hughes *et al.* 2016; Margold *et al.* 2018). The retreat also occurred coeval with northward migration of the Polar Front and strengthening of ocean currents, which brought relatively warm Atlantic water north to Iceland (Eiríksson *et al.* 2000; Jennings *et al.* 2000; Geirsdóttir *et al.* 2009). Following the deglaciation, shorelines were formed at 150 m.a.s.l. at Stóri-Sandhóll in Skorradalur, a tributary valley of Borgarfjörður (Fig. 1B) (Ashwell 1975; Ingólfsson & Norðdahl 2001). The high altitude of these shorelines can be seen as a further evidence for the rapid retreat because the quick adjustment time of the Icelandic crust for loading/unloading would otherwise inhibit their formation (Ingólfsson & Norðdahl 2001; Norðdahl & Ingólfsson 2015).

The Bølling chronozone (c. 14.7-14.1 cal. ka BP) in western Iceland was characterized by relatively mild climate with ocean surface temperatures similar as it is today and marine regression (Ingólfsson *et al.* 2010; Norðdahl & Ingólfsson 2015). It is not known how far inland glaciers retreated in the western part of Iceland, but in general the glaciers retreated far inland; for example, evidence from north Iceland show that it retreated at least 50 km inside the present coastline (Fig. 1A) (Sæmundsson 1991; Norðdahl *et al.* 2008; Norðdahl *et al.* 2012). Sediments containing marine fossils of Allerød age

(Allerød: c. 13.9-12.7 cal. ka BP), are found in south-western, western and northeastern Iceland, including the lower Borgarfjörður region (Ingólfsson 1988; Geirsdóttir & Eiríksson 1994; Norðdahl & Pétursson 2005). Investigation of these sediments shows that in the late Allerød, climate and coastal waters started to cool and glaciers re-expanded followed by crustal depression and rising relative sea levels (Norðdahl & Pétursson 2005; Ingólfsson *et al.* 2010). The Younger Dryas (YD; c. 12.7-11.5 cal. ka BP) was a period of abrupt cooling in the Northern Hemisphere (Bakke *et al.* 2009; Renssen *et al.* 2015) and the influence of cold arctic water increased off the western coast of Iceland (Jennings *et al.* 2000). The glacier expansion and climate deterioration that had started in the Allerød continued into the YD. This can be seen on the distribution of glacial landforms, raised beaches and ice contact deltas as well as the exposure ages of bedrock (Geirsdóttir & Eiríksson 1994; Geirsdóttir *et al.* 1997; Geirsdóttir *et al.* 2000; Andrés *et al.* 2019; Norðdahl *et al.* 2019).

In the Early Holocene, around 11.2 cal. ka BP, glaciers in southern, eastern and northern parts of Iceland experienced readvances or temporary halts in retreat (Norðdahl & Einarsson 2001; Norðdahl & Pétursson 2005; Geirsdóttir *et al.* 2009). These expansions have been suggested to have been mass balance driven, possibly related to the Preboreal oscillation which was a brief period of deteriorating climate in the North Atlantic region (Björck *et al.* 1997; Rasmussen *et al.* 2011). The Preboreal Oscillation is also detected in Greenland ice cores around 11.3-11.5 cal. ka BP (Rasmussen *et al.* 2007; Rasmussen *et al.* 2011). There is, however, an uncertainty about the ice extent in the western/south-western part of Iceland during the YD and Early Holocene both due to paucity of data and lack of chronological control (Norðdahl & Pétursson 2005; Pétursson *et al.* 2015; Patton *et al.* 2017). This hampers correlation between different glacial and climate records and thus, limits our understanding of what drove past glacier fluctuations.

4. Regional setting

4.1 Geography

The main study area is located in the Melasveit district in lower Borgarfjörður, western Iceland (Fig. 1). It is a coastal lowland area, partly surrounded by steep mountains and situated between the large fjords of Borgarfjörður and Hvalfjörður (Fig. 1B). Evidence for glacier activity is widespread in the area. The bedrock has been sculpted by glaciers during the Pleistocene glaciations and striations indicate that glaciers located in Borgarfjörður,

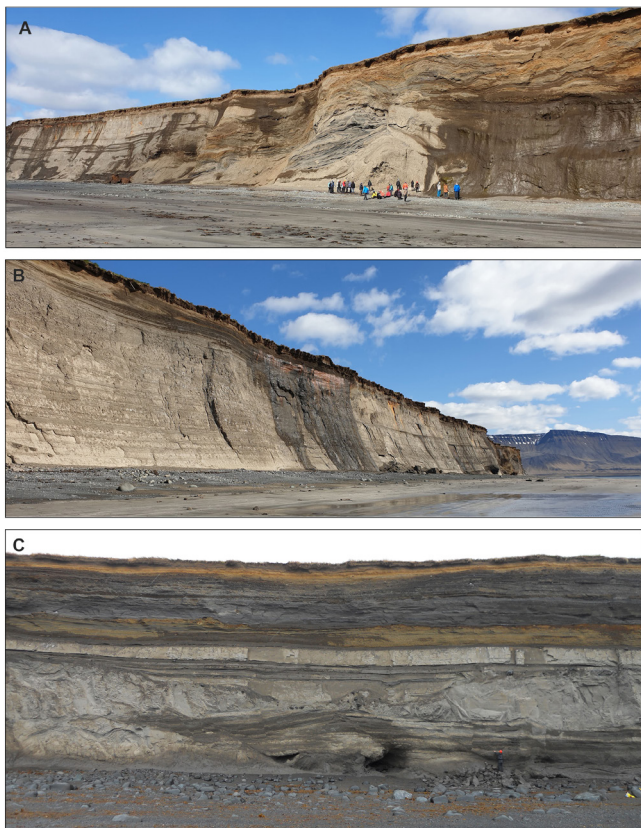


Figure 2. The Melabakkar-Ásbakkar coastal cliffs. A: Thrust stacked and folded glaciomarine diamicton, sand and gravel within the Ás moraine. Displacement was from the north (from left to right). The deformed sediments are overlain by laminated, glaciomarine silt and sand. B: Undeformed, bedded/laminated glaciomarine sediments exposed in Melabakkar-Ásbakkar. The height of the section is around 25 m. C: Thrust stacked and faulted glaciomarine sediments within the Melaleiti moraine. The deformed sediments are unconformably overlain by a sequence of undeformed glaciomarine and littoral deposits

Hvalfjörður and the Svínadalur valley did at some point coalesce in Melasveit (Ingólfsson 1988). Most of the bedrock in the lowlands is blanketed by a variety of glacial and post-glacial sediments and landforms and extensive glaciomarine sediment sequences and glaciotectonic landforms are exposed in the coastal cliffs of Belgsholt, Melabakkar-Ásbakkar, and Skipanes (Fig. 1B, 2). These cliffs are in total approximately 6 km long, up to 30 m high and are near-vertical due to ongoing coastal erosion. Further inland is the Skorholtsmelar end moraine which is the most prominent Late-Weichselian landform in the area (Fig. 1B, 3). With the length of 5 km and a width of 2.5 km, Skorholtsmelar is one of the largest preserved moraines from the deglaciation in Iceland. The highest points rise up to 40 m above the surrounding landscapes (Ingólfsson, 1988; Norðdhal et al. 2008). Its configuration, surrounding geomorphology and the distribution of boulders on the moraine's western side, indicate that it was formed by a glacier advance from Borgarfjörður.

4.2 Previous research and remaining stratigraphic and chronological problems

The sediments in the area have long been recognized as being of Late Weichselian age and studied since geological research in Iceland commenced in the 18th century (Ingólfsson 1984). In the 1920's, Bárðarson (1923, 1927) described the stratigraphy in the region and sampled fossils for analyses. He interpreted the sediments as representing a single retreat of the Late Weichselian ice sheet, sea transgression and generally warming climate. However, the work of subsequent scholars has shown that the deglaciation history is more complicated (Ingólfsson 1987, 1988; Hart 1994; Ingólfsson & Norðdahl 2001).

Ingólfsson (1987, 1988) conducted extensive research in the region in order to reconstruct the Late-Weichselian history of the lower Borgarfjörður area. His study sites included many sections and glacial landforms both in Borgarfjörður and Hvalfjörður. The chronology was based on a number of radiocarbon-dated fossils retrieved from various sedimentary units. More recent research on terrestrial landforms and sediments includes documentation of raised beaches and isostatic rebound during and after the deglaciation (Magnúsdóttir & Norðdhal 2000; Ingólfsson & Norðdahl 2001; Norðdahl & Pétursson 2005). The resulting evidence on the timing and number of glacier advances is somewhat contradictory. Ingólfsson (1988) suggested, based on the nature of glaciotectonic structures and stratigraphic relationships, that the sequence exposed in Melabakkar-Ásbakkar coastal cliffs had been overrun twice by the Borgarfjörður ice stream. He suggested that the first advance took place approximately 14.0 cal. ka BP and resulted in extensive deformation of glaciomarine sediments. According to this reconstruction, the second advance occurred sometime after c. 13.0 cal. ka BP, was more restricted and only affected the northern part of the Melabakkar-Ásbakkar sequence (Ingólfsson, 1988). Ingólfsson also proposed that the Skorholtsmelar moraine could have been formed by either of the two advances that also deformed the sediment sequence at the Melabakkar-Ásbakkar cliffs (Ingólfsson 1988). Hart (1994) and Hart and Roberts (1994) mapped glaciotectonics in two restricted places at Melabakkar-Ásbakkar, in the northern and southern parts of the section. Their main findings mostly supported the series of events reconstructed by Ingólfsson (1987, 1988), although they contrastingly concluded, based on the nature of deformation structures, that the southern part of the cliffs had undergone pro-glacial deformation by a glacier advancing from Hvalfjörður (Fig. 1B).

The timing of the series of events proposed by Ingólfsson (1988) is partly challenged by the presence of undeformed Early Bølling shorelines at 120-150 m.a.s.l in Skorradalur, and YD shorelines at 60-80 m.a.s.l. extending from Skorholtsmelar to the mouth of Skorradalur (Fig. 1B), because they would not have been pre-

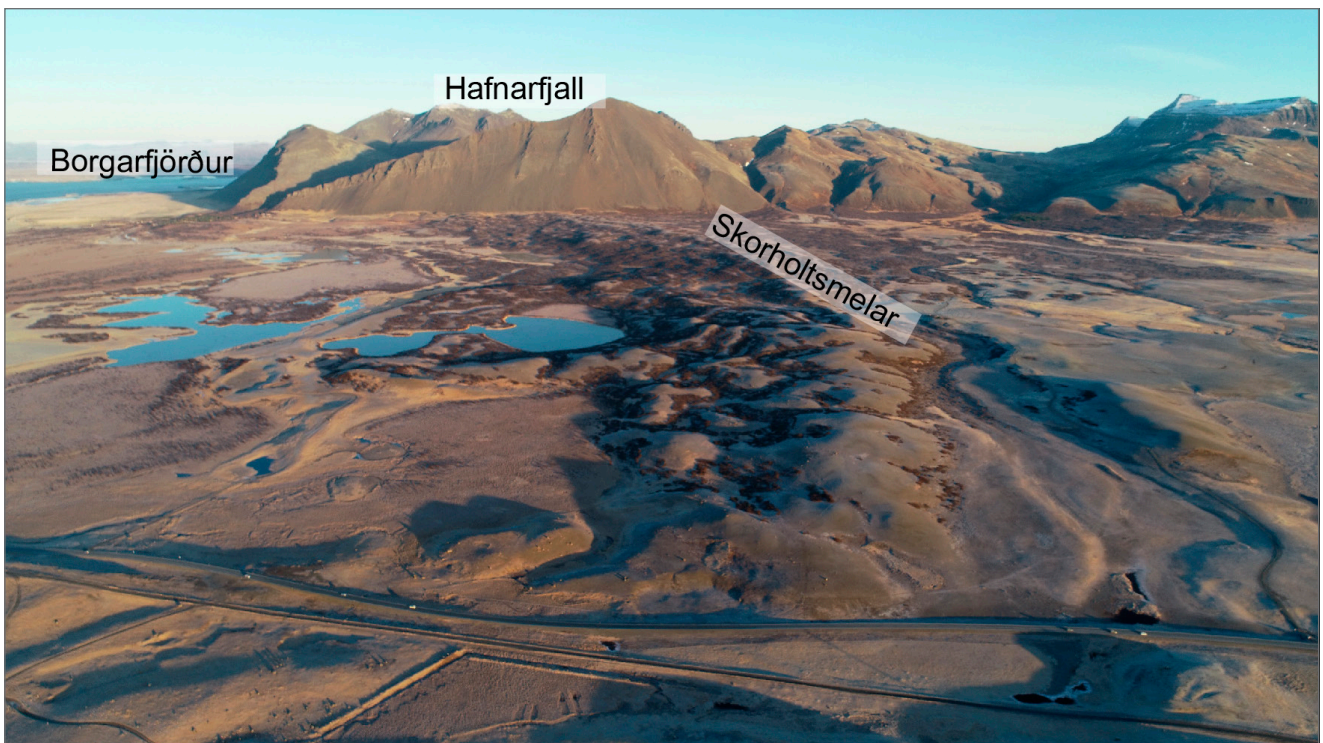


Figure 3. The Skorholtsmelar end moraine. Photo: Ágúst Guðmundsson.

served if the Borgarfjörður glacier would have advanced after their formation (Magnúsdóttir & Norðdahl 2000; Norðdahl & Pétursson 2005). In more recent publications, the area and surrounding lowland regions are considered to have been ice free during the YD and Early Holocene (Norðdahl *et al.* 2008; Ingólfsson *et al.* 2010; Pétursson *et al.* 2015). However, this study supports Ingólfsson's (1987, 1988) earlier hypothesis of YD advances and moreover indicates that the region was under the influence of fluctuating glacier(s) until the Early Holocene, suggesting that this part of Iceland was more extensively glaciated around that time than previously assumed.

5. Methods

5.1 Field mapping of sedimentology and glacioteconic structures

The sedimentology, stratigraphy and structural architecture of the coastal cliffs of Melabakkar-Ásbakkar, Belgsholt and Skipanes was documented in detail over the course of three summer field seasons (2013-2015). The results of this mapping were used in all the papers in this study (Papers I-III). The sections are largely clean due to constant coastal erosion and were therefore mostly ready for description. The sections were photographed and mapped in detail by drawing scale diagrams and logs in the field. Lithofacies and sedimentary structures

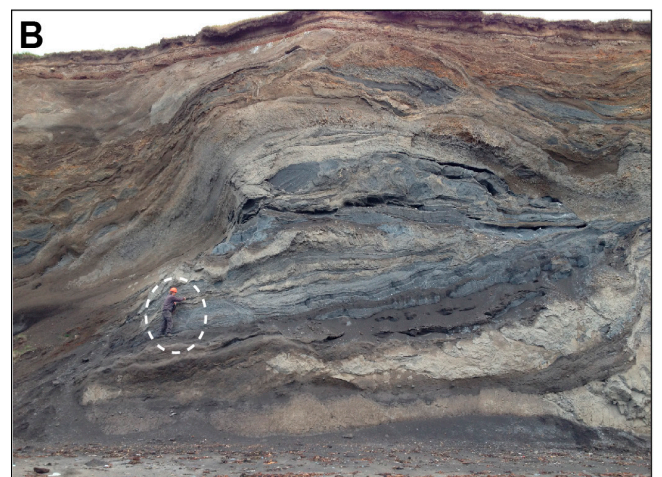


Figure 4. A: Measurement of strike and dip of a large, sediment filled normal fault at Melabakkar-Ásbakkar. B: Structural measurement of a large, overturned fold.



Figure 5. Preperation for terrestrial laser scanning at Melabakkar-Ásbakkar in spring 2014. Photo: Ívar Örn Benediktsson.

were documented according to Krüger and Kjær (1999) and Evans and Benn (2004). The description of the sedimentology and stratigraphy was partly based on earlier reconstructions of Ingólfsson (1987, 1988) and special emphasis was placed on recording the sediment type and sedimentary structures, bed geometry and nature of contacts to provide information on the sedimentary environments. The sediments in the coastal cliffs were grouped into eight major units based on sedimentary characteristics and stratigraphic location.

Glaciotectonic structures were described following guidelines presented in e.g. Phillips and Lee (2011) and Phillips (2017) with the aim of gaining information about glaciotectonic processes and structural evolution of the sequence. Studies of the glaciotectonics included structural measurements such as strike and dip of planar features (i.e. faults, tilt of beds) and orientation of folds axes with compass and clinometer (Fig. 4), which are key to interpreting directions of principal stress (ice flow). The structural features were plotted on a lower hemisphere stereographic projection using the Stereonet 9 software (Allmendinger *et al.* 2012; Cardozo & Allmendinger 2013).

5.2 Terrestrial LiDAR scanning

In spring 2014, the entire Belgsholt and Melabakkar-Ásbakkar cliffs were scanned using a terrestrial, high-resolution RIEGL VZ 1000 Light Detection and Ranging (LiDAR) scanner (Fig. 5). Key locations where scanned in high resolution while lower resolution scanning was performed in other parts. The position of the scanner was recorded and photos were used to apply the right colour to the scans. The scans (point clouds) were exported into Bentley Pointools to generate the images used as the ba-

sis for the section diagrams that are presented in papers I-III in this thesis. The scans were also used to measure the height and length of the cliffs as well as the geometry of individual units/beds and structures. The ability to do that is especially useful in parts of the cliffs that are not accessible and can therefore not be measured directly in the field.

LiDAR scanning can be used to perform a detailed mapping of geological surfaces in three dimensions (3D) (Bellian *et al.* 2005; Hartzell *et al.* 2014). It has been used in various disciplines including geographic surveying, mapping glacial surfaces and geological outcrop studies (Bonnafe *et al.* 2007; Jónsson *et al.* 2014; Dowling *et al.* 2015; Finlayson *et al.* 2019). This technology is based on a laser that is shot towards a target, where it bounces off and is subsequently detected by the instrument. The instrument measures the time it takes for the laser to enter the scanner to measure the distance of each measuring point (Bellian *et al.* 2005; Bonnafe *et al.* 2007).

5.3 Micromorphology

Sixteen samples were collected for micromorphology analyses in spring 2014. The samples were collected systematically within thin zones of highly strained sediments, located directly under glacially-transported blocks of sediments (thrust blocks). The research questions primarily revolve around the transportation mechanism of the sediment rafts, role of subglacial porewater and ice flow during transportation (Paper II).

The analysis of thin sections allows us to investigate sediment micromorphology- deformational and sedimentary structures that are too small to be seen with the naked eye. Microscale structures can provide much more detail of the depositional and deformation histories than



Figure 6. Microscopic analysis of a thin section.

macro-scale analyses alone; thus, micromorphology can be very helpful when investigating poly-deformed sequences (van der Meer 1993; Menzies 2000; Phillips & Lee 2011; van der Meer & Menzies 2011).

The samples were collected using 10x10x5 cm Kubi-ena tins, carefully cut into the sediments. The orientation of the samples were marked on the tins and they were then transported to the British Geological Survey thin section laboratory in Keyworth, UK, where thin sections were prepared. The thin sections were analysed under a standard petrological microscope and a stereomicroscope in order to investigate microscale structures and sediment properties (Fig. 6). The description of the samples was carried out following the terminology of van der Meer (1987, 1993) and Menzies (2000).

5.4 Radiocarbon (AMS ^{14}C) dating

Most of the glaciomarine units exposed in the cliffs contain shells of marine molluscs. In the summers of 2014 and 2015, shells were collected from selected locations in the region (Fig. 7). The ages of the shells were determined by using ^{14}C dating to estimate the timing of deposition of the units they were enclosed in. Twenty-two samples were measured at the Radiocarbon Dating Laboratory at Lund University and the acquired ages were calibrated using the marine13 dataset (Reimer *et al.* 2013) and the Radiocarbon Calibration Program (CALIB 7.1) (Stuiver *et al.* 2019), (Stuiver *et al.* 2019) using $\Delta R 24 \pm 23$ to accommodate for local deviation in the modern reservoir effect (Håkansson 1983). The resulting ages are presented in Paper III. The shells can in some places be

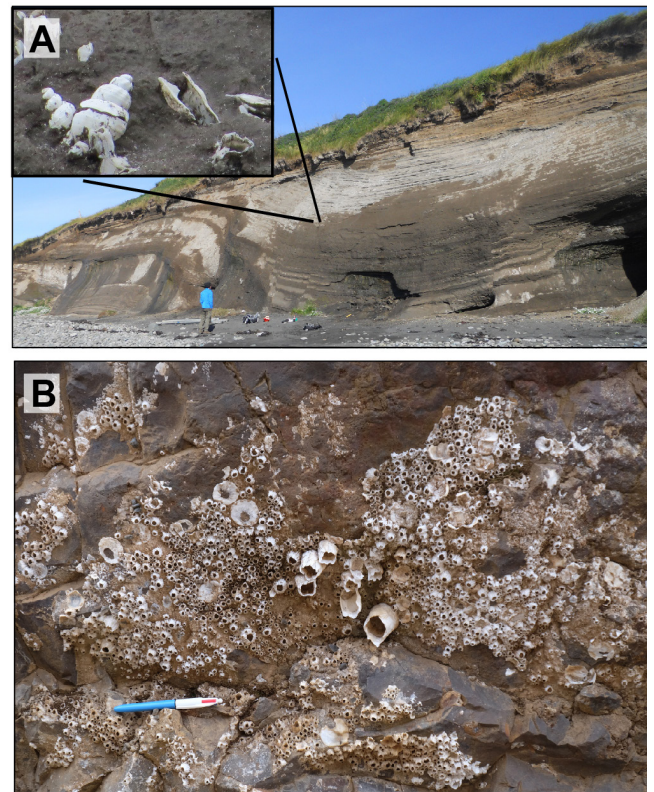


Figure 7. A: Folded and laminated glaciomarine silts and sands in the Belgsholt coastal section (Fig. 1B). These sediments contain well-preserved molluscs that were sampled for radiocarbon dating. B: *Balanus balanus* shells attached to raised sea cliff at around 70 m altitude at Fossamelar in the mouth of Skorradalur (see locations in Fig. 1B).

found in their original position within the sediments or attached to bedrock, whereas most units only contain shell fragments (Fig. 7). Where possible, unbroken fossils were sampled as they are less likely to be reworked, thus more likely to provide the true age of the deposit. Shells (broken or unbroken) that are enclosed in deformed sediments are presumed to provide maximum ages of the deformation (moraine construction). *In situ* shells found in undeformed sediments overlying the moraines could be used as minimum constraints for the age of the moraine construction.

The ^{14}C dating method is based on the decay rate of the radioactive ^{14}C isotope, which is continuously being produced in the atmosphere and has a half-life of approximately 5700 years. Living organisms take in carbon (including ^{14}C) from the environment they live in but when they die this uptake stops. The time since the organism died can be measured by the amount of ^{14}C relative to the amount of stable isotopes in the sample/fossil. This dating method is suitable for samples that are younger than approximately 50000 years after which the concentration of remaining ^{14}C is too low (Walker 2005).

Particular care must be taken when marine organisms are used for ^{14}C dating. The carbon exchange with the atmosphere occurs mainly at the sea surface and it can take long time for it to reach the lower parts of the water column. Thus, marine organisms living on the ocean

floor take up “old” carbon, which can result in overestimation of their age. This marine-reservoir effect has to be corrected for when dating marine samples. Furthermore, reservoir effects are known to change spatially and temporally e.g. due to changes in ocean currents (Ólafsdóttir *et al.* 2010). It has been suggested that due to greater influence of arctic sea water during the Late Weichselian the reservoir age of the water column may have been up to few hundred years higher than today (Eiríksson *et al.* 2004). Consequently, the calibrated ages presented in this study could be considerably younger than the presented values. However, the reservoir ages off the western coast of Iceland have not been established. Therefore this study uses the modern measured value (Håkansson 1983) to be consistent with previous publications from this region (Ingólfsson 1987, 1988; Magnúsdóttir & Norðdahl 2000; Ingólfsson & Norðdahl 2001). The ages presented in the text and on figures are calibrated median probability ages, rounded to the nearest 100 cal. years. The radiocarbon ages and the 2 sigma cal. BP age range for the samples are given in Table 1 and 2 in Paper III.

6. Results: Summary of papers

Although the main work for the thesis was carried out by the author, several other researchers contributed to this study as listed in Table 1. Those people whose names are

in brackets provided viewpoints, comments or help in the field but are not co-authors on the papers.

6.1 Paper I

Active retreat of a Late Weichselian marine-terminating glacier: an example from Melasveit, western Iceland. Sigfúsdóttir, T., Benediktsson, Í. Ö., and Phillips, E: 2018, Boreas 47, 813-836. <https://doi.org/10.1111/bor.12306>

The aim of Paper I was to resolve the depositional and glaciectonic history recorded by the over 5 km long coastal cliffs of Belgsholt and Melabakkar-Ásbakkar. The cliffs provide a detailed record of past glacier dynamics and the inter-relationship between glaciectonic and sedimentary processes that occur at the margins of a marine-terminating glacier. The results from this study were used to shed light on these processes and on past glacier dynamics in the region.

The large-scale stratigraphy and structural architecture of the coastal cliffs was described and analysed in the field using standard methods for structural and sedimentological investigation. Furthermore, the cliffs were scanned with a terrestrial LiDAR and the resulting images used as a base for scale diagrams and for measurements of unit contacts and thicknesses. The sediments were grouped into eight sedimentary units (A-H; Fig. 8) based on sediment properties and stratigraphic location. The units usually appear in correct stratigraphic order although

Table 1: Author's contribution

	Paper I	Paper II	Paper III
Concept and study design	T. Sigfúsdóttir Í. Ö. Benediktsson E. Phillips	T. Sigfúsdóttir E. Phillips Í. Ö. Benediktsson	T. Sigfúsdóttir Í. Ö. Benediktsson
Field work	T. Sigfúsdóttir Í. Ö. Benediktsson E. Phillips	T. Sigfúsdóttir E. Phillips Í. Ö. Benediktsson	T. Sigfúsdóttir Í. Ö. Benediktsson
Micromorphological analysis		T. Sigfúsdóttir E. Phillips	
Data interpretation	T. Sigfúsdóttir Í. Ö. Benediktsson E. Phillips	T. Sigfúsdóttir E. Phillips Í. Ö. Benediktsson	T. Sigfúsdóttir Í. Ö. Benediktsson
LiDAR	(M. Kirkham) (E. Haslam)		
Figures	T. Sigfúsdóttir Í. Ö. Benediktsson	T. Sigfúsdóttir	T. Sigfúsdóttir
Writing	T. Sigfúsdóttir Í. Ö. Benediktsson E. Phillips	T. Sigfúsdóttir E. Phillips Í. Ö. Benediktsson	T. Sigfúsdóttir Í. Ö. Benediktsson
Comments on manuscript	(P. Möller)		

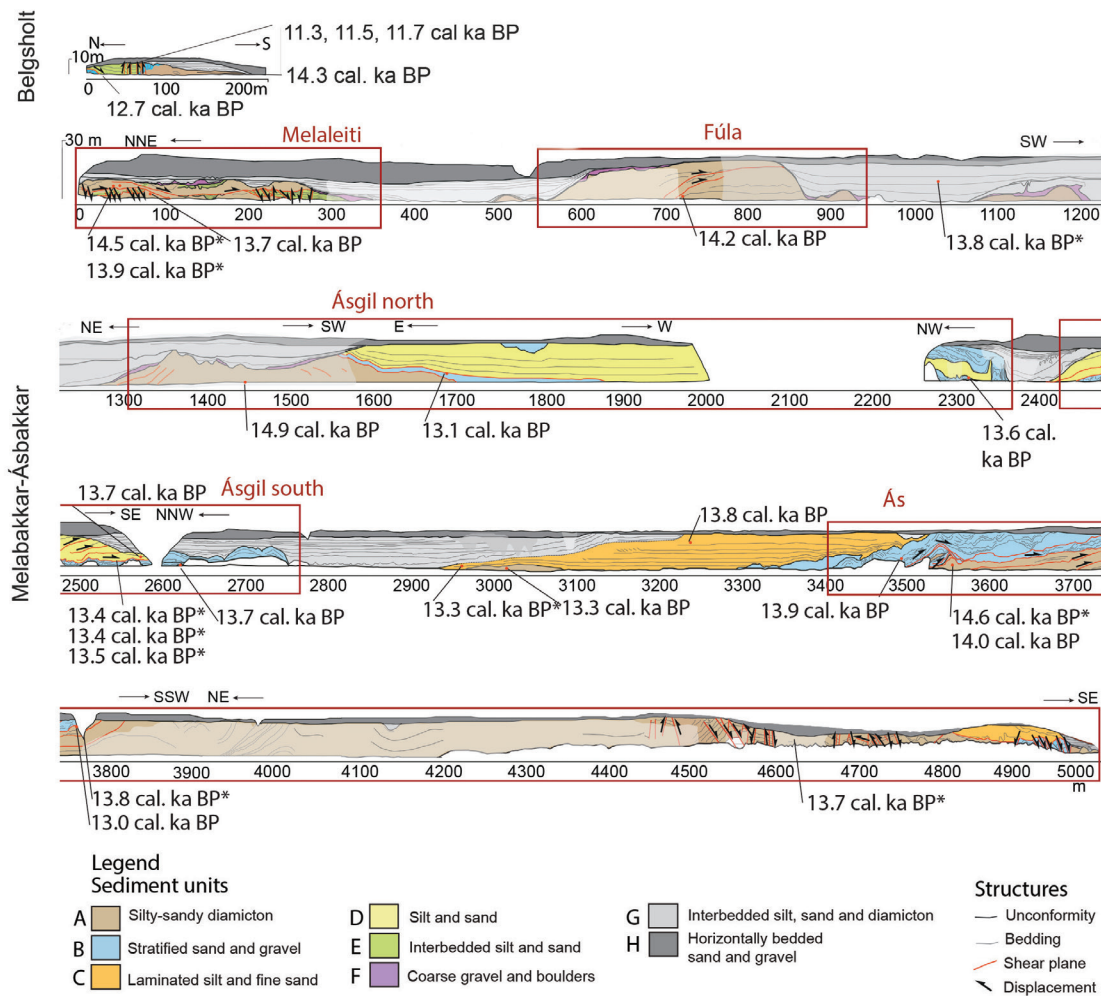


Figure 8. A scale diagram of the Melabakkar-Ásbakkar coastal cliffs based on LiDAR scans and photographs. The drawing is vertically exaggerated (2x). The shaded areas indicate parts of the section that were wet or covered in thin debris that hampered detailed analysis. Units A-E are deformed and form the moraines while Units F-H are undeformed and overly the moraines. The locations of the glaciotectonic moraines in the cliffs are outlined with red boxes. Calibrated radiocarbon ages of shells sampled from the cliffs are marked in the diagram indicating maximum ages of the sediments and the deformation. Ages marked with an asterisk are from Ingólfsson (1987). Figure modified from Papers I and III.

it is locally disrupted by overprinted deformation.

The results showed that at least seven, buried, glaciotectonic moraines are exposed in the cliffs. The orientation of structural features within the moraines (faults, beds and fold axes) indicate an ice push from the north-west or north-east, which indicates that they were formed by a glacier emanating from Borgarfjörður.

The southernmost and the largest of the moraines (called Ás) is over 1.5 km wide and at least 30 m high in the cliffs (Fig. 8). The northern, ice-proximal part of the Ás moraine is dominated by large-scale thrusting while the ice-distal part is characterised by folds that become smaller in amplitude towards the south (away from the glacier). The structurally lower part of the moraine comprises fossiliferous glaciomarine diamicton (Unit A) and the upper part mostly consists of sand and gravel (Unit B) interpreted as being deposited by meltwater at the margins of the glacier. Other moraines in the series are structurally less complex and are mainly built up by thrust blocks of glaciomarine sediments (Units A

and C-E). They are, like the Ás moraine, usually interleaved with penecontemporaneous, ice-marginal sand and gravel of Unit B. Generally, the moraines become smaller towards the north. The depressions between the moraines are filled in with bedded and undeformed glaciomarine deposits (Unit G). The entire glaciogenic sequence is unconformably overlain by littoral sand and gravel of Early Holocene age (Unit H) (Ingólfsson, 1987, 1988).

Based on this detailed study it was concluded that the southernmost and largest of the moraines, the Ás moraine, marks the maximum extent of a glacier advancing southwards from Borgarfjörður. After the glacier retreated from its maximum position it oscillated several times during an active retreat constructing the other moraines at/in front of the ice margin during successively smaller readvances. Sediment rates in front of the glacier were high, constantly supplying material for the construction of new moraines. As the glacier retreated, the moraines were buried in well-bedded, unde-

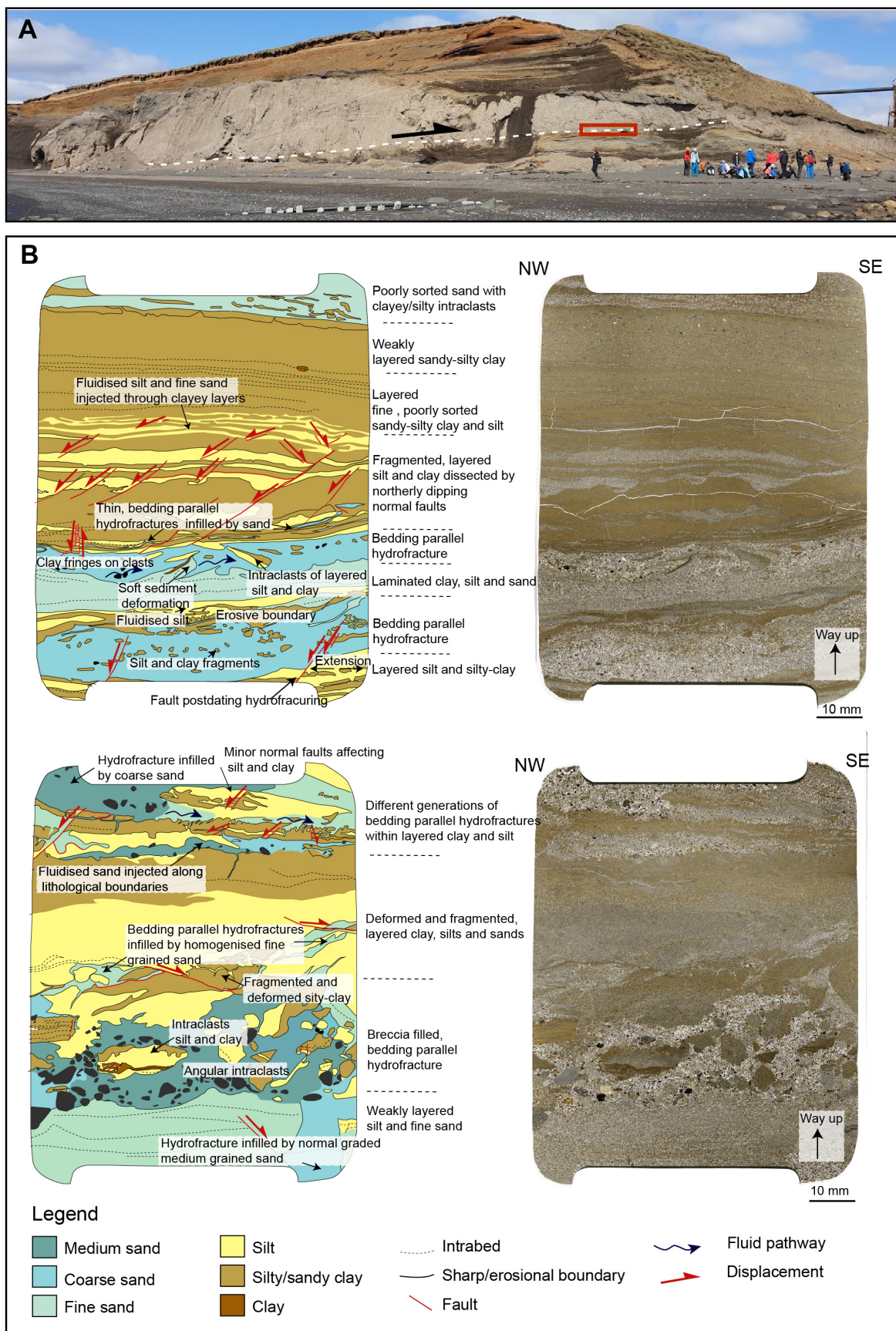


Figure 9. A: The Ásgil thrust block moraine, exposed in the central part of the Melabakkar-Ásbakkar coastal cliffs. The moraine is composed of stacked blocks of glaciomarine silts and sands that have been emplaced upon stratified sand and gravel. It is unconformably overlain by undeformed, post-glacial sediments. The red box shows the sampling site of the thin sections in B and the dashed lines indicate the basal detachment. B: Interpretation diagrams and scans of two thin sections collected close to the leading edge of the moraine. The thin sections show that the base of the thrust block is dissected by erosive sand layers representing sediment liquefaction and hydrofracturing. Only minor shearing is detected indicating that the thrust block was decoupled during its transport supported by overpressurised water along its base.

formed glaciomarine sediments.

Based on this reconstruction and previously published radiocarbon ages from the glaciotectonised sediments (Ingólfsson, 1987, 1988), it is suggested that the readvances and subsequent active retreat of the Borgarfjörður glacier occurred after c. 13.4 cal. ka BP rather than in two distinct expansions during the Bølling and Younger Dryas, as previously suggested (Ingólfsson 1988). The results of this study exemplify depositional and glaciotectonic processes that occur in ice-marginal/proglacial marine environments and clearly demonstrate that the deglaciation of Borgarfjörður was highly dynamic.

6.2 Paper II

Micromorphological evidence for the role of pressurised water in the formation of large-scale thrust-block moraines in Melasveit, western Iceland. Sigfúsdóttir, T., Phillips, E., and Benediktsson, Í. Ö. Quaternary Research, in press. doi:10.1017/qua.2019.48

The main aim of paper II was to study the processes involved in the construction of large thrust-block moraines. Particular emphasis was placed on understanding the nature of deformation associated with thrust planes and how pressurised water facilitates the detachment, transport and accretion of unlithified and unfrozen sediment blocks.

Paper I showed that the moraines exposed in the coastal cliffs of Melbakkar-Ásbakkar were mostly formed by thrust-stacking of glaciomarine sediments blocks. In paper II, two of these moraines, Melaleiti and Ásgil (south) (Fig. 8), were selected for a detailed analysis of the processes governing the glaciotectonic thrusting. Both moraines are composed of subhorizontal sediments blocks that largely preserve the original sedimentary structures. As the moraines were formed in a subaqueous setting, sediment freezing is unlikely to have been involved in the transport and preservation of the thrust blocks. In this study, 16 micromorphological thin sections were analysed from deformed sediments along the major detachments in order to investigate in detail the processes involved in the displacement of the thrust blocks (Fig. 9). The thin sections were analysed and interpreted in the context of the macroscale stratigraphy and glaciotectonics.

The detachments are characterized by relatively thin zones of cross-cutting, erosive sand layers interpreted as hydrofractures primarily developed parallel to bedding (Fig. 9). The hydrofractures record repeated phases of sediment liquefaction and injection during transport of the thrust blocks. In micro-scale there is little evidence of shearing (i.e. faulting and folding) observed along the leading edges of the thrusts. This, as well as preservation of primary sediment features in the footwall and the hanging wall, indicates that the leading edges of the thrust blocks were decoupled from the underlying depos-

its. The decoupling was supported by high water pressures along the detachments. Sediment deformation is more prominent further up-ice in the moraines indicating that, as the thrust-block moraines evolved, frictional drag (and shearing) increased. The deformed sediments along the detachments are cross-cut by hydrofractures, which reflect events of water escape to the surface. The final phase records brittle faulting, which indicates that dewatering of evolving moraines preceded the cessation of the displacement of the blocks.

This study stresses the role of over-pressurised pore-water within submarginal/pro-glacial sediments in the transport of unfrozen and unlithified thrust blocks during large-scale glaciotectonism. The hydrogeology can be the key factor in controlling the style of deformation during the detachment, transport, and stacking of the thrust blocks.

6.3 Paper III

Refining the history of Younger Dryas and Early Holocene glacier advances in the Borgarfjörður region, western Iceland. Sigfúsdóttir, T., and Benediktsson, Í. Ö., submitted to Boreas.

Paper III presents a revised reconstruction of the deglaciation history of the Borgarfjörður region based on studies of past glacier dynamics and glaciotectonics (Paper I and II), stratigraphic documentation of two new sites, 22 new radiocarbon datings as well as a re-assessment of data from previously published studies.

Radiocarbon ages of shells collected from the glaciotectonic moraines in Melasveit in this study and by Ingólfsson (1987, 1988) were used to constrain the timing of the moraine formation. Shells collected from the Melabakkar-Ásbakkar moraines ranged in age between c. 14.9 and 13.0 cal. ka BP (Fig. 8). The youngest sample was from from the Ás terminal moraine, which is the southernmost and oldest moraine in the series. Since the other moraines are structurally younger, this indicates that all of the moraines, including the Ás terminal moraine, formed after 13.0 cal. ka BP. Well-preserved shells from the folded glaciomarine silt and sand at Belgsholt range in age between 11.7 and 11.3 cal. ka BP (Fig. 8). The age of the shells are thought to indicate the approximate time of deposition thus, implying that the Belgsholt moraines was formed after 11.3 cal. ka BP. The Skipanes moraine, located southeast of the Ás terminal moraine (Fig. 1B) was formed between c. 13.7 and 11.5 cal. ka BP according to the ages of shells from deformed Unit A (maximum ages) and *in situ* shell in the undeformed, overlying Unit E (minimum age).

Overall, the results of paper III suggest that ice-free conditions prevailed in the Melasveit between c. 14.9 and 13.0 cal. ka BP (Fig. 10). After 13.0 cal. ka BP, a marine-terminating glacier in Borgarfjörður advanced,

Deglaciation of Borgarfjörður

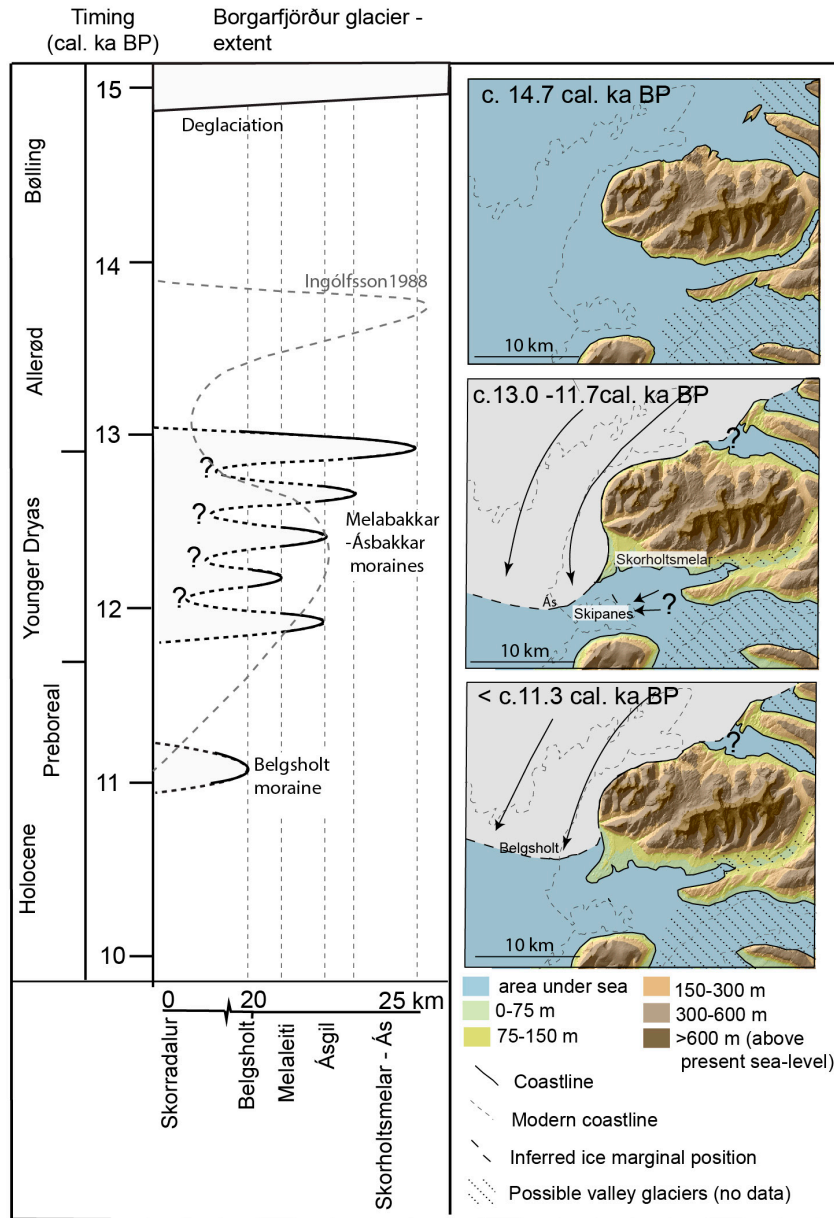


Figure 10. A time-distance model of the advances and retreats of the Borgarfjörður glacier during the Late Weichselian and Early Holocene. The question marks represent unknown ice-marginal position. The schematic time slices show the reconstructed aerial extent of the Borgarfjörður glacier and the approximate sea level position during three different time intervals. The reconstructions are based on radiocarbon ages, altitude of raised shorelines, geomorphology, stratigraphic and glaciotectonic studies. Mountain glaciers are likely to have been present during this time but as their size is unknown they are not drawn. Figure modified from Paper III.

resulting in the extensive deformation of pre-existing glaciomarine sediments and the formation of the Skorholtsmelar-Ás terminal moraine (Fig. 10). Between c. 13.0 and 11.7 cal. ka BP, the glacier readvanced several times during an active northward retreat from Skorholtsmelar-Ás resulting in the formation of the series of glaciotectonic moraines exposed in the Melabakkar-Ásbakkar coastal cliffs. Based on the glaciotectonic architecture and radiocarbon dates from the Skipanes ridge, a glacier may also have advanced into the area from the east around this time (between c. 13.7 and 11.5 cal. ka BP). The timing of the glacier expansions in the Borgarfjörður region coincides with the timing of widespread glacier expansions in

Iceland and the North Atlantic region during the Younger Dryas (c. 12.7-11.5 cal. ka BP).

After a relatively short period of improved climate conditions indicated by retreating glaciers and the reappearance of marine fauna between c. 11.7 and 11.3 cal. ka BP, the Borgarfjörður glacier readvanced at least to a position about 5 km within the previous ice limit at Ás/Skorholtsmelar (Fig. 10) to construct the Belgsholt moraine. This is the first recorded Early Holocene glacier advance in this region and indicates that the deglaciation of the area occurred later than previously assumed.

7. Discussion

7.1 Revised glacial history of the Borgarfjörður region - a sequential model

The overall goal of this study was to reconstruct the glacial history and dynamics in the lower Borgarfjörður region in order to both contribute to further understanding of the deglaciation of this part of Iceland and to provide insight into the depositional and deformational processes in glaciomarine settings. Mapping of the stratigraphy and glaciotectonic architecture of the coastal cliffs in Melasveit was fundamental in achieving this goal. In Paper I, a step-wise model of advances and retreats of the Borgarfjörður glacier during the Late Weichselian was proposed based on detailed sedimentological and glaciotectonic investigation of the Melabakkar-Ásbakkar and Belgsholt coastal cliffs. Paper III refines the glacial history of the area on the basis of these reconstructions, radiocarbon datings from sediments in the area as well as reassessment of previous studies. The sequential structural model from Paper I is presented below, complemented with chronological data from Paper III and illustrated in Fig. 11:

1. Following the LGM deglaciation, around 14.7 cal. ka BP, the study areas were situated below sea-level and marine/glaciomarine sediments were widely deposited in the lower Borgarfjörður region (Ingólfsson 1988) (Figs. 10, 11). Previous studies have shown that the sea level was up to 150 m above present sea level in the mouth of Skorradalur and around 105-120 m on the mountain slopes surrounding Melasveit/Leirársveit around this time (Fig. 1B) (Ingólfsson & Norðdahl 2001). It is not known how far inland glaciers retreated but these shorelines as well as mollusc bearing glaciomarine sediments show that the glaciers did at least retreat inside the mouth of the Skorradalur tributary valley (Ashwell 1967; Ingólfsson & Norðdahl 2001). The age span of marine molluscs sampled from deformed sediments in the coastal cliffs in Melasveit support ice-free conditions in that area between c. 14.9 and 13.0 cal. ka BP.
2. After 13.0 cal. ka BP, a glacier advanced out of Borgarfjörður. This resulted in extensive deformation of marine sediments containing shells and shell fragments that have given radiocarbon ages ranging between c. 14.9 and 13.0 cal. ka BP (Unit A; Fig. 8) (Ingólfsson 1988; Ingólfsson *et al.* 2010; Paper III). At its maximum position, the glacier formed the prominent Skorholtsmelar-Ás moraine, which is the largest and southernmost moraine exposed in the coastal cliffs of Melabakkar-Ásbakkar. The moraine was formed by large-scale glaciotectonic thrusting and deposition of ice-marginal sand and gravel. The sand and gravel were subsequently deformed as the glacier readvanced or continued to advance. The Ás moraine is correlated with the Skorholtsmelar moraine further inland; together they delineate the maximum extent of a post-LGM glacier into the area (Ingólfsson 1988) (Paper I).
3. Between c. 13.0 -11.7 cal. ka BP, the Borgarfjörður glacier advanced several times during a general northward retreat and constructed the thrust-block moraines at Ásgil north, Fúla and Melaleiti (Fig. 11). Glaciomarine and ice-marginal sediments were continuously deposited during these glacier oscillations and later pushed to form moraines (Fig. 11). These syntectonic sediments only contain fragmented, reworked shells. Thus, only maximum depositional ages can be derived with radiocarbon dating. Radiocarbon dating of shell fragments obtained from these sediment units gave ages ranging between 13.1-13.9 cal. ka, which overlap with the ages derived from the underlying (older) Unit A. Based on this stratigraphic relationship, these units are interpreted to be younger than 13.0 cal. ka BP. In general, the moraines become younger towards the north. However, after the glacier had retreated to some position north of the Melabakkar-Ásbakkar cliffs it advanced to Ásgil in the middle part of the cliffs (Fig. 11), overriding the moraines at Melaleiti and at Fúla. This resulted in a deposition of subglacial gravel and boulders on-lapping the thrust-block moraines in the northern part of the cliffs. Despite erosion (smoothing) and possibly some extensional faulting, these overridden moraines remain relatively intact. The Skipanes moraine was deposited between 13.7 and 11.5 cal. ka BP, possibly by a glacier advancing from the east (Fig. 10). This suggests that other glaciers in the regions i.e. from Svínadalur and Hvalfjörður advanced and that the glacier advances were widespread in the region during this time. No molluscs of this age have been found in the region, which is most likely explained by the presence of glaciers in the area during this time.
4. After c. 11.7 cal. ka BP, the Borgarfjörður glacier retreated and the depressions between the Melabakkar-Ásbakkar moraines continued to be infilled by bedded glaciomarine sediments (Fig. 11). Based on the age of marine molluscs in Belgsholt (ranging between 11.7-11.3 cal. ka BP) and *in situ* molluscs at Skipanes (11.7-11.4 cal. ka BP), the Melasveit/Leirársveit area was ice-free at that time. The finding of a *Balanus balanus* shell attached to bedrock at around 70 m a.s.l. at Fossamelar in the mouth of Skorradalur (Figs. 1B, 4) and radiocarbon dated to 11.7 cal. ka BP, may suggest that glaciers retreated at least to that position and that the relative sea level was at least 70 m above present in that location.

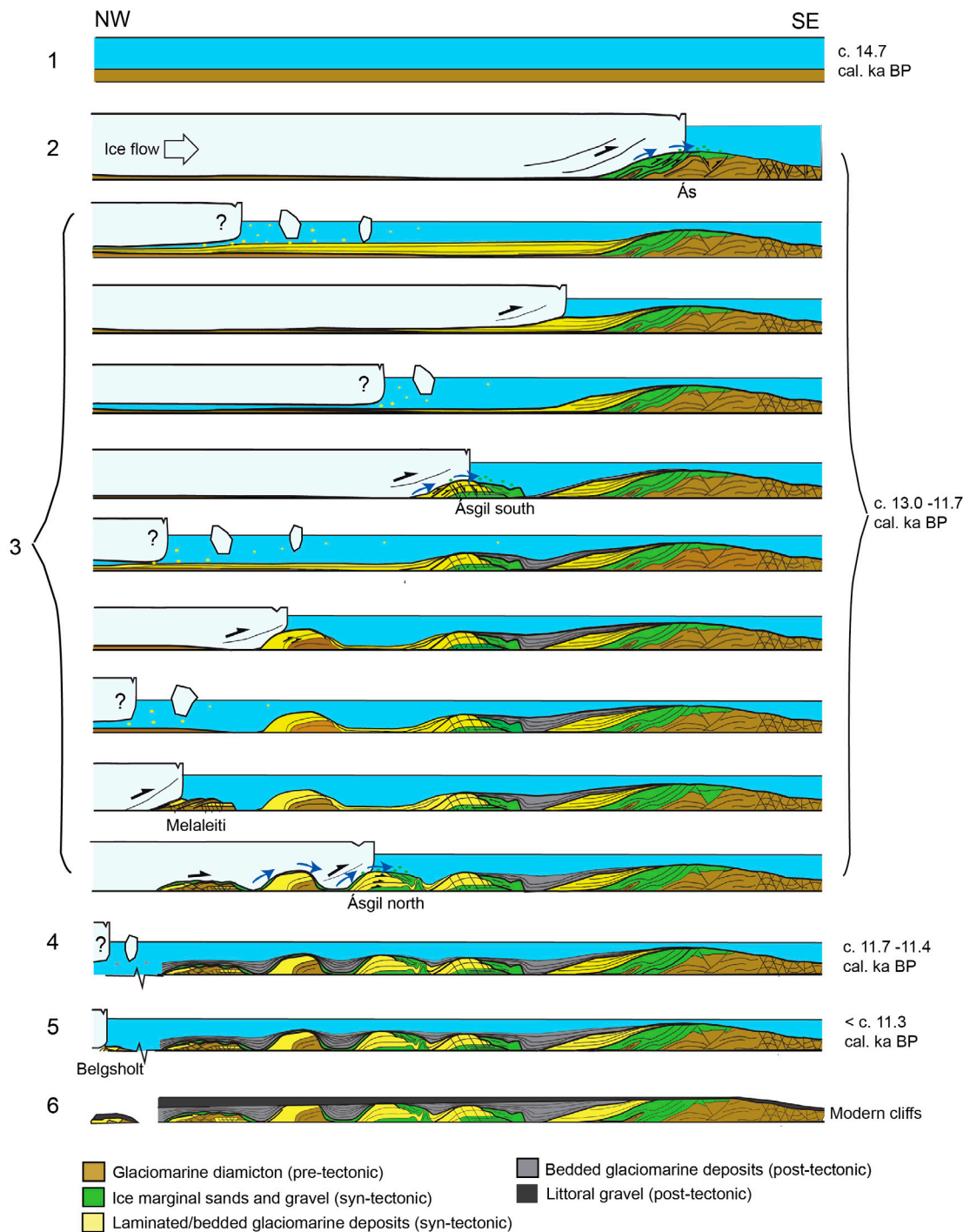


Figure 11. A sequential model demonstrating the formation of the glaciotectionic moraines exposed in the Melabakkar-Ásbakkar. The sequence of events is described in section 7.1. Black arrows indicate displacement and blue arrows indicate water flow. Figure modified from Paper I.

5. After 11.3 cal. ka BP, the Borgarfjörður glacier readvanced and formed the Belgsholt moraine, which is the northernmost and youngest moraine exposed in the Melabakkar-Ásbakkar coastal cliffs.
6. The relative sea level lowered due to isostatic rebound. Littoral and aeolian sediments deposited on top of the glaciomarine sediments and landforms (Ingólfsson 1987, 1988), and as a result the moraines have a poor morphological expression directly

above the cliffs. Due to ongoing coastal erosion the moraines are now exposed in the Belgsholt and Melabakkar-Ásbakkar coastal cliffs (Fig. 11).

7.2 Implications for the deglaciation history of western Iceland

The aforementioned sequence of events differs considerably from earlier reconstructions that attributed the large-scale glaciotectionics in lower Borgarfjörður mainly to an advance in late-Bølling, after around 14.0 cal. ka BP (Ingólfsson 1988; Norðdahl & Pétursson 2005; Norðdahl *et al.* 2008; Ingólfsson *et al.* 2010). This study indicates that the timing of the advance and the dynamic retreat that followed, occurred during the Younger Dryas (c. 12.7-11.5 cal. ka BP). During that cold spell, glaciers in Iceland commonly expanded to the coastal areas in response to colder air temperatures and noticeable cooling and glacier influence off the southwestern coast of Iceland (Rundgren 1995; Jennings *et al.* 2000; Geirsdóttir *et al.* 2009; Ingólfsson *et al.* 2010). This indicates that the increased mass balance of the IIS allowed the Borgarfjörður glacier to grow large enough to reach the present coastal areas. The glacier readvance in the Early Holocene (after c. 11.3 cal. ka BP) extended to Belgsholt around 5 km within the YD limit (marked by the Ás-Skorholtsmelar moraine). The minimum age of this advance is not well constrained although it most likely occurred before c. 10.6 cal. BP. That is based on regional sea level curves and stratigraphic evidence (i.e. lake cores) that suggest that glaciers had retreated from most lowland areas around that time (Norðdahl *et al.* 2008; Geirsdóttir *et al.* 2009; Pétursson *et al.* 2015). Relatively little has been known about the Early Holocene glacier extent in the western part Iceland (Norðdahl & Pétursson 2005). However, evidence from the southern- and eastern parts of Iceland show glacier expansions around 11.2 cal. ka BP (Geirsdóttir *et al.* 2000; Norðdahl & Einarsson 2001; Norðdahl & Pétursson 2005; Ingólfsson *et al.* 2010). Thus, this study suggests that the Borgarfjörður glacier advanced around similar time as other glaciers in Iceland, possibly due to temporarily increased mass balance linked to climate forcing in the Early Holocene (Preboreal) (Björck *et al.* 1997). This correlation is however somewhat speculative due to insufficient time constraints. An alternative explanation for the Early Holocene advance is that it was dynamically driven, possibly a result of instability of glaciers following rapid glacier retreat in the Late Weichselian. Studies elsewhere i.e. from Svalbard (Farnsworth *et al.* 2018; Larsen *et al.* 2018) indicate a very active glaciodynamic behaviour of glaciers around the YD and Early Holocene transition which appear to be asynchronous to climate records.

Some stratigraphic problems still remain unsolved in the study area. Previously, undeformed shorelines have been used as an evidence for ice-free conditions in the lower Borgarfjörður region (Magnúsdóttir & Norðdahl 2000; Norðdahl & Pétursson 2005). Bølling aged shorelines are found at 120-150 m a.s.l. in Skorradalur and 60-80 m shorelines stretching from Skorholtsmelar to

Skorradalur (Fig. 1B) have been correlated (but not directly dated) to the YD. In Paper III, it is suggested that the 60-80 m shorelines may have been formed during the Early Holocene rather than the YD. This is supported by the *Balanus balanus* of Early Holocene age (11.7 cal. ka BP) that is attached to bedrock at c. 70 m altitude in the mouth of Skorradalur. It should be noted that only one sample was radiocarbon dated from this location. This study does not explain the preservation of the Bølling shorelines or how they survived two substantial subsequent advances during the YD and Early Holocene. However, the simplest explanation may be that while the Borgarfjörður valley-fjord was occupied by a large outlet glacier or ice stream, a tributary glacier in Skorradalur did not extend to the outer part of the valley where the Bølling shorelines are preserved (Figs. 1B, 10). This explanation remains speculative but it reflects the paucity of chronological data that could further constrain the timing of glacier advances and shoreline formation in this region.

7.3 Controls on the styles of deformation

In order to provide information about the processes controlling the formation of glaciotectionic moraines, the structural architecture of each of the moraine exposed in the coastal cliffs was documented and the structural evolution of each of the moraines reconstructed (Paper I). Furthermore, in Paper II, two thrust-block moraines were selected for a micromorphological analysis with the aim of investigating in more detail how glaciotectionic thrusting occurs, and especially how pressurised water affects this process.

The size, morphology and internal architecture of glaciotectionic moraines are controlled by a variety of factors, most importantly, the magnitude and rate of which glacial stress is applied, coupling of the ice to the substratum, the bedrock topography, the thickness and composition of the deforming sediments and the hydrological properties of the foreland (van der Wateren 1995; Bennett 2001; Benn & Evans 2010).

The internal structures of the moraines observed in the coastal cliffs of Melabakkar-Ásbakkar and Belgsholt are dominated by thrust and folded massive-to-stratified glaciomarine silt, sand and fine-grained diamicton (Paper I). In the coastal section at Ás (Fig. 8), the ice-proximal part of the Skorholtsmelar-Ás moraine is dominated by large-scale thrusting. In the ice-distal part, the architecture is characterised by folds which decrease in amplitude towards the south (away from the glacier). Although the morphology of the moraine is not expressed immediately above the cliff, the multi-crested appearance is evident in the Skorholtsmelar moraine around 5 km further inland (Fig. 1B and 3). This may be used to support that the crests of the Skorholtsmelar moraines are

morphological expressions of the folds formed due to compressional proglacial/ice-marginal deformation of the sediment pile (Paper I). Similar structures have been recorded in large moraines e.g. in front of Eyjabakkajökull, Iceland (Benediktsson *et al.* 2010), and Holmströmbreen, Svalbard (Boulton *et al.* 1999), and may form during a single, large-scale advance. Other moraines in the Melabakkar-Ásbakkar series are structurally less complex. They are mostly formed by thrust stacking of large slabs of sediments, usually with a relatively minor degree of folding. The sediments in all of the moraines are cross-cut by large hydrofractures and major detachments are commonly lined with fluidised sediments (Paper I and II) indicating that overpressurization of porewater accompanied the advances (Rijsdijk *et al.* 1999; van der Meer *et al.* 2009; Phillips & Hughes 2014) (Paper II).

Pressurised groundwater plays an important role in glaciotectionic processes as well as ice dynamics (Boulton & Caban 1995; Boulton *et al.* 2001; Phillips *et al.* 2007; Sole *et al.* 2011; Phillips *et al.* 2013). For example, the focusing of water along discrete surfaces can facilitate detachment and transport of thrust blocks and lead to the formation of glaciotectionic moraines (Benediktsson *et al.* 2008; Phillips & Merritt 2008; Vaughan-Hirsch & Phillips 2017). Permafrost has also been considered as an important factor aiding in glaciotectionic thrusting as it provides the foreland strength necessary to transmit stress far beyond the margins (Aber *et al.* 1989; Boulton & Caban 1995; Boulton *et al.* 1999; Burke *et al.* 2009; Benediktsson *et al.* 2010) or acts as basal plane on which thrust blocks can slide (e.g. Benediktsson *et al.* 2015). As the moraines in Melasveit were constructed in a subaquatic setting it can be assumed that the sediments comprising the thrust blocks were unfrozen and water-saturated during deformation, and thus, permafrost cannot be used to explain their preservation. This suggests that sustained overpressurised water along the bounding thrusts would have been necessary for the sliding of thrust blocks. Analyses of structures along major detachments within two of the moraines (Ásgil and Melaleiti; Paper II) indicated that repeated events of sediment fluidization, hydrofracturing and water-escape took place along the detachments. The fluctuating water pressures most likely controlled the changing style of deformation during the transport and emplacement of the thrust blocks (Fig. 12).

Overall, the internal architecture of the Melabakkar-Ásbakkar and Belgsholt moraines is consistent with subaquatic end-moraines that have been described elsewhere, which are typically composed of glaciotectionised sediments interfingering with thick, coarse grained fans (Boulton 1986; Bennett *et al.* 2000; Lønne 2001; Benn & Evans 2010; Lønne & Nemeč 2011; Johnson *et al.* 2013). Despite the differences in glacier dynamics and sedimentation between terrestrial and subaqueous settings, the principles and processes that result in glaciotectionic formations are considered to

be similar (Boulton 1986; Bennett 2001). Thus, it is assumed that the same glaciotectionic models can be applied for both settings. However, some factors such as the water-saturated properties of these deposits as well as the ubiquity of water may all increase the likelihood of glaciotectionic deformation in subaquatic environments (Paper II). Glaciomarine deposits typically consist of fined-grained, poorly permeable sediment which may favour fluid overpressurisation (Fitzsimons & Howarth 2018). In the case of the Melasveit moraines the stratified nature of the deposits may have favoured the development of the décollements within weak layers (i.e. sorted silt and sand) sealed between less permeable layers (Paper II) (Bluemle & Clayton 1984; Van der Wateren 1985). At the ice-margins, the local concentrations (and accumulation) of highly permeable, coarse-grained sand and gravel may have aided in the formation of large-glaciotectionic moraines by acting as a pinning point for the glacier and provide core around which the sediments deformed (Lønne 2001; Fitzsimons & Howarth 2018). This would allow transmission of shear into the subsurface and increase coupling between the glacier to the substratum. The sediment draining would, however, be less efficient in subaquatic settings compared to terrestrial environments due to higher submarginal water pressures and lower pressure gradient due to the weight of the water column in front of the ice (Paper II). This may have been a factor allowing the subhorizontal thrust blocks to be transported relatively long distances (a few hundred meters) over the coarse grained sediments, initially without destructive deformation.

7.4 Glaciodynamic significance of the Melabakkar-Ásbakkar moraines

Large, glaciotectionic moraines like the ones in Melasveit are typically associated with surges (Boulton *et al.* 1999; Lovell & Boston 2017). The rapid flow of glaciers during surges is thought to facilitate the formation of large thrust-moraines and development of pressurised melt-water systems (Kamb 1987; van der Wateren 1995; Benediktsson *et al.* 2008). This may be used to suggest that retreat moraines were formed by successively smaller speed-up/surges of the Borgarfjörður glacier during a general recession from the Skorholtsmelar-Ás terminal moraine.

Glacier landsystems characteristic for surging glaciers have been developed in order to identify the tracks of such glaciers in the terrestrial record (Evans & Rea 1999; Ingólfsson *et al.* 2016). Studies of landform records produced by surges of marine-terminating glaciers in Svalbard showed that they exhibited many common characteristics with terrestrial landform records, which, apart from glaciotectionic terminal moraines, include crevasse-squeeze ridges and streamlined landforms within

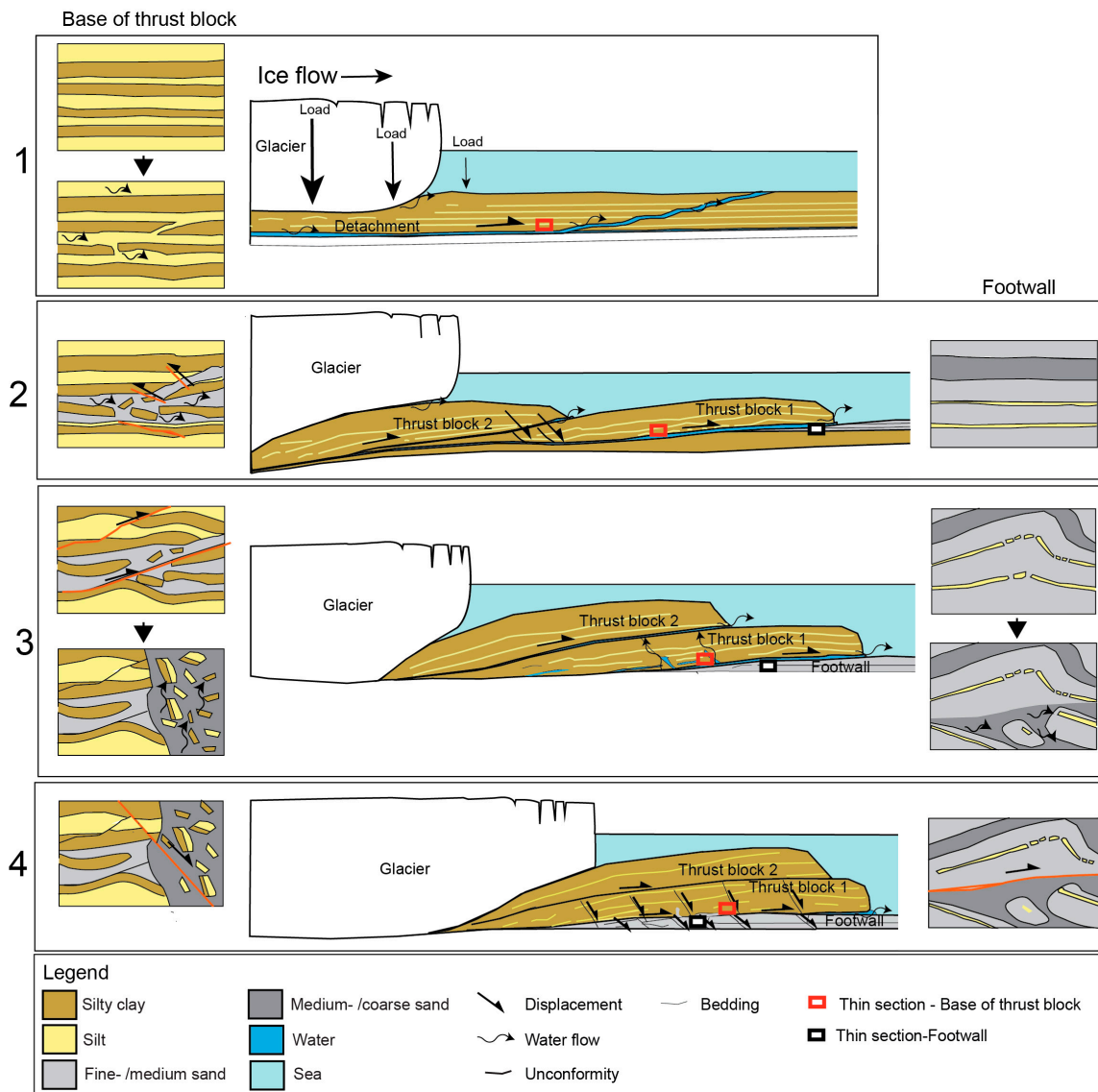


Figure 12. A sequential model explaining micro- and macroscale processes during large-scale glaciectonic thrusting based on investigation of the Melaleiti and Ásgil thrust-block moraines (Paper II). Stage 1: Groundwater pressure rose in response to a glacier advance. This caused liquefaction of the silt and sand, enabling decoupling of sediment blocks. Stage 2: Repeated phases of sediment liquefaction and injection occurred along the detachments. The deformation associated with the transport of the sediment blocks was focused within this relatively thin, water lubricated zone and as a result, they remained largely intact. Stage 3: The leading thrust block was transported on top of permeable sands and gravels in the terminal zone of the glacier. Initially, the thrust block slid over the water-saturated sand and gravel without much internal deformation showing that it was de-coupled from the substratum. However, the frictional drag (and shearing) increased due to water escape towards the margins and possibly increased overburden pressures under the evolving glaciectonic landform. Stage 4: Further draining of the sediments led to brittle deformation (faulting) and lock-up of the thrust-blocks. Figure from Paper II.

the surge limit (Ottesen & Dowdeswell 2006; Ottesen *et al.* 2008; Flink *et al.* 2015; Burton *et al.* 2016). However, while terrestrial glaciers usually stagnate and melt- *in situ* after surges (Evans & Rea 1999; Evans & Rea 2017), marine-terminating glaciers primarily retreat by calving (Benn *et al.* 2007). Consequently, the ice-margins are typically still active and retreat moraines are commonly seen in front of surging marine-terminating glaciers whereas they are rarely seen in front of their terrestrial counterparts (Boulton 1986; Ottesen *et al.* 2008). This difference in dynamic behaviour can even be seen between terrestrial and submarine parts of the same outlet glacier (Aradóttir *et al.* 2019).

While the terminal moraine at Ás can be correlated with the Skorholtsmelar moraine further inland, the other moraines are only seen in the coastal cliffs. This may possibly reflect the contrast between the dynamics of the part of the glacier where it terminated in relatively deep water (at Melabakkar-Ásbakkar-Belgsholt) to the dynamics further inland where it terminated on land or in very shallow water (at Skorholtsmelar).

There may be many reasons for the dynamic behaviour of the Borgarfjörður glacier. Marine-terminating glaciers tend to respond in a very complex way to external forcing such as changes in atmospheric- and oceanic temperatures, sea levels and local water depths (i.e. due to

sedimentation) (Straneo *et al.* 2013; Moon *et al.* 2014; Cook *et al.* 2016; Brinkerhoff *et al.* 2017). Also, glaciers may experience instability driven speed-ups following rapid retreat, i.e. following the removal of supporting ice-shelf or pinning point (De Angelis & Skvarca 2003). Although overall sizes of marine-terminating glaciers are dependant on mass balance changes, their short-term length changes are often decoupled from climate, which makes them rather poor indicators of past short-term climate fluctuations (Motyka & Beget 1996; Pfeffer 2007; Post *et al.* 2011; McNabb & Hock 2014; Moon *et al.* 2014).

Whether each of the advances that built the Melabakkar-Ásbakkar moraines were caused by external forcing or glaciodynamic instability (surges), they are thought to have formed during an overall dynamic retreat driven by decreasing mass balance of the Borgarfjörður glacier, most likely following the culmination of the YD (Paper III). The moraine series resembles what can be seen in front of surging, terrestrial glaciers in Iceland where the surges have become successively smaller in response to warming climate since the Little Ice Age (LIA) (Bennett *et al.* 2004; Benediktsson *et al.* 2008; Benediktsson *et al.* 2009; Striberger *et al.* 2011; Benediktsson *et al.* 2015). Similar pattern can be seen in front of modern and recently retreating, surging marine-terminating glaciers e.g. in Svalbard (Ottesen *et al.* 2008; Flink *et al.* 2015).

7.5 Implications for future research

The present study contributes to a better understanding of the glacial and environmental history of the Borgarfjörður region. However, there are still opportunities to improve the temporal- and spatial resolution of this record and thus, our understanding on the drivers behind the past glacier fluctuations.

This study places the formation of the Melabakkar-Ásbakkar moraines within the YD. However, the formation of each of the moraines within this time frame is uncertain. Detailed sedimentological studies of the rhythmically bedded units in between the moraines could help to put tighter constraints on the time that passed between their formation as well as providing information on the depositional environments. It was hypothesised by Ingólfsson (1987) that the rhythmically bedded units in the sequence may represent annual layering (varves), which could be used to better estimate the depositional rate. However, it is very difficult to separate varves from other rhythmically bedded glaciomarine units without proper time constraints (Schimmelmann *et al.* 2016). Our search for *in situ* fossils (micro- and macro) from these undeformed units was unsuccessful, but it is possible that a more extensive and systematic search, especially for micro-fossils, would provide some result. If these units

could be dated it would provide minimum constraints for the age of the underlying moraines.

In order to learn more about the regional glacier expansions, other dating techniques could be used. Cosmogenic nuclide dating has increasingly been used to obtain information on the timing of glacier retreats (Balco 2011; Bentley *et al.* 2017). This method is based on measuring the time a surface has been exposed to cosmic-ray activity (Walker 2005; Stroeven *et al.* 2011). In Iceland, ^{36}Cl is the most commonly used cosmogenic nuclide as it can be used for basalts (Principato *et al.* 2006; Licciardi *et al.* 2008; Brynjólfsson *et al.* 2015; Andrés *et al.* 2019). With careful planning, this dating method could potentially be used to further constrain the age of deglaciation of the fjord/valleys and the deposition of the Skorholtsmelar moraines. Furthermore, more extensive mapping of surface deposits in the region would be useful in order to link different landforms in the area. This would also be useful for better understanding the link between the glacier landforms and sea-level changes. A systematic search and collection of fossils from other sections (i.e. deltas and raised shorelines) in Borgarfjörður and surrounding regions may be used to shed light on the age of the coastlines and thus, the past sea level fluctuations.

It is possible that the moraines exposed in the coastal cliffs and/or other moraines/landforms may be buried offshore. Sub-bottom stratigraphy and glaciotectonics can be mapped using geophysical methods (Jakobsson *et al.* 2016). For example, seismic profiles have widely been used to map and interpret submarine glacial landforms (Huuse & Lykke-Andersen 2000; Ottesen *et al.* 2005; Rydningen *et al.* 2013; Vaughan-Hirsch & Phillips 2017). Possibly sediment cores could be used together with such profiles for stratigraphical studies and to correlate the landforms with glacier landforms onshore. Identification of submarine landforms would aid in a more complete understanding on the past glacier dynamics.

8. Conclusion

This study sheds light on sedimentary and glaciotectonic processes that occur in submerged, ice-marginal settings and highlights the dynamic nature of marine-terminating glaciers. It also has implications for the structural evolution of large thrust-block moraines, in particular the role of pressurised water in the construction of such moraines. Furthermore, the study refines the history of glacier advances and retreats in the Borgarfjörður region and contributes to further understanding of the glacier history and dynamics during the deglaciation in Iceland. The main conclusions of this thesis are the following:

- The coastal cliffs of Melabakkar-Ásbakkar and

Belgsholt reveal a series of ice-marginal moraines formed by a marine-terminating glacier that advanced southwards from Borgarfjörður. The southernmost and oldest moraine in the series (Ás moraine) is over 1.5 km wide and 30 m high in the cliffs and is correlated with the large, multi-crested Skorholtsmelar moraine further inland. The Skorholtsmelar-Ás moraine complex marks the maximum extent of the Borgarfjörður glacier after the LGM-deglaciation. Based on the age of marine molluscs found enclosed in deformed marine sediments within the moraine, it is concluded that the moraine formed after 13.0 cal. ka BP. This timing indicates that the advance was coeval with climate cooling and widespread glacier expansions in Iceland during the Younger Dryas.

- During its general northward retreat from Skorholtsmelar-Ás, the Borgarfjörður glacier advanced several times. This resulted in the formation of a series of glaciotectionic moraines, which are visible in the coastal cliffs of Melabakkar-Ásbakkar and Belgsholt. During this retreat, bedded/laminated glaciomarine sediments rapidly accumulated in front of the oscillating glacier. They provided source material for new moraines in the series and this contributed to the large size of the moraines. Based on stratigraphic and chronological evidence this active retreat can be placed between 13.0 and 11.7 cal. ka BP (Younger Dryas). After the glaciers receded from the moraines, the depressions between them were filled in and the moraines became buried under glaciomarine sediments.
- The internal structure of the moraines shows that they were predominantly formed by large-scale thrusting and folding of glaciomarine sediments. The deformed and emplaced glaciomarine sediments are interleaved with sand and gravel deposited by meltwater at the grounding line of the glacier. These ice-marginal sands and gravels were locally deformed by ice-push and -overriding and are therefore integrated into the glaciotectionics.
- The detachment of the thrust blocks forming the bulk of the moraines was enabled by overpressurization of subglacial/ice-marginal porewater, which led to the liquefaction of weak layers within the deforming, glaciomarine sequence. The detached blocks of sediments were transported with the glacier, aided by high water pressures being maintained during their transportation. Thus, the thrust blocks were in effect decoupled from the substrate during transportation. This allowed the unfrozen and unlithified blocks to be largely preserved intact.
- In the Early Holocene, around 11.7 cal. ka BP, the Borgarfjörður glacier had retreated to Skorradalur, 20 km further into the Borgarfjörður fjord. After 11.3 cal. ka BP, the glacier readvanced to Belgsholt, which is located around 5 km within the Younger Dryas ice-limit. This is the first recorded major Early Holocene advance in this region but appears to occur around similar time as glacier expansions elsewhere in Iceland. It is uncertain if it was driven by changes in mass-balance or glaciodynamic forcing.
- Structural analysis and radiocarbon ages from the glaciotectionic moraine at Skipanes south of the Ás-Skorholtsmelar moraine, show that it was formed between c. 13.7 and 11.5 cal. ka BP, possibly from a glacier advancing from the east. This implies that glacier advances in this region of western Iceland were not restricted to the Borgarfjörður glacier.
- The study indicates that the glaciodynamic behaviour in the Borgarfjörður region was complex and shows that the area was deglaciated later than previously thought. There are still many possibilities to improve the temporal- and spatial resolution of the glacial record. This would contribute to an improved understanding of the nature and timeline of the relationship between glaciotectionics, glacier dynamics and environmental changes.

Svensk sammanfattning

Glaciärer är väldigt effektiva på att forma landskapet och skapa nya sediment och landformer genom erosion, deposition och deformation. Genom att studera dessa landformer och sediment kan värdefull information erhållas om de processer som formade dem, glaciärens historia samt klimat- och miljöförändringar.

Detta projekt fokuserar på glaciala landformer och sediment i den lägre-Borgarfjörður regionen, västra Island. Vid slutet av den senaste istiden avancerade en stor glaciär in i området, vilket resulterade i storskalig deformation (glacitektonisk deformation) av existerande sediment. Området var vid denna tidpunkt beläget under havsnivån och glaciären slutade därför i havet. På grund av landhöjningen efter den slutgiltiga deglaciationen är nu glacimarina sediment och glaciala landformer skapade av glaciären belägna på torra land. Ett antal skärningar förekommer genom många av dessa landformer och erbjuder ett sällsynt tillfälle att i detalj studera en serie av glaciala landformer formade i en subakvatisk miljö.

Målet med den här studien är att undersöka deformation vid en isrand och deposition i en glacimarin miljö, öka förståelsen för glacitektoniska processer vid isränder, samt att öka kunskapen om den regionala glaciationshistorien och tidigare isdynamik.

De huvudsakliga studielokalerna var kustklipporna vid Belgsholt, Melabakkar-Ásbakkar och Skipanes, vilka är nästan 6 km långa totalt och upp till 30 m höga. Den exponerade stratigrafien och glacitektoniken vid klipporna analyserades i fält och med högupplöst LiDAR. Prover togs från klipporna för att undersöka mikrostrukturer i mikroskop. Skal av marina mollusker samlades in för kol-14-datering och för att avgränsa tidsramen för de glaciala fluktuationerna.

Resultaten visade att en serie av begravda ändmoräner är exponerade vid Melabakkar-Ásbakkar och Belgsholts kustklippor. Samtliga moräner bildades av sammanpressade sediment vid isränderna och staplande av stora sedimentblock från havsbotten. Detta lösgörande och transport av sedimentblock underlättades genom övertryck av grundvatten som inträffade i samband med glaciärens frammarscher. Smältvatten från glaciären förde också med sig stora mängder sediment ut i havet. De mest grovkorniga sedimenten (sand och grus) avsattes vid isränderna och blev därefter deformerade av isframryckningen. De mer finkorniga sedimenten transporterades längre bort från isränderna och bildade där tjocka sekvenser av stratifierade/laminerade glacimarina sediment.

Den sydligaste belägna moränen i serien är också den störste och indikerar den maximala utbredningen av Borgarfjörður-glaciären. Denna framryckning inträffade mest sannolikt mellan 13 000 och 11 700 år sedan (under Yngre Dryas), vilket indikerar att den var samtida med utbredda glaciärframryckningar annorstädes i Island och i den Nordatlantiska regionen. Andra moräner i serien påvisar temporära återframryckningar, möjligtvis orsakade av återupprepade glaciärsvämningar/hastighetsökningar när glaciären blev successivt mindre på grund av glaciärens minskande massbalans. Den sista påvisade framryckningen skedde under Tidig Holocen (omkring 11 300 år sedan) och visar på att den slutliga deglaciationen av denna region skedde senare än man tidigare har trott.

Allt som allt, den här studien beskriver deformation och deposition i subakvatiska miljöer samt processer involverade i skapandet av stora glacitektoniska moräner. Studien ökar dessutom vår förståelse för Islands glaciationshistoria och belyser det dynamiska beteendet av glaciärer under den senaste deglaciationen.

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LUNDQUA publications

At the Department of Geology, Quaternary Sciences, Lund University, three series are published, named "Thesis", "Report" and "Uppdrag". The "Thesis" series contains doctor dissertations; the "Report" series primary material, often of a monographic character, which cannot be published in extenso in ordinary scientific journals; the "Uppdrag" series contains selected examples of expert reports, generally in Swedish, which may be of some general interest.

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