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Glacial geomorphology and Late Quaternary glacial History of Hornstrandir, NW Iceland

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Geology	
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Abstract

The Late Quaternary glacial history of Hornstrandir, NW Iceland, have been investigated. The area is of special interest because it's almost unstudied. Several researchers have proposed that ice free plateaux and nunataks existed in Iceland during the Last Glacial Maximum (LGM) and Hornstrandir has been considered a likely candidate for such conditions.

Methods such as geomorphological mapping, sediment descriptions of coastal sections and sampling of material for radiocarbon dating, tephra and cosmogenic exposure dating have been applied. Detailed geomorphological maps of the area are also presented. Landforms such as terminal and lateral moraines, hummocky moraines, flutes, rock glaciers, rivers and lakes have been mapped by detailed field investigations and by visual interpretation of orthorectified aerial photographs.

Cosmogenic exposure dating has demonstrated that the entire Hornstrandir was covered by ice during the LGM. Cold based ice that preserved the periglacial surface beneath, was situated on the upland plateaux. Coastal sections have shown that cirque glaciers in Hornstrandir coalesced to form valley glaciers that flowed northwards towards the shelf break. The plateaux didn't deglaciate until 18 – 14 kyr BP. During the Bølling Interstadial, sea level stood at least 5 – 9 m above the present. By Younger Dryas time, cirque glaciers in Hornstrandir once again formed glaciers that at least reached out to the present coast. Terminal moraines have been used to estimate that the total glaciated area at some point during deglaciation was 44 km^2. The Saksunarvatn tephra (erupted 10180 ± 60 cal. yr BP) has been sampled at two locations, indicating that most of Hornstrandir was ice-free at Preboreal time. Neoglaciation on Hornstrandir is reflected in raised beaches yielding ages between ~2100 – 1300 cal. yr BP. During the Little Ice Age (LIA) cirque glaciers reached their Holocene maximum. The total glaciated area during the LIA has been estimated to 8.2 km^2.

Sammendrag (Norwegian summary)

Den Sen-Kvartære glasiasjonshistorien til Hornstrandir på NV Island, har blitt undersøkt. Veldig lite kvartærgeologisk arbeid er blitt gjort i området så Hornstrandir er derfor av spesiell interesse. Under den siste istids maksimum har det blitt foreslått at flere områder på Island var isfrie og Hornstrandir har blitt foreslått som en sannsynlig kandidat for slike forhold.

Hornstrandir har blitt undersøkt gjennom geomorfologisk kartlegging, logging av sedimentære snitt, prøvetaking av tefra, organsik materiale og steinprøver for kosmogen nuklid datering. Detaljerte geomorfologiske kart har også blitt produsert. Landformer som rand- og sidemorener, dødislandskap, fluter, steinbreer, elver og innsjøer er kartlagt gjennom feltarbeid og tolkning av flybilder.

Kosmogene nuklid dateringer har antydet at hele Hornstrandir sannsynligvis var dekket av is under siste istids maksimum, hvor kald is dekket de høytliggende platåene. Sedimentære snitt ved kysten har vist at botnbreene på Hornstrandir dannet dalbreer som beveget seg nordover mot kontinentalsokkelen. Platåene ble først isfrie for 18000 – 14000 år siden. I løpet av perioden Bølling Interstadial stod havnivået 5 -9 m høyere enn i dag. Ved Yngre Dryas tid, dannet botnbreer igjen dalbreer som i hvert fall nådde ut til dagens kyst. Randmorener er blitt brukt til å estimere at det totale isdekte området under deglasiasjonen etter Yngre Dryas var 44 km^2. Asken “Saksunarvatn tefra” er funnet ved to lokaliteter og indikerer at det meste av Hornstrandir var isfritt i Preboreal tid. På Hornstrandir er den Neoglasiale perioden representert ved strandvoller, datert ~2100 – 1300 år gamle. I løpet av den lille istid vokste botnbreene til sitt Holocene maksimum. På Hornstrandir er det blitt estimert at 8.2 km^2 var isdekt under den lille istid.

Preface

This thesis is written as a part of my Master of Science (M.Sc.) degree in Geology at the Department of Geology and Mineral Resources Engineering at the Norwegian University of Science and Technology (NTNU).

I would like express my gratitude to my advisor Anders Schomacker for letting me do this project and for all the valuable help and feedback I have received, both during fieldwork and in the writing process for the thesis. A special thanks to my co-advisor Skafti Brynjólfsson for great discussions and help throughout the project. Jón Bjarni Friðriksson is thanked for great field assistance and discussions during our time in Hornstrandir.

I would also like to thank my fellow students at NTNU and UNIS, for making the last five years of study a great experience.

Lastly, I would like to thank my family for all their support. A special thanks to Nils Hole for read-throughs and for generally showing a great interest in this project.

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1. Introduction

Hornstrandir is located at the northernmost part of the Vestfirðir peninsula in Iceland. The area is of special interest because it's Quaternary and glacial geology is almost unstudied. There is an ongoing discussion on whether or not some areas in Iceland remained ice-free during the last glaciation. Hornstrandir has been considered a likely candidate for such ice-free conditions and perhaps hosting a flora that managed to survive the glaciation. The Little Ice Age extent of cirque glaciers is also a topic that is under constant discussion.

The aim of this thesis is to improve the glacial history of the area. Appropriate methods such as geomorphological mapping, sediment descriptions of coastal sections and sampling of material for radiocarbon, tephra and cosmogenic exposure dating have been applied.

Another key purpose to this project is to present detailed geomorphological maps from Hornstrandir. These have been produced by detailed field investigations and by visual interpretation of orthorectified aerial photographs.

The thesis is divided into seven main chapters. Chapter 1 presents the study area and introduces the previous work that has been conducted in the region. Chapter 2 presents the different methods that have been applied for the thesis. Chapter 3 presents the results that have been obtained during fieldwork, remote sensing, dating of erratic boulders and bedrock and geochemical analysis of tephras and ^{14}C material. Chapter 4 combines the relevant literature and the results to interpret the Late Quaternary glacial history of Hornstrandir. Chapter 5 sums up the conclusions made in the previous chapter, while chapter 6 and 7 presents the reference list and appendix for the thesis.

1.2 Study area

The study area encompasses the Hornstrandir nature reserve, which is the northernmost part of the Vestfirðir peninsula in Iceland. The region covers a total area of 580 km^2 and is connected to the rest of Vestfirðir by an approximately 6 km thick neck. The residents at Hornstrandir made their living by hunting, fishing and agriculture until the area was abandoned in the mid-1900s. Today the area is used for recreation and tourism, mostly during the summer. There are no roads leading up to the nature reserve so the only way to Hornstrandir is by boat. The nature reserve was established in 1975. A figure of Hornstrandir, with the general topography and the most important geographical names used in the text is shown in Figure 1.1.

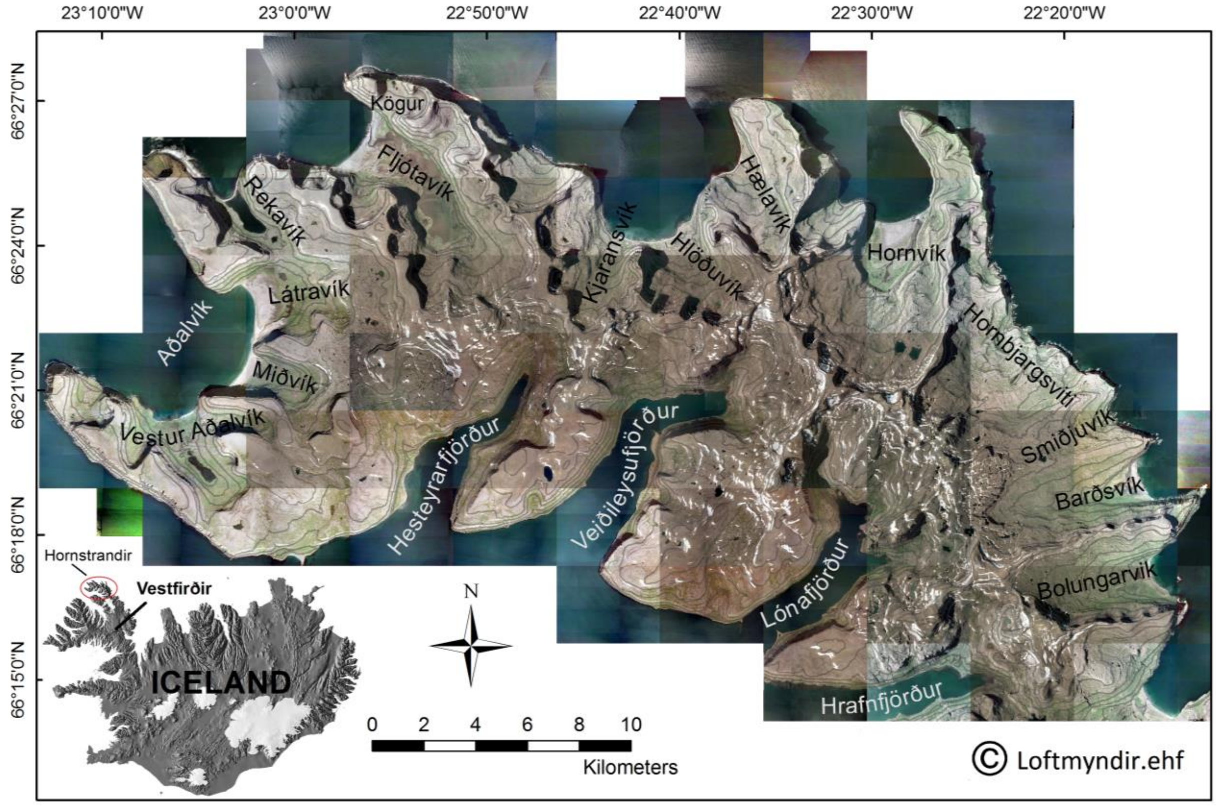


Fig. 1.1: The study area is situated at the northernmost part of the Vestfirðir peninsula in Iceland. The main geographical names are presented on aerial photographs provided by The Icelandic Institute of Natural History.

1.2.1 General geomorphology

The most striking features of Hornstrandir are its short and wide valleys. Examples are Hlöðuvík, Hælavík and Kjaransvík. The valleys in Hornstrandir contain several cirques that occur either alone or as composite ones. They are usually situated in the head of the valleys and most of the cirques are facing in a north-easterly direction. The altitude of cirque floors is usually between 200-300 m a.s.l. and the height of the headwall varies between 150-300 m. Fourteen of the cirques in Hornstrandir still contain small cirque glaciers or remnants of ice. Most of the cirques containing glaciers are situated at the east side of the peninsula. The valleys often end as broad coastal lowlands. Another striking feature of Hornstrandir is the step-like topography, caused by the Neogene flood basalts that the bedrock consists of. At least eight fjords are carved into Hornstrandir. The fjords on the northern coast are broad and short, while the fjords on the southern coast are long and narrow with lengths varying between 7 and 9 km. The fjords lead to an upland plateau between 400 and 700 m a.s.l. Around Aðalvik in the west, the plateau surface lies around 400 m a.s.l. It rises towards the east and at Hornvík mountain tops reach up to 700 m a.s.l. The shelf around Hornstrandir is no deeper than 100 m, and the 50 m depth curve lies about 5 km off the coast in the west and northwest.

1.2.2 Bedrock geology

In a geological context, Iceland is a young landmass. Three main geological bedrock formations occur in Iceland. The oldest is the Tertiary Basalt formation which was formed in the Neogene. Next is the Grey Basalt formation which was formed in the Pliocene and early Pleistocene, while the Moberg formation was formed in the late Pleistocene and Holocene. The bedrock in Hornstrandir is mainly composed of Neogene flood basalts with thin interbedded sedimentary layers, while some of the mountain tops and plateau surfaces in the east consist of acid extrusives (Fig. 1.2). The bedrock is part of a basalt area, which was formed by intensive volcanic activity at the start of sea floor spreading in the north Atlantic (Einarsson, 1973). Basaltic magma has low viscosity and often flows long distances from the eruption site (Einarsson and Douglas, 1994). The study area is located at least 250 km from the active rift zones in Iceland, so there are currently no active volcanoes on Hornstrandir (Flóvenz and Saemundsson, 1993).

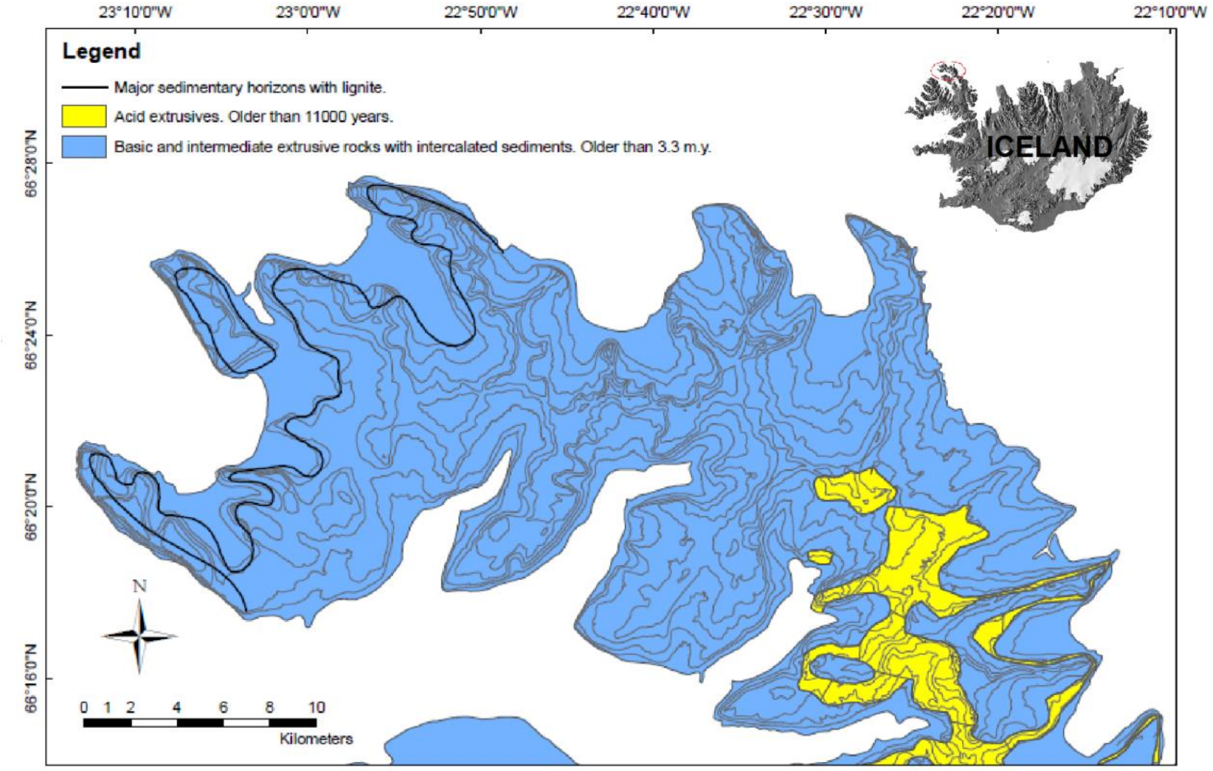


Fig. 1.2: An overview map showing the bedrock geology in Hornstrandir.

1.2.3 Surface deposits

There are only a few references on the surface deposits in Hornstrandir to be found in the literature. The first observations were made by Thoroddsen during the summers of 1886 and 1887. He recognised that the landscape had been glacially sculpted and observed both glacial striae and glacial deposits at numerous localities. Kjartansson (1969) observed raised beaches in Hornvík and on the eastern flank of Kögur (Fig. 3.2). He also mapped outcrops of till in Hælavík and Hlöduvík and saw that alluvial and aeolian deposits covered most of the Hornstrandir lowlands. The Hjort et al. (1985) expeditions recorded that the upper plateau was covered with mature block fields consisting of local bedrock. The plateaux showed no signs of being covered by active glaciers. They also noted that the valleys and coastal uplands were covered with Late Weichselian and early Holocene tills. The lower parts of Hælavík and Hlöduvík contained well developed hummocky topography, while seven cirques in Hlöduvik, Hælavík and Hornvík showed clear signs of having been glaciated recently (in the Little Ice

Age; LIA). The cirques had one to several fresh looking moraines in front of them and the area behind was also looking freshly deglaciated with a sparse vegetation cover (Hjort et al., 1985).

1.2.4 Climate

The climate of Iceland is classified as cool, temperate maritime (Einarsson, 1984). Iceland's location in the middle of the North Atlantic makes it very sensitive to oceanographic changes, which strongly affect the climate on Iceland. The Norwegian Atlantic Current passes to the south on its course northwards. One of its branches, the "warm" Irminger Current, circles the west side of Iceland. Meanwhile, a branch of the cold East Greenland current flows in a southerly direction through the Denmark Strait West of Iceland. The transition zone between these two currents is defined as the polar front and its position affects precipitation and temperature patterns on Iceland (Fig. 1.3) (Malmberg, 1985; Andrews et al., 2000).

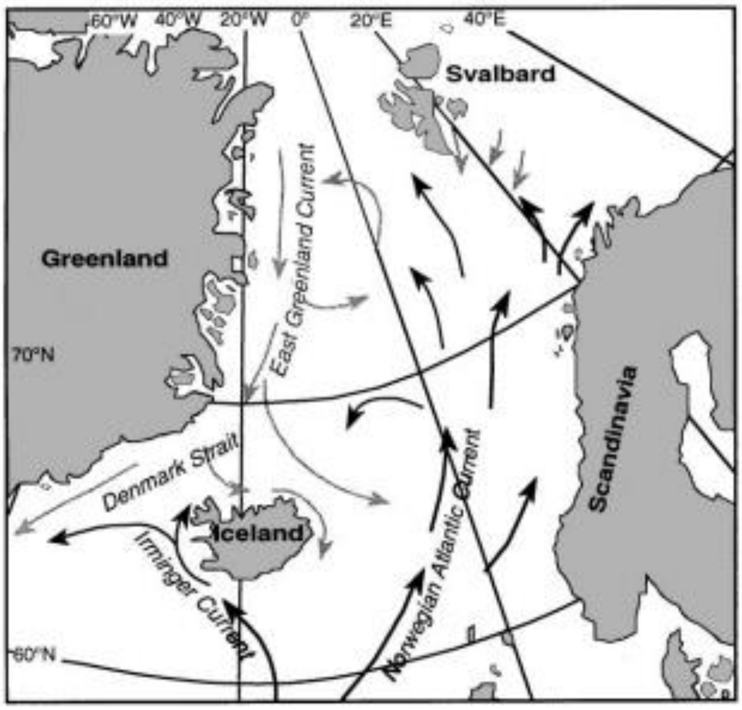


Fig. 1.3: Present day oceanographic setting in the north Atlantic region. Black and grey arrows marks warm and cold ocean currents, respectively (Andrews et al., 2000).

Hornstrandir lies within the low-Arctic zone, according to the mean air temperature in July and the temperature of the sea (Einarsson, 1984). At present, there are no manned meteorological stations located on Hornstrandir. The station at Hornbjargsviti (Fig. 1.1) in the East, have climate records from the period 1949 - 1994. The recorded annual mean temperature from the meteorological normal period 1961 - 1990 was 2.1 °C, while the recorded annual mean precipitation was 1373 mm (data collected 13.10.2014 from Vedur.is). The weather station at Bolungarvík that lies 25 km southwest of Hornstrandir, is the closest weather station that is still operating and has climate records from the periods 1949 - 1952 and 1995 - present. The mean annual temperature from 1995 – 2013 in Bolungarvík was 3,6 °C, while annual mean precipitation was 815 mm (data collected 13.10.2014 from Vedur.is) (Fig. 1.4). The mean wind direction on the peninsula is from the northwest (Einarsson, 1984). Permafrost occurs on the high plateaux, and Hjort et al. (1985) encountered frozen conditions at a depth of 15-30 cm below the surface at 450-500 m a.s.l. in July 1982.

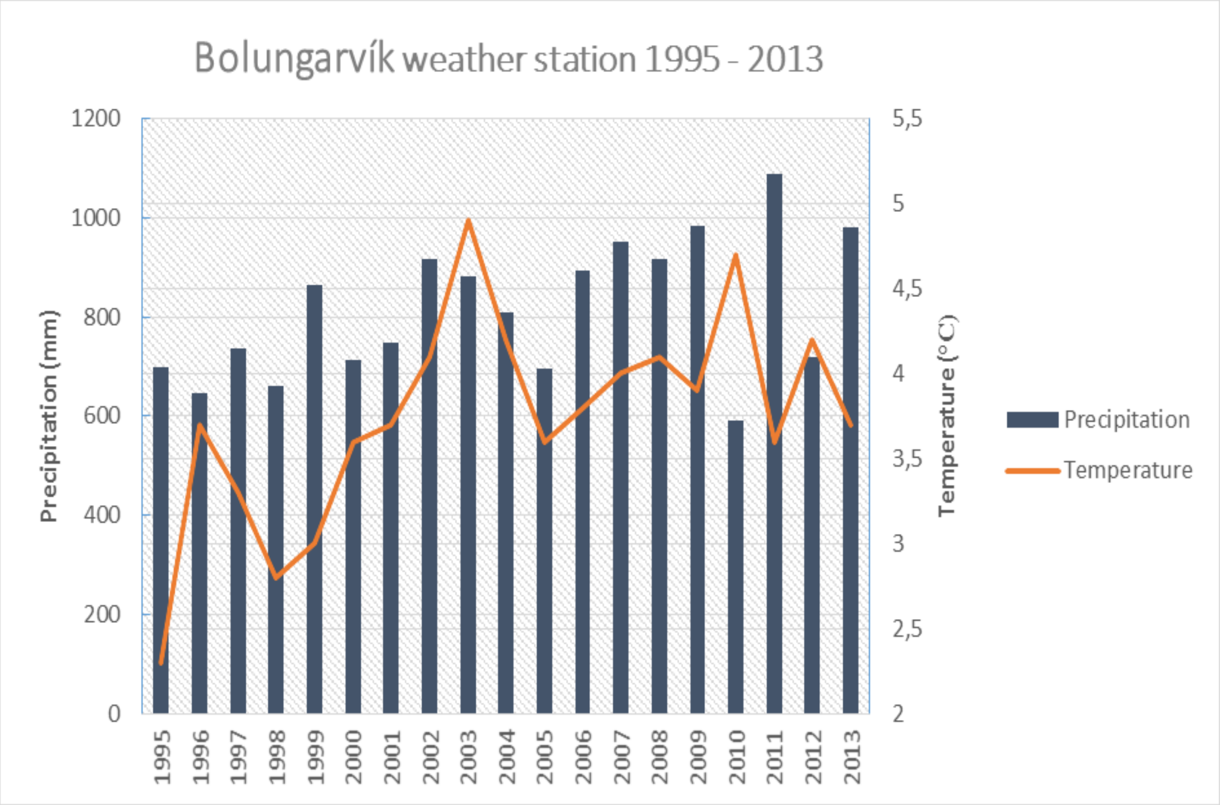


Fig. 1.4: Precipitation and temperature recorded at the Bolungarvík weather station. Data provided by vedur.is.

1.3 The Quaternary

On a million year timescale, Earth has switched between periods with extensive ice cover (icehouse conditions) and periods with little or no ice cover (greenhouse conditions) (Frakes et al., 2005). Currently the Earth is in an icehouse state, due to the large ice sheets in the polar regions. The start of this icehouse period began around 34 million years ago with the onset of a large Antarctic ice sheet (Barrett, 1996; Anderson et al., 2002). Glaciations in the northern hemisphere began around 3.2 Ma (Zachos et al., 2001), but it was at the start of the Quaternary period that the northern hemisphere underwent a cyclic growth of continental size ice sheets (Benn and Evans, 2010).

The Quaternary period covers the most recent 2.58 million years of Earth's history. It is subdivided in into the Pleistocene and Holocene epochs. The Pleistocene covers the years between 2.58 Myr - 11.7 kyr and is characterized by sequences of several glacials and interglacials (Imbrie et al., 1993). The Holocene is the current interglacial and covers the last 11,700 years (Cohen et al., 2013) (Fig. 1.5).

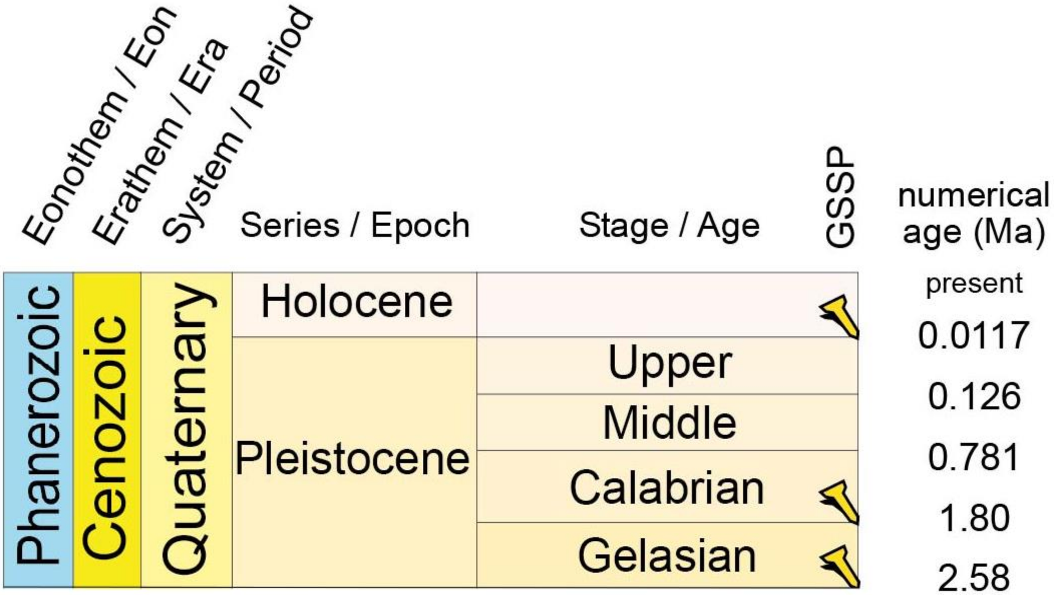


Fig. 1.5: Time scale of the Quaternary period (Cohen et al., 2013).

The sequence of glacial and interglacial periods is strongly linked to cyclical changes in the Earth's orbit round the sun. Three orbital cycles have been identified. The *eccentricity* refers to Earth's orbit around the sun. The orbit is becoming more or less elliptical on a cycle of about 100,000 years. The *obliquity* refers to the Earth's axis. It is relative to the orbital plane and fluctuates over a 41,000-year cycle. The direction of tilt of the Earth's axis is also relative to the distant stars and undergoes a 23,000-year cycle (*precession*). Taken together, these cycles cause variations in the amount of solar radiation which is received by the Earth. These mechanisms are the fundamental inputs to the Earth's climate system (Hays et al., 1976; Imbrie et al., 1993).

The global ice volume and timing from each glaciation has been calculated from oxygen isotope ratios in marine sediments. Each marine isotope stage (MIS) is numbered back in time, with cold periods (glacials) assigned even numbers and warm periods (interglacials) assigned with odd numbers. The Holocene is named MIS-1, the last glacial maximum (LGM) is called MIS-2 and so on (Fig. 1.6) (Bradley, 1999; Benn and Evans, 2010). The dominant glacial cycle since the glaciations began, has been a 40,000-year cycle which corresponds to the obliquity. This cycle switched around 800-900 kyr to a 100,000-year cycle, which is close to the eccentricity cycle. Many mechanisms have been proposed to account for this switch, but a satisfying answer is yet to be given (Shackleton, 2000).

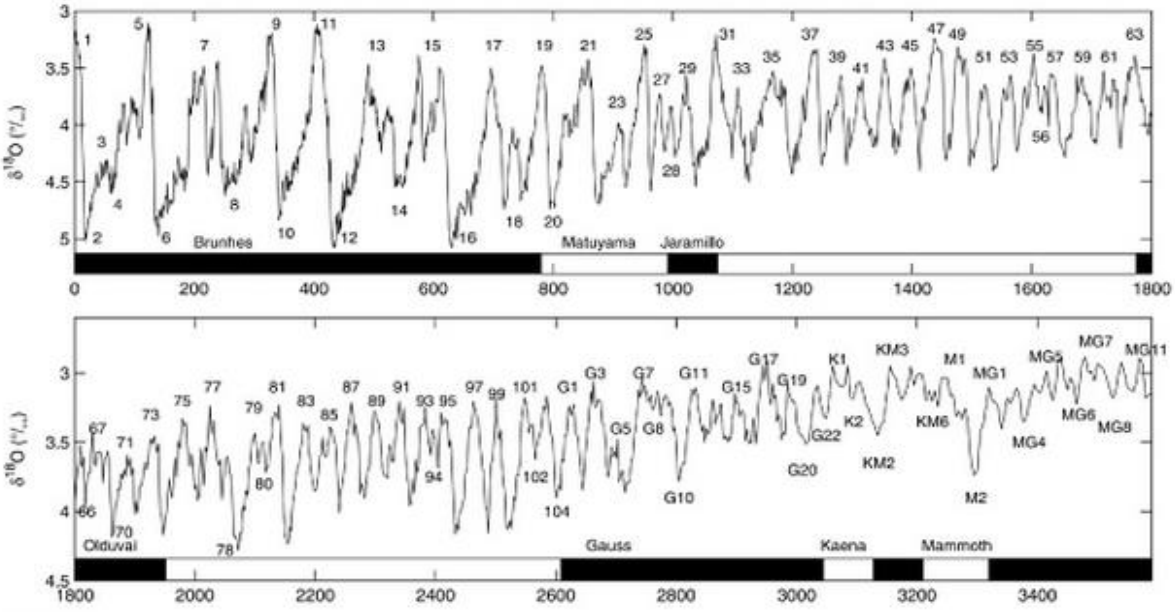


Fig. 1.6: Marine isotope records (Bradley, 1999).

1.4 The Quaternary geology of Iceland

Pliocene to Late Quaternary glaciations

Stratigraphic and sedimentological studies indicate that Iceland has experienced over 20 glaciations during the last 4-5 Myr (Aronson and Sæmundsson, 1975; Watkins and Walker, 1977; Geirsdóttir et al., 2006). Direct terrestrial evidence lacks for most Quaternary glaciations, but Iceland’s position on the Mid-Atlantic Ocean Ridge and on top of a hot spot, means that Weichselian strata in Iceland, not only are preserved in glaciogenic and non-glaciogenic sedimentary formations, but also in subaerial and subglacial bedrock formations. The glacial history of Iceland is therefore, obtained from data collected from sedimentary sequences on land, from offshore sediment cores, as well as from the lava-pile of Iceland (Norðdahl and Pétursson, 2005; Geirsdóttir et al., 2007). The number of glacial cycles that are recorded on Iceland, is also in reasonable agreement with the number of glaciations that are retrieved from the delta 18-O record from deep-sea sediments (Geirsdottir et al., 2009). Precise dating of each glacial cycle is difficult, but numerous K–Ar dates from lava flows provide a reliable overall time frame and allow correlation between glacial deposits in different parts in Iceland (Aronson and Saemundsson, 1975; Watkins and Walker, 1977).

Based on sporadic outcrops of glacial deposits within deeply eroded Pliocene rock sequences, it is believed the initial glaciation of Iceland occurred between 5 and 3 Ma (Geirsdóttir and Eiriksson, 1994; Helgason and Duncan, 2001). These glaciations however, are interpreted as representing local glacier activity rather than a regional ice-sheet glaciation, since none of these glacial deposits are traceable over long distances (Geirsdottir et al., 2009). The first progressively advancing ice sheet in Iceland dates back to ca. 2.9 Myr, but the associated deposits suggests that the glaciation was restricted to the highlands (Watkins and Walker, 1977). By 1.5 Myr approximately seven near full-scale glacial-interglacial cycles are found in Eastern Iceland. Glacial deposits are lying on striated lava flows but underlying fluvial and lacustrine sediments capped by younger lava flows (Geirsdóttir et al., 2007). The glacial stratigraphy of Iceland from 1.5 Myr to the last glaciation is fragmentary, apart from the Tjörnes section in Northern Iceland that contains nine stratigraphically separated glacial deposits. Studies from this section suggest an increase in the intensity of glaciation after 1 Myr when the 100 kyr ice-volume cycle developed (Geirsdóttir and Eiriksson, 1994).

The last glacial maximum (LGM)

Several different reconstructions of the Icelandic ice-sheet during the last glacial have been proposed. Theories range from extensive glaciation with no ice-free areas (Larusson, 1983; Buckland and Dugmore, 1991) to a refugia model with ice-free areas where vascular plants could survive glaciation (Hoppe, 1982; Einarsson and Albertsson, 1988; Ingólfsson, 1991).

During the LGM, ice streams and outlet glaciers from ice divides in central Iceland terminated at or close to the shelf edge (Spagnolo and Clark, 2009). The extent of the LGM ice sheet on Iceland is shown in Fig. 1.7a (Kaldal and Víkingsson, 1991; Principato et al., 2006). Evidence suggests that the Vestfirðir Peninsula in NW Iceland may have supported a dynamically independent ice cap with valley glaciers or ice streams originating within an ice-divide near the centre of the peninsula (Hoppe, 1982; Hjort et al., 1985; Andrews et al., 2002b; Principato et al., 2006; Principato and Johnson, 2009). It has also been hypothesized that small ice-free areas may have existed along the coastal mountains, particularly in the northwest, north and east (Ingolfsson, 1991; Andrews et al., 2000). Deglaciation of the LGM ice sheet began by 15 cal. kyr BP and was rapid but step-like. The first indication of regional advance or halt in deglaciation are found from late Allerød and early Younger Dryas time (Norðdahl and Pétursson, 2005). During the Younger Dryas (YD), the ice sheet extended across coastal sites that had been ice-free since the initial deglaciation (Fig. 1.7b). The recession of the YD ice sheet was stepwise and is reflected in series of terminal moraines in the highlands (Ingólfsson et al., 2010).

Holocene

The first glacier advance or still-stand of the Holocene time occurred in the early Preboreal around 9.8-9.6 kyr BP (Fig. 1.7c). The event is called the Buði stage (Hjartarson and Ingólfsson, 1988; Ingolfsson, 1991). This advance probably terminated around 7.8 kyr BP and the following glacier distribution is the one that is present on Iceland today (Kaldal and

Víkingsson, 1991). Data suggests an onset of glacier expansion (neoglaciation) around 5 kyr BP which can be roughly correlated between different parts of Iceland and coincides with wider environmental changes (Gudmundsson, 1997). Specific glacier advances have been dated to 5-4.5 kyr BP, ca. 4.2 kyr BP, ca. 3 kyr BP, 2 kyr BP and 1.5-1.2 kyr BP. During the LIA, glaciers in Iceland began to advance in the late 18th century and were at their maximum in the late 19th century (Gordon and Sharp, 1983; Ingólfsson et al., 2010).

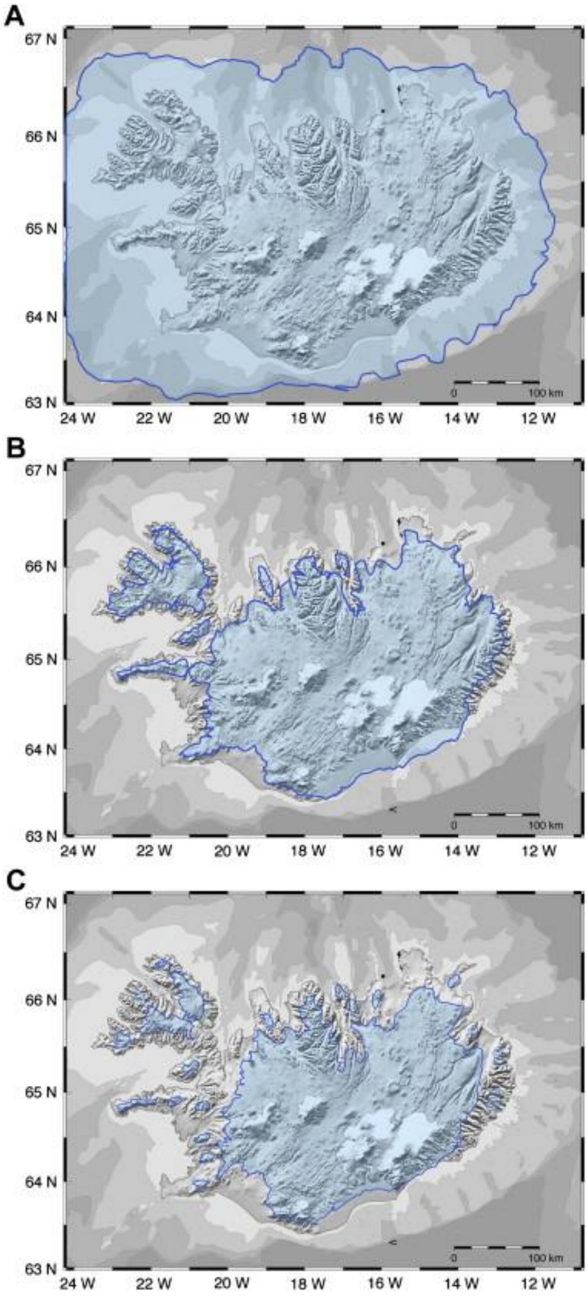


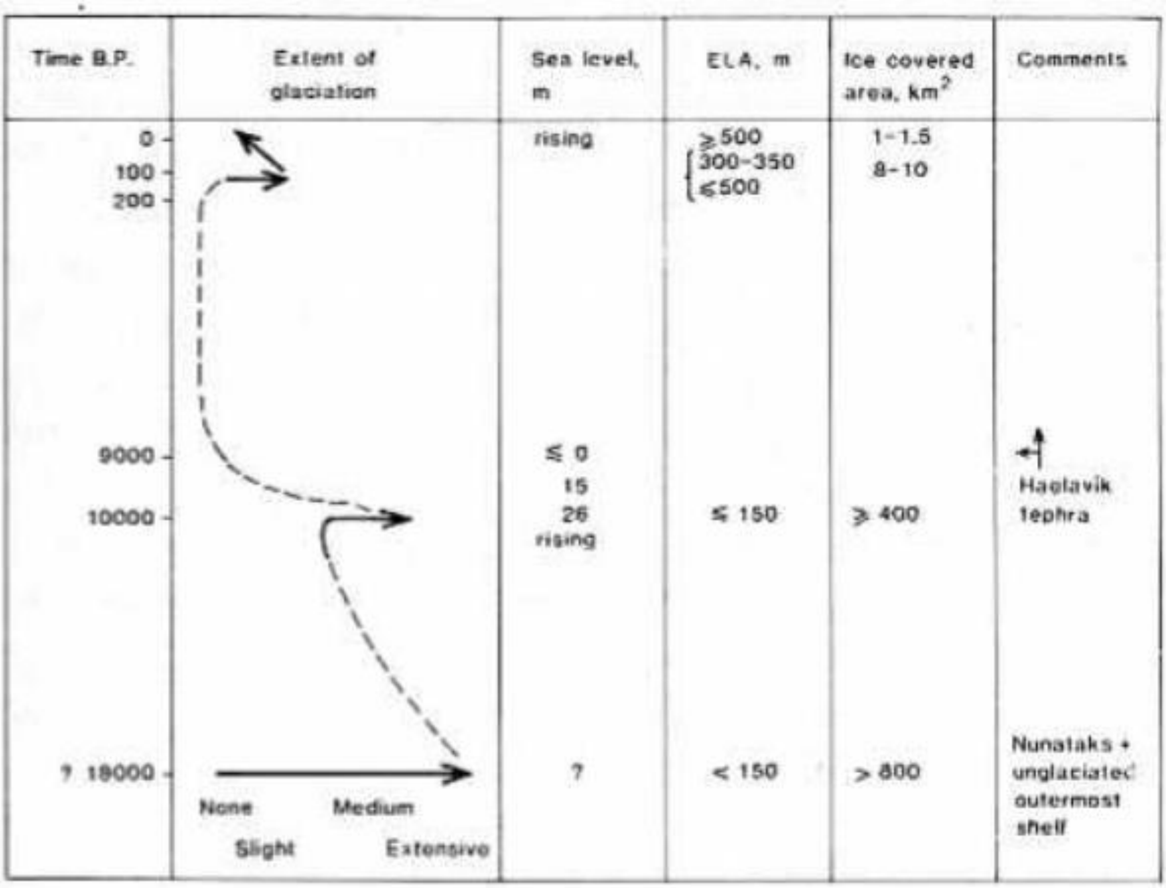
Fig. 1.7A: Inferred LGM **B:** YD **C:** Preboreal ice extent in Iceland (Geirsdottir et al., 2009).

1.5 Previous research at Hornstrandir and Vestfirðir

Little is known about the glacial history on Hornstrandir and the area is therefore of special interest because it is almost unstudied. A reconnaissance study was done in the early 1980's by Hjort et al. (1985), but since then little work have been done in the area. Before the Hjort et al. expeditions, only scattered references from Hornstrandir can be found in the literature.

The earliest studies from Hornstrandir were done in 1886 and 1887. The Icelandic geologist Thorvaldur Thoroddsen recognised that the whole landscape of the Vestfirðir peninsula was characterized by glacial erosion. He concluded that during the last glacial, the area had been covered by an extensive ice cap, which was independent from the main Icelandic ice-sheet. The ice cap however, could not have reached further than out to the valleys and fjords, due to the absence of submarine valleys on the shallow banks of the Hornstrandir coast (Thoroddsen, 1982a; 1982b). Thorarinsson (1937) later modified Thoroddsens view and suggested that during the last glacial, the whole Vestfirðir peninsula was characterised by small ice fields on the plateaux between the fjords, while the central area was covered by a large continuous ice cap. Outlet glaciers flowed from the central highlands through the fjords, gradually leaving more space for local glaciers and nunataks (Thorarinsson, 1937).

In the reconnaissance study done by Hjort et al. (1985), the authors studied coastal sections and air-photographs of the area, along with re-examination of available data in the geological literature. The authors recognised that the high plateaux showed no signs of having been covered by active glaciers. By using the plateaux surfaces as an upper limit for actively eroding glaciers, they concluded that during the maximum glaciation, glaciers in Hornstrandir could not have reached more than 6-10 km off the present coast. The logged coastal sections showed that during the last deglaciation in Hælavík and Aðalvík, there was an early retreat on to presently dry land, followed by a renewed glacial advance and then a final deglaciation. By that time the sea stood 26-27 m higher than today, before a regression to or below the present sea level. A summary of the study is shown in Fig. 1.8.



Time B.P.	Extent of glaciation	Sea level, m	ELA, m	Ice covered area, km^2	Comments
0		rising	≥500	1-1.5	
100			300-350	8-10	
200			≤500		
9000		≤ 0			
10000		15 26 rising	≤ 150	≥ 400	Haelavik tephra
? 18000		?	< 150	> 800	Nunataks + unglaciated outermost shelf
	None Medium Slight Extensive				

Fig. 1.8: Summary of the conclusions made by Hjort et al. (1985).

Unlike Hornstrandir, the Vestfirðir peninsula has been the subject to extensive research during the last decade. It has been proposed that Vestfirðir was covered by an independent ice sheet during the last glacial. The glacial history of Vestfirðir is therefore of interest when looking at the glaciation history at Hornstrandir.

Marine cores from Djúpáll have suggested that Vestfirðir was covered by ice during the LGM (Fig. 1.9a) (Andrews et al., 2000; Geirsdóttir et al., 2002; Andrews et al., 2002b). Cosmogenic surface exposure dating of boulders, has shown that the coastal uplands on eastern Vestfirðir were ice free by approximately 20 kyr, while deglaciation of the fjords and valleys occurred after the coastal uplands during the Bølling Interstadial and is dated to 14.6 cal. kyr BP (Fig. 1.9b) (Principato et al., 2006). This leaves the question whether ice-free area, such as nunataks, could have hosted refugia for vascular plants surviving glaciation. Coastal mountain areas, such as Vestfirðir and Hornstrandir have been considered likely candidates (Hoppe, 1982; Hjort et al., 1985; Einarsson and Albertsson, 1988; Ingolfsson, 1991; Rundgren and Ingólfsson, 1999). Other theories suggest a more extensive ice cover model with no ice-free areas, where colonization occurred during the earliest Holocene on ice rafts and in flood debris, from a rapidly decaying Scandinavian ice sheet (Buckland and Dugmore, 1991).

It is also commonly assumed that two independent ice sheets were present on Iceland during the LGM, with one covering Vestfirðir and the other covering mainland Iceland. This hypothesis is based on several observations on Vestfirðir such as raised marine beaches, glacial erosion patterns and geomorphological features (Hansom and Briggs, 1991; Principato et al., 2006; Principato and Johnson, 2009). Hjort et al. 1985 argued for a restricted LGM ice sheet over Vestfirðir, with an ice margin terminating ca 6 km off the northern Hornstrandir coastline. Alternative hypotheses suggest that the mainland and Vestfirðir ice sheets coalesced into one single ice sheet, which encompassed the whole of Iceland (Andrews et al., 2000; Andrews et al., 2002b; Andrews and Helgadottir, 2003). On Vestfirðir, substantial ice streams are thought to have flowed north and south from Gláma and west from Drangajökull through Ísafjarðardjup (Ingólfsson and Norddahl, 2001; Roberts et al., 2007) (Fig. 1.9a).

Exact reconstructions of the Younger Dryas ice sheet configuration on Vestfirðir have been difficult to make. However, studies based on surface exposure dating and marine cores have suggested a configuration as shown in Fig. 1.9c. The outermost moraine in Kaldalón has been dated to 11.7 kyr BP and the formation of the moraine corresponds to a stillstand or readvance during the Younger Dryas (Principato et al., 2006). The occurrence of the Vedde ash has proven as excellent marker for the Younger Dryas and is dated to 12 cal. kyr BP (Grönvold et al., 1995). Although the Vedde ash is abundant in marine cores, it is yet to be found in terrestrial sites on Vestfirðir, which leads to the conclusion that a large portion of eastern Vestfirðir was ice-covered during the Younger Dryas (Principato et al., 2006).

The Preboreal ice margin is constrained by the presence of the Saksunarvatn Ash and is dated to 10.2 kyr BP (Grönvold et al., 1995). The Saksunarvatn ash provides an important link between marine and terrestrial records, because it is present in both environments. Its presence supports deglaciation on most of eastern Vestfirðir by Preboreal time (Fig. 1.9d) (Andrews et al., 2002b).

At most localities in Iceland, LIA advances were the most extensive during the Holocene (Ingolfssón et al., 2010). At Hornstrandir, Hjort et al. (1985) recorded that 7-10 cirques in Hlöðuvík, Hælavík and Hornvík showed clear signs of having been glaciated recently. Glaciers in Hlöðuvík and Hælavík reached 150 m below the altitude of their floors, while glaciers in Hornvík reached 50 m below the cirque floor. They also estimated that the total glaciated area on northern and western Hornstrandir during the Little Ice Age was 8-10 km^2. Lichenometric studies showed that the maximum LIA extent was reached around AD 1860 (Hjort et al., 1985).

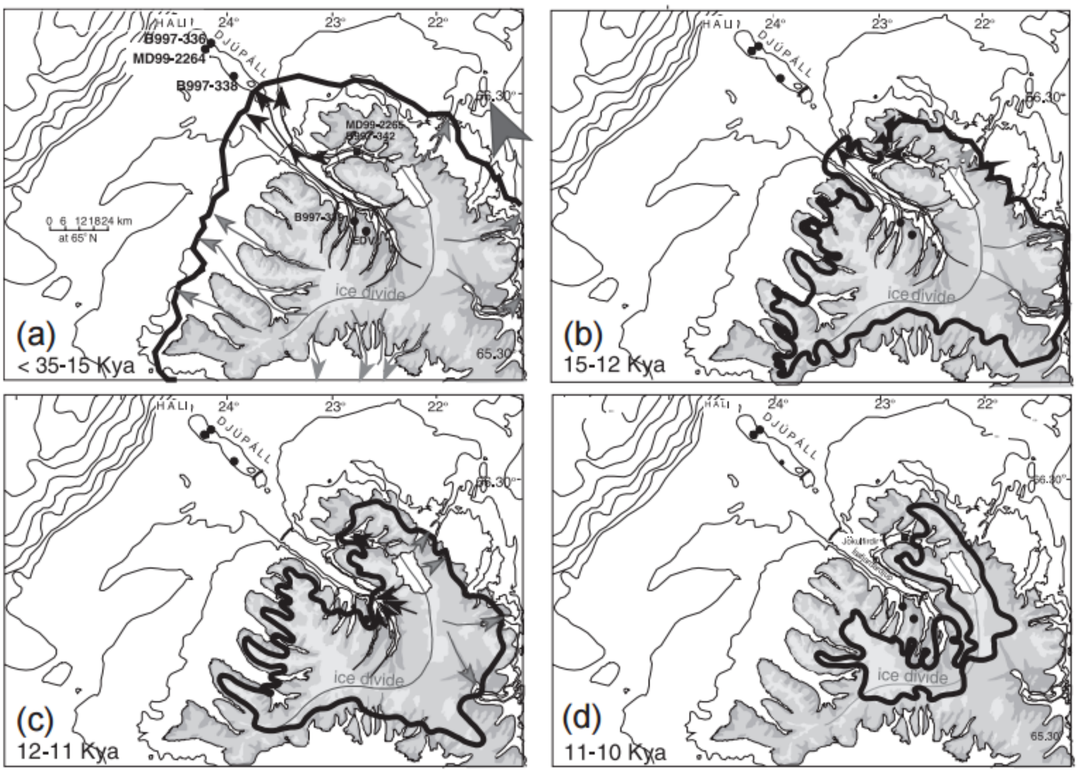


Fig. 1.9: A **s**eries of maps that presents possible ice sheet configurations on Vestfirðir during **A:** Last Glacial Maximim, **B:** Bølling Interstadial, **C:** Younger Dryas, **D:** Preboreal (Geirsdóttir et al., 2002).

2. Methods

2.1 Fieldwork

During two weeks in July 2014, fieldwork was carried out at Hornstrandir. Valleys, mountain plateaux, cirques and coastal lowlands were manually surveyed. Landforms and sediments were described, interpreted and classified according to genesis. The locations of landforms, sediments and coastal sections were recorded with a Garmin GPSMAP 62sc, with a horizontal accuracy of c. ±3 m. Seven coastal sections were described and logged. At various sites, tephra samples and organic material for radiocarbon dating were taken, for further analysis. For logging coastal sections, a folding ruler and measuring tape were used to measure heights. Shovels and scrapers were used to clean the sections. On the plateaux were rock samples of bedrock and erratic boulders taken for cosmogenic surface exposure dating.

2.2 Geomorphological mapping

The Geographical Information System (GIS), ESRI ArcMap 10.2, was used to manually digitize all the landforms and features that were examined in the field. Due to limitations in fieldwork time, the whole study area could not be surveyed manually. Coastal sections and valleys in Hlöðuvík, Hælavík and Kjaransvík have been surveyed in detail. The rest of the Hornstrandir has been mapped by visual interpretation of orthorectified aerial photographs in ArcMap 10.2. The aerial photographs have been provided by The Icelandic Institute of Natural History and have a 0.5-m size and date from 2005 and 2006. A Digital Elevation Model (DEM) with 20 m ground resolution from 2011 has also been used. The ISN93/WGS84 has been used as a reference system. *Terminal and lateral moraines, flutes, raised beaches, hummocky moraines, rivers* and *lakes* were mapped. Polygons have been drawn to represent different sediments and surfaces, while polylines have been used to represent streamlined features such as e.g. rivers and flutings. Other morphological features such as landslides, debris flows, solifluctation patterns and vegetation cover were not mapped.

2.3 Coastal section logging

Coastal sections were logged at seven different locations in Hornstrandir (Fig. 3.12).

Valuable information on Quaternary environments can be gained by studying glacial sediments. Sediment descriptions are used to make interpretations about the depositional environment based on sediment properties such as lithology, texture, bedding, sedimentary structures and palaeo-current data. The distinctive properties of many glacial sediments allow interferences to be made about former glacier types, the mode of sediment deposition, ice-flow directions and the sources of sediment supply. Sedimentary sequences also reflect sediment accumulation over time and therefore environmental change can be obtained with both temporal and spatial aspects. Fossils can also occur abundantly in Quaternary strata and these fossils makes for excellent climatic proxies (Lowe and Walker, 1997).

Quaternary sediments are usually unconsolidated and are divided in two main groups: inorganic (clastic) deposits and biogenic sediments. The clastic sediments consist of mineral particles ranging in size from very fine clays to large boulders. Biogenic sediments consists of remains of plants and animals (Hubbard and Glasser, 2005).

Graphic data charts for the presentation of glacial stratigraphy are widely used in the literature and many forms of data charts have been developed. For this project the data chart presented by Krueger and Kjaer (1999) has been used. The legend used for the sedimentological logs is shown in figure 3.13.

2.4 Tephrochronology

Tephra samples were taken from coastal sections in Kjaransvík and Hælavík. The samples were later made into polished thin sections at NTNU. The geochemistry of the tephra samples was analysed at the University of Copenhagen, Denmark. A JEOL Super probe JSL 8200 with an acceleration voltage of 15 kV, a 10-nA beam current and a beam diameter of 7µm were used. In addition to natural and synthetic minerals, glass standards (K22_ ATHO and K15_KL2) were used as standards.

Many of the volcanic systems in Iceland have chemical characteristics (fingerprints) that allow their products to be distinguished from other volcanic systems. By analysing the tephra samples, it is therefore possible to pinpoint the exact volcanic system responsible for the tephra (Larsen and Eiriksson, 2008).

During a volcanic eruption, large amounts of ash are ejected into the atmosphere. These materials are often spread over large areas downwind of the volcanic source. The tephra will rapidly accumulate and form a thin ash cover in places like lakes, on peat surfaces, on river terraces, on the sea bed and in glacier ice. Acid ash beds often stand out as distinctive light-coloured horizons in sedimentary sequences, while basaltic tephra are black or dark-coloured. They are usually found in sediment cores or in coastal sections (Einarsson and Douglas, 1994). On the geological timescale, volcanic eruptions is essentially an instantaneous event and the tephra layers provide distinctive and often widespread isochronous marker horizons. These horizons offer a valuable basis for inter-site correlation (Walker, 2005). The age of the tephra can be dated by radiocarbon dating of organic material associated with the ash layer, or by K-Ar dating, fission track, luminescence or ESR dating of the tephra itself (Lowe and Walker 1997).

2.5 Radiocarbon dating

Organic material was sampled from driftwood, found in coastal sections in Kjaransvík and Hælavík. The samples were dried and submitted for radiocarbon dating at the Ångström Laboratory, Uppsala University. The ^{14}C ages of the driftwood samples were calibrated with IntCal09 according to Reimer et al. (2013).

Radiocarbon dating gives an absolute age of organic material by using the radioactive isotope ^{14}C. Organic material is usually abundant in lacustrine, marine, glacial and soil sections and this makes radiocarbon dating an excellent tool for dating Quaternary stratigraphy. Although the method only spans over a small portion of the Quaternary, it is one of the most widely used dating techniques. ^{12}C, ^{13}C and ^{14}C is the three forms of carbon, where ^{12}C and ^{13}C are stable isotopes and ^{14}C is unstable. ^{12}C is by far the most abundant and comprises around 98.9% of all naturally occurring carbon. ^{13}C forms around 1.1% and ^{14}C forms about 1000 ppm. All living organisms absorb carbon through photosynthesis or breathing and the ratio of the different carbon isotopes in living organisms and the atmosphere is always the same. In other words, levels of ^{14}C in living plants and animals are the same as in the atmosphere.

However, when an organism dies, it gets isolated from its ^{14}C source. Since ^{14}C is a radioactive isotope it will decay to ^{14}N and the amount of ^{14}C will decrease over time. The decay rate is known. By measuring the amount of ^{14}C in dead organisms, it is therefore possible to calculate the age to the organism. The half-life of a ^{14}C atom is 5730 years. This means that the dating method spans approximately over the last 45,000 years (Libby, 1955; Lowe and Walker, 1997; Walker, 2005). Two approaches are used to measure the amount of ^{14}C in a sample; *conventional radiocarbon dating* and *accelerator mass spectrometry (AMS)*. The conventional method counts beta particle emissions from ^{14}C atoms over a period of time in order to determine the rate of emissions and hence the activity of the sample. AMS counts the actual number of ^{14}C atoms in a sample of material (Bowman, 1990). The samples from Hornstrandir were analysed by AMS.

2.6 Cosmogenic exposure dating (^{36}Cl)

Three rock samples from erratic boulders were taken on the plateaux on Hornstrandir, for cosmogenic exposure dating purposes (Fig 3.23). The samples were prepared and dated at the PRIME-Lab, Purude University in USA.

In Quaternary science, cosmogenic exposure dating has been used to determine exposure ages of rock surfaces. The Earth’s surface is constantly bombarded by cosmic rays (high-energy charged particles). When these particles collides with atoms within a rock mineral, they can dislodge protons from the atom, thus creating an isotope or a different element. These dislodged isotopes are absorbed within the mineral and the concentration of the accumulated isotopes are directly related to the time the rock sample has been exposed for cosmic rays (Walker, 2005). For the rock samples from Hornstrandir are Chlorine-36 (^{36}Cl) nuclides used to date the surface exposure age.

A number of assumptions underlie cosmogenic exposure dating. Firstly, it is assumed that the rock sample being dated doesn’t contain any cosmogenic isotopes from previous exposure. Second, it is assumed that the surface has not been eroded significantly since the time of initial exposure. Carefully field sampling can to some extent sort this, but it remains a source of uncertainty. Shielding from cosmic radiation, by either snow, soils or sediments can also underestimate the exposure age of a sample. All of these assumptions generate uncertainties in the cosmogenic exposure ages. At present, the uncertainties are in the range of 10 – 20%. However, improved understanding of the factors contributing to cosmogenic nuclide production rates mean that the total uncertainty in exposure ages is continually improving (Gosse and Phillips, 2001).

3. Results

3.1 Mapped landforms

Several glacial and periglacial landforms have been mapped in the Hornstrandir area, by field observations and extensive interpretation of orthorectified aerial photos. Figure 3.1 provides an overview of the different locations that have been mapped. Figs 3.2, 3.3, 3.4 and 3.5 presents the distribution of the landforms that are mapped in Hornstrandir. Firstly, the different glacial and periglacial landforms that have been mapped are presented and examples are given from Hornstrandir. Then the geomorphology in Hlöðuvík, Kjaransvík and Hælavík are described. Separate maps have been made from these locations (Figs 3.6, 3.7 and 3.8).

Moraines:

Ice-marginal moraines are ridges formed by the deposition or deformation of sediments at the margin of an advancing or stationary glacier. The outermost moraine, which marks the limit of a glacier advance, is known as a terminal moraine. Younger moraines formed within a terminal moraine, which are formed by minor readvances or stillstands, during an overall glacier recession are called recessional moraines. Terminal and recessional moraines may be subdivided into frontal and lateral components (Benn and Evans, 2010).

The moraines at Hornstrandir have been mapped in two different colour classes. *LIA moraines* (brown colour) are moraines which are interpreted to have been formed from the LIA until present. The LIA moraines appear as curved ridges in front of cirque glaciers or recently glaciated cirques. They are less vegetated than older ones and they generally look more fresh. The outermost LIA moraines indicate the maximum extent of the glaciers during Little Ice Age. The zones within the moraines are interpreted as the LIA subglacial surface. This surface consists of basal till with little or no vegetation, and is sometime fluted. Most LIA moraines are found at an elevation between 300 – 400 m a.s.l. LIA moraines in Hlöðuvík are situated at a height of 280 – 300 m. Figure 3.9B presents a reconstruction of the glacier extent on Hornstrandir during the LIA. The extent of LIA glaciers have been drawn to the outermost LIA moraines. In glaciated cirques without any moraines, only the present glacier ice is mapped. It has been estimated that 21 cirques were glaciated during the LIA. Together, the total glaciated area during the LIA has been calculated to 8.2 km^2. Hjort et al. (1985) calculated the total LIA glacier extent to be 8 – 10 km^2, which fits well the estimate from the present study.

Moraines that are interpreted older than the LIA are mapped as *Old moraines* (black colour). The moraines in Hornstrandir mainly occur as end moraines in front of cirques. Their length ranges from 30 – 500 m. They look more weathered than LIA moraines, are wider and have more rounded shapes (Fig. 3.11A). The outermost *Old moraines* in several valleys have been used to create a map, estimating the glaciated area on Hornstrandir at some point during deglaciation of the Vestfirðir ice sheet (Fig. 3.9A). The total glaciated area, indicated from the *Old moraines* have been estimated to 44 km^2. The age of these moraines are discussed in chapter 4.

Presently are fourteen of the cirques still containing small cirque glaciers or remnants of ice. Most of the moraines are situated in front of cirques that face in a W-SW direction. These cirques face the lee side of the main wind direction (The main wind direction is E, NE according to Einarsson, 1976) and are therefore more likely to accumulate enough snow to create cirque glaciers. The most distinctive sets of both LIA moraines and Old moraines are found up in the valley in Fljótavík (Fig. 3.10A).

Hummocky moraines:

Hummocky moraines refer to a moundy and irregular topography. The term has been used in a wide range of senses and the origin is still debated. Most authors however, refer to hummocky moraines as moraines that have been deposited during melt-out of debris mantled glaciers (Benn and Evans, 2010).

Hummocky moraines have been remotely mapped at several locations in Hornstrandir, for example in Hesteyrardalur and at Vestur Aðalvík (Fig. 3.4). Hummocky moraines were also observed and mapped in Hlöðuvík (Fig. 3.10D) and Hælavík during the fieldwork. The hummocky moraines consist of mature and well vegetated diamicts.

Flutes:

Flutes are streamlined ridges of sediment aligned parallel to former glacier flow. Flutes are formed during movement of a glacier where weak, saturated sediments are squeezed under pressure into small lee-side cavities behind obstructions on the bed (Benn and Evans, 2010). The height and width vary from a few tens of centimetres to a few meters. They usually occur in clusters and commonly begin on the lee side of lodged boulders, continuing down-glacier as narrow ridge for distance of few to several hundred meters, although this is not always the case. Due to low preservation potential, flutes are most common on modern glacier forelands, rather than in older terrain (Gordon et al., 1992; Benn and Evans, 2010).

Flutes are only found at two localities in Hornstrandir. One set of flutes is situated in front of the glacier in cirque 3 in Hlöðuvík (Fig. 3.10B). The flutes are usually about 20-100 m long, constituting of coarse grained diamicts. The second set of flutes was remotely observed and is located in front of the glacier in Blöndudalir (Fig. 3.5). All flutes are mapped within the LIA moraines.

Assorted periglacial landforms on the plateaux:

Up on the high plateaux around Hlöðuvík, Kjaransvík and Hælavík, several periglacial features were examined in the field. This includes features such as blockfields, polygons, sorted stripes, tors and weathered bedrock. The blockfields consist of considerably weathered sub-angular to angular blocks. Diamicts were observed at a few locations (Fig. 3.10E). However, it was difficult to make a certain classification of its origin, whether it was locally weathered bedrock or glacial deposits. Polygons are also present on the plateaux. They consist of medium to coarse grained sediments and are usually between 1 – 3 m in diameter. All in all is there little evidence of any recent cover of actively eroding glaciers on the high plateaux.

However, glacially transported erratic boulders are scattered on the plateaux, suggesting that the plateaux have been covered by ice at some point.

Rock glacier:

Rock glaciers are located at the foot of free rock faces and take the form of 20-100 m thick tongue- or lobe-shaped bodies covered by coarse debris. Rock glaciers flow at a rate of 0.1-1 m a year, making them considerably slower than normal glaciers (Humlum, 1996). The origin of rock glaciers is unclear, and a few different types of rock glaciers have been suggested. Some authors suggests a non-glacial (periglacial) origin (e.g. Wahrhaftig and Cox, 1959; Barsch, 1992), others have argued that rock glaciers are glacier derived (e.g. Potter, 1972; Humlum, 1988). Others suggests a landslide origin for some rock glaciers (e.g. Johnson, 1984; Humlum et al., 2007).

A landform located at the head of Mannadalur is interpreted to be a rock glacier (Fig. 3.10F). The interpretation is purely based on the interpretation of aerial photographs, since the area could not be surveyed manually during fieldwork. The formation is a lobe shaped tongue with very little or no vegetation. The structure and geomorphology closely resemble rock glaciers as they are described by Humlum (1996). Whether this is, an active or relict rock glacier is not known. However, in a study of rock glaciers in the Tröllskagi peninsula, N-Iceland, Farbrot et al. (2007) mapped active rock glaciers with terminus down to an elevation of 800 – 900 m a.s.l. The proposed rock glacier in Mannadalur has a terminus at 150 m a.s.l. suggesting that the rock glacier is no longer active.

Raised beaches

Raised beach ridges may serve as indicators of past sea level and shoreline positions (Otvos, 2000). Raised beaches are present at several locations in the valley lowlands and coastal plains at Hornstrandir. Distinct sets of raised beaches are mapped in Fljótavík and Hornvík. These sets of raised beaches are based on visual interpretation from aerial photographs, where they occur as straight or curved ridges (Fig. 3.10C). It is common that the ridges dam up lakes or redirect rivers. At Hlöðuvík, a distinct beach ridge is present. It is located about 2 m over the present storm beach (Fig. 3.11B).

Lakes

Apart from Fljótsvatn, Staðarvatn and Rekavíkvatn, there are no major lakes situated at Hornstrandir. Small lakes are spread out evenly throughout the area. Most lakes are situated in the valley lowlands, while very few lakes occur up on the plateaux. The lakes seem to occupy structural depressions in the bedrock rather than being formed as moraine-dammed lakes. Exceptions are however found in Hælavík where a set of moraines has dammed up several small lakes. Small dams and lakes have also been created in the hummocky moraines that are observed at different locations. Fljótsvatn, the biggest lake in Hornstrandir, has a total area of 4.6 km^2 and receives its water from nine cirques surrounding the lake. None of these cirques are presently containing glaciers.

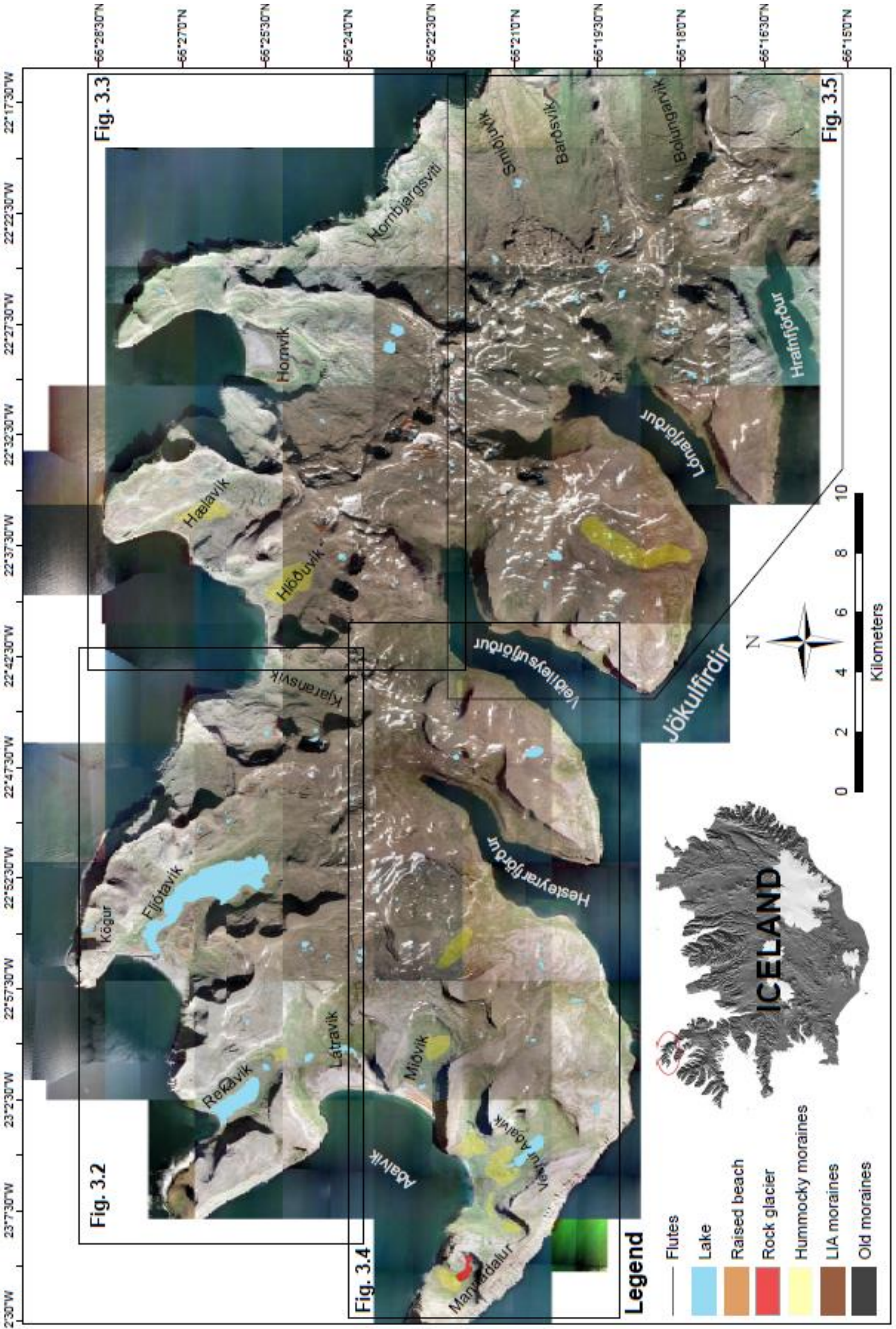


Fig. 3.1: An overview map of the geomorphology at Hornstrandir. See Figs 3.2, 3.3, 3.4 and 3.5 for more detailed maps. See digital supplementary data for full version of the map.

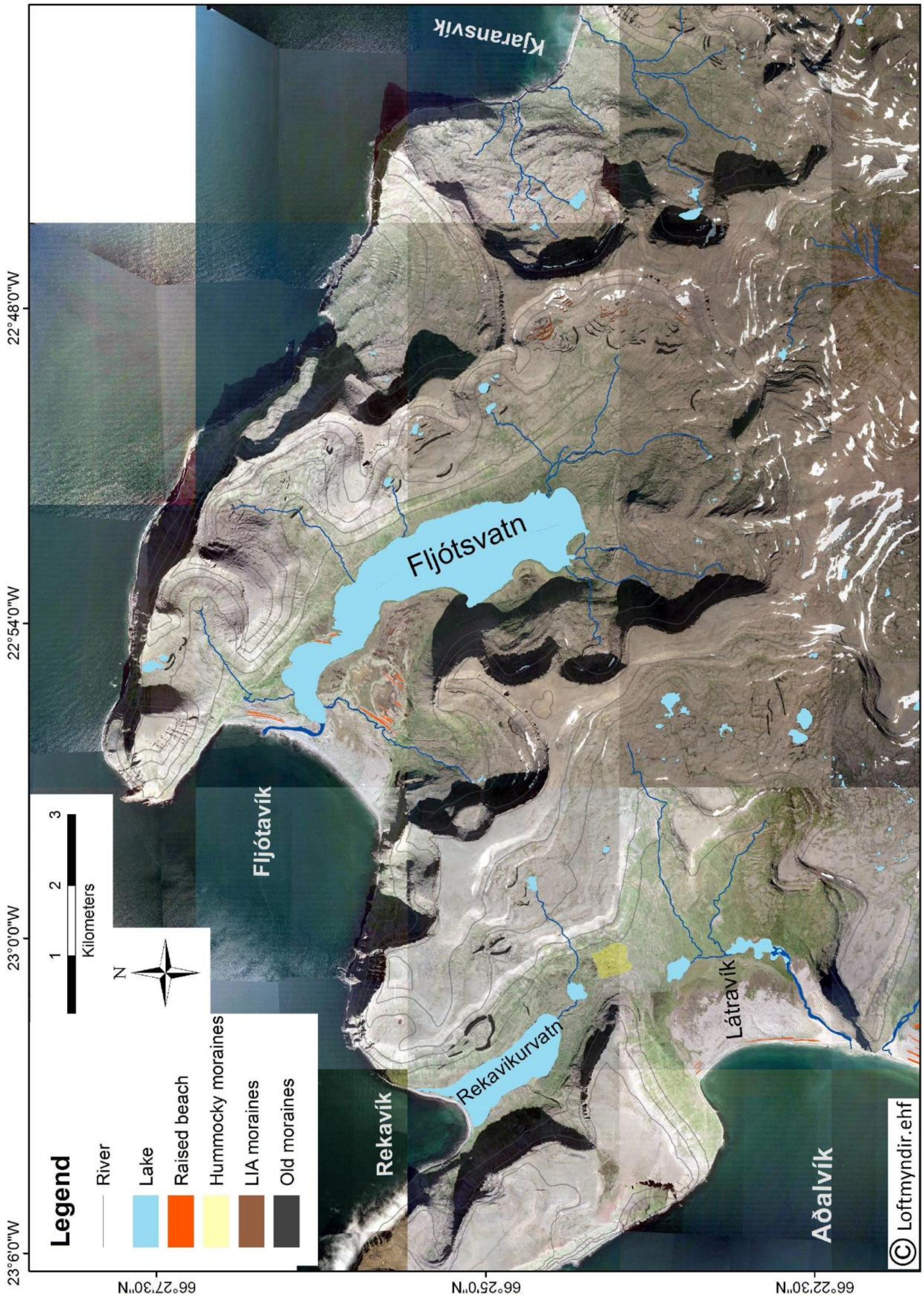


Fig. 3.2: An overview map of the geomorphology at the north-western part of Hornstrandir.

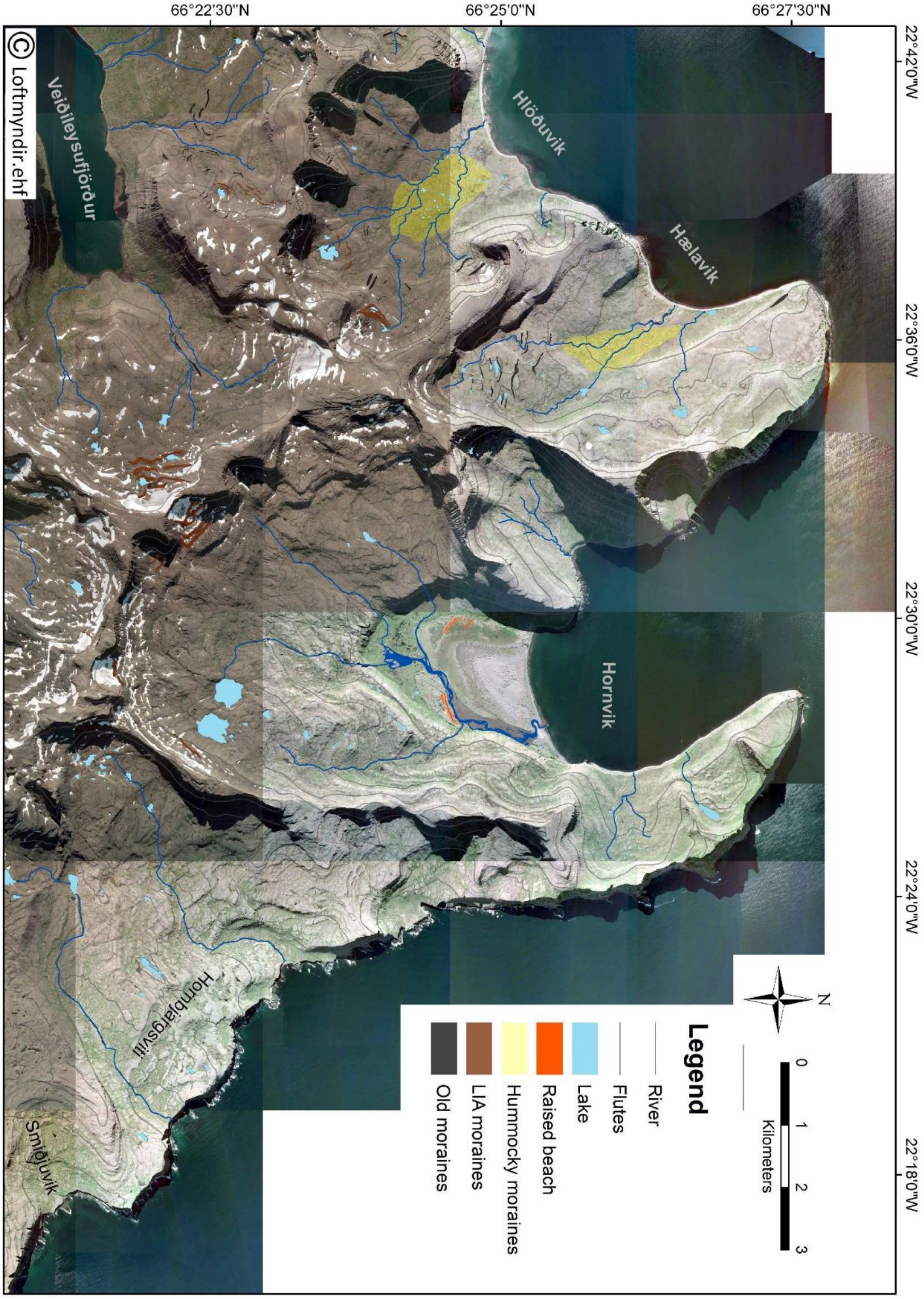


Fig. 3.3: An overview map of the geomorphology at the north-eastern part of Hornstrandir.

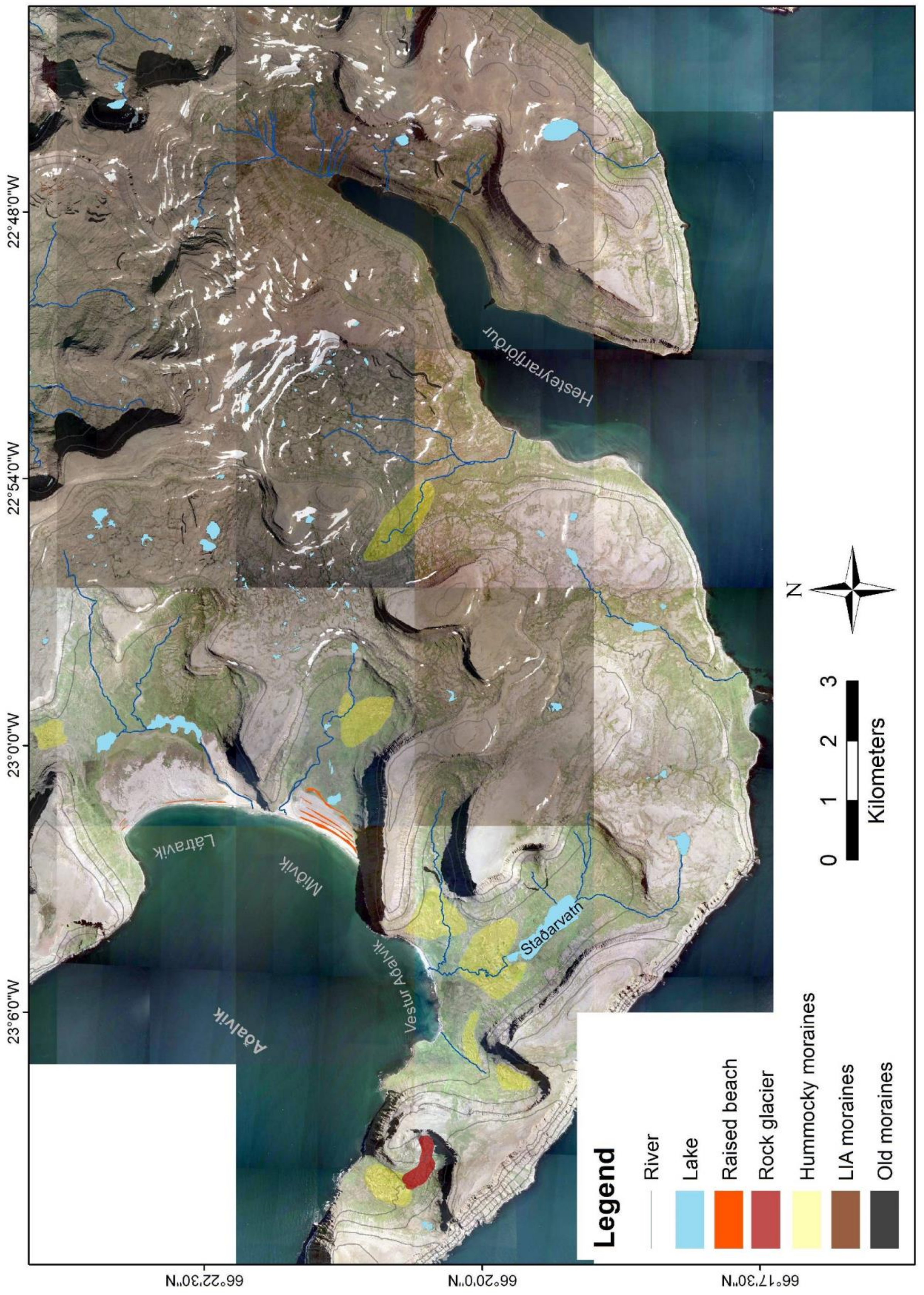


Fig. 3.4: An overview map of the geomorphology at the south-western part of Hornstrandir.

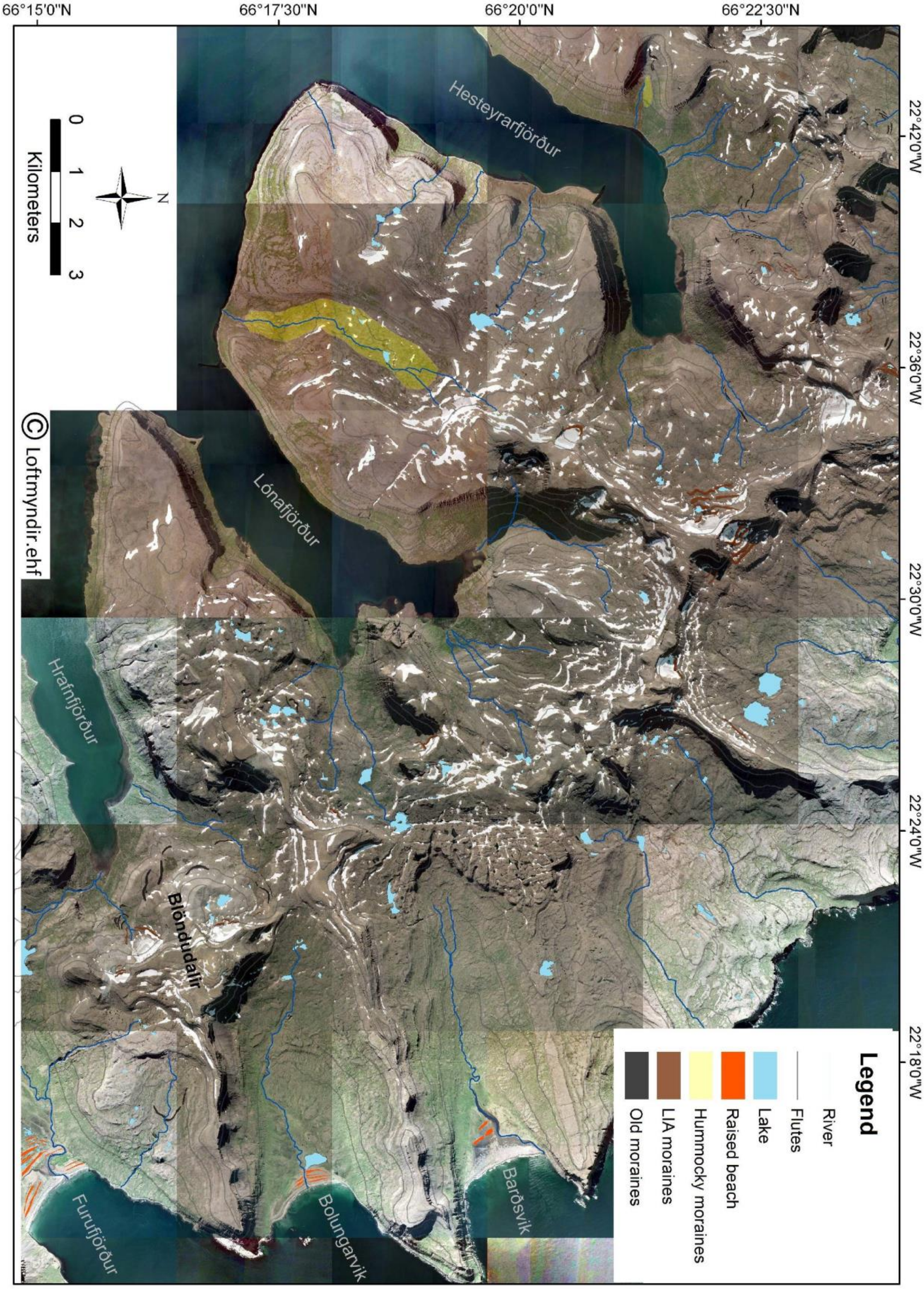


Fig. 3.5: An overview map of the geomorphology at the south-eastern part of Hornstrandir.

3.2 Hlöðuvík

A detailed map of the glacial geomorphology in Hlöðuvík is presented in Fig. 3.6.

The coastal section in Hlöðuvík is about 3 km long. The valley inside Hlöðuvík is about 2 km wide and 4 km long. The valley lowlands are characterized by well vegetated hummocky moraines. Several small lakes occur in the irregular terrain. Six main rivers drain the cirques at the head of the valley and they eventually merge into one near the coast. Snow melt is the main water source for these rivers.

Only one cirque, Cirque 3, out of the seven cirques in Hlöðuvík contains glacier ice. However, five of the cirques in Hlöðuvík are fronted by small moraines, suggesting that at least these cirques were glaciated at some time. Moraines in front of cirques 1, 2 and 6 are mapped as *Old moraines*. These moraines are fairly weathered and surrounded by a mature vegetation cover. Moraines in cirque 3 and 4 are mapped as LIA moraines. These moraines occur as a complex of several well developed ridges, consisting of gravelly and boulder-rich diamicts. The moraines are sparsely vegetated and look fresher than the other moraines. The moraine complex in cirque 3 is approximately 500 m long and 150 wide. Due to snow cover, the height of the moraines was impossible to measure. The surface within the recent moraines looks much fresher than the surface outside them. A fluted surface is mapped within the LIA terminal moraines in cirque 3. Due to snow cover during the fieldwork the flutes were impossible to observe in the field. The flutes are however very distinct on the aerial photographs (Fig. 3.10B). The flutes vary in length between 20-80 meters. Three medial moraines are mapped in Hlöðuvík. Two are situated between cirques 3 and 4, while one is located between cirques 6 and 7.

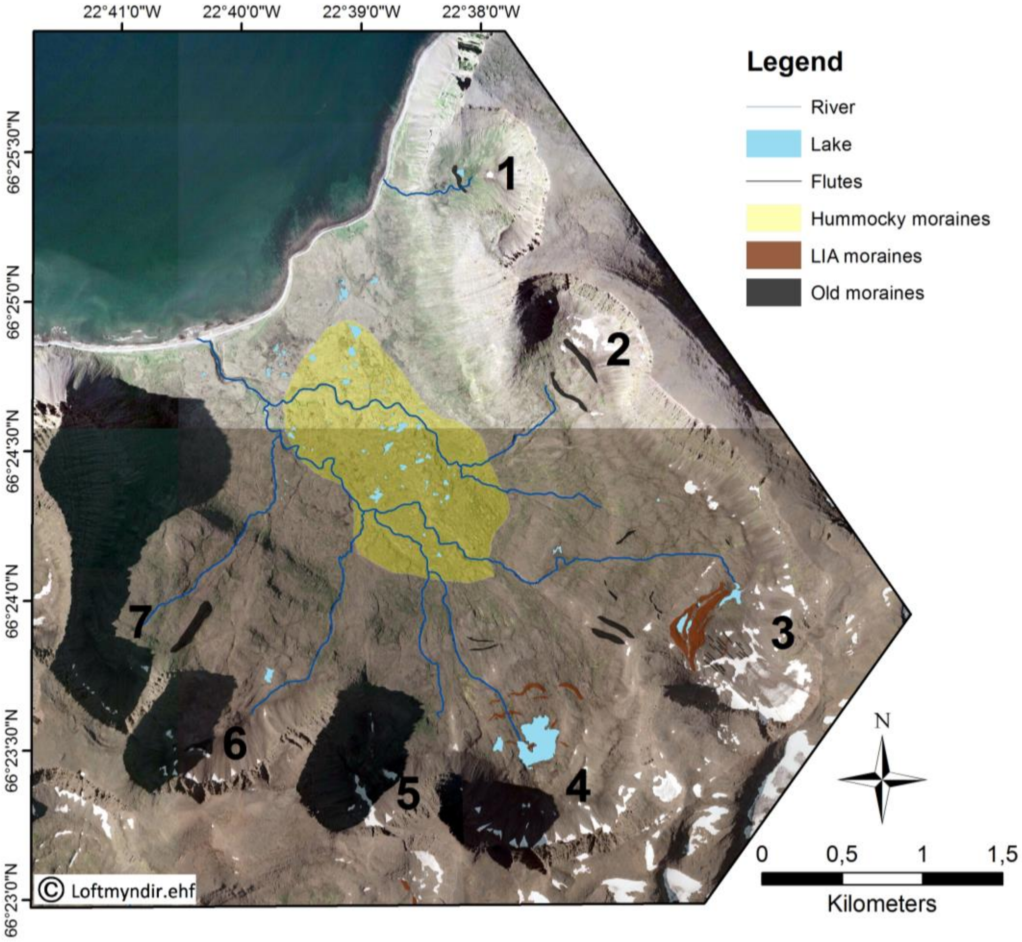


Fig. 3.6: A glacial geomorphology map of Hlöðuvík.

3.3 Kjaransvík

A detailed map of the glacial geomorphology in Kjaransvík is presented in figure 3.7.

The coast along Kjaransvík is about 2 km long. The valley inside is approximately 4 km long and 4 km wide. Five cirques are situated in Kjaransvík. Cirque 1 are facing W, cirque 2 are facing NW, cirque 3 are facing N, while cirque 4 and 5 are facing NE. None of the cirques host glacier ice at present. Two of the cirques in Kjaransvík have moraines in front of them. All of these moraines are interpreted as *Old moraines*. They have a good amount of vegetation cover and look considerably older and more weathered than the recently formed LIA moraines (Fig. 3.11A). Generally Kjaransvík does not show signs of having been glaciated recently.

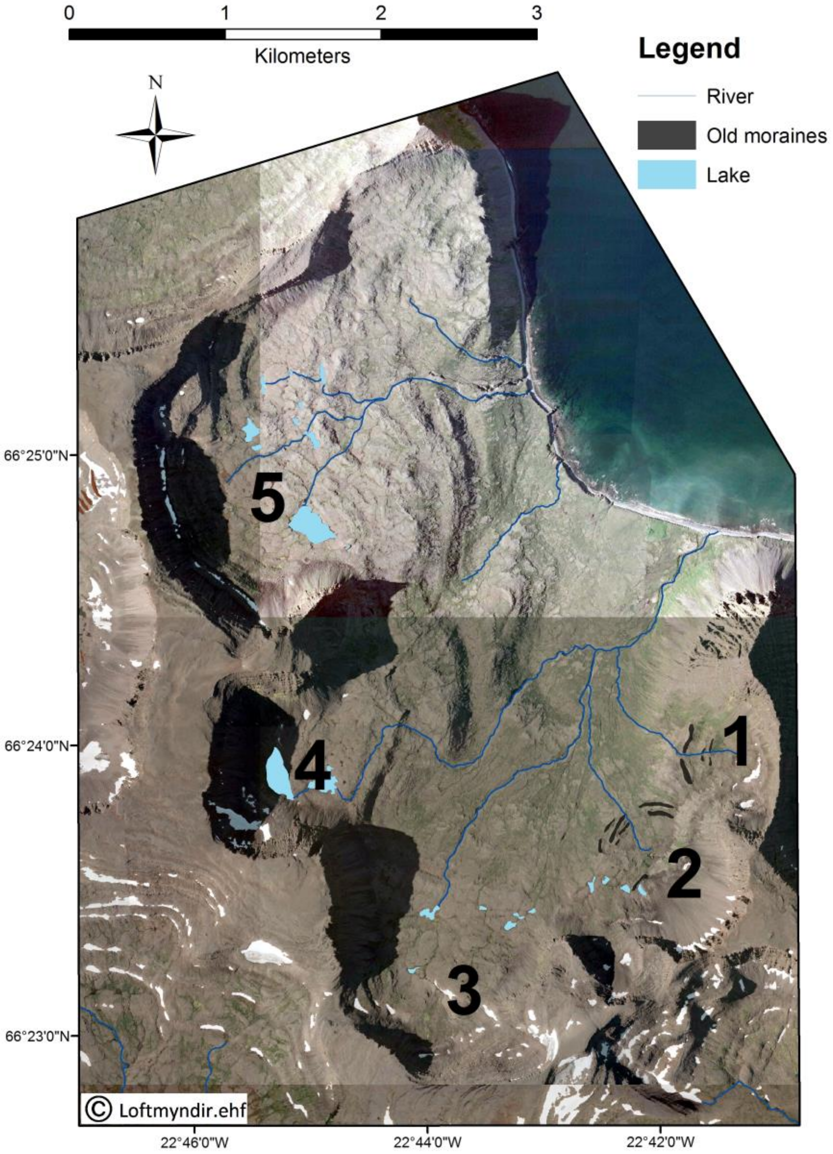


Fig. 3.7: A glacial geomorphology map of Kjaransvík.

3.4 Hælavík

A detailed map of the glacial geomorphology of Hælavík is presented in figure 3.8.

The coast along Hælavík is about 3 km long. The valley inside Hælavík is approximately 3 km wide and 4 km long. The valley lowlands resemble Hlöðuvík with an irregular and hummocky topography at the east side of the valley. However, the hummocky moraines are not as well developed in Hælavík as in Hlöðuvík. Two main rivers flow down through the valley. The main water source is snow melt and small lakes and dams further up-valley.

Only three poorly developed cirques are situated in Hælavík. Cirque 1 and 2 are facing W while cirque 3 is facing NW. None of these cirques show any signs of having been glaciated recently. Several sets of *Old moraines* have however, been mapped at the head of the valley. The moraines proved to be difficult to recognize in the field. However, on the aerial photographs they are clear and distinct. Several ridges that dam up lakes are interpreted as *Old moraines*. The sediments are coarse grained diamicts and the moraines are fairly vegetated and look weathered. Hjort et al. (1985) mapped a lateral moraine at about 55 m a.s.l. 500 m inside the west end of Hælavíkurbjarg. This moraine is also recognised on the aerial photographs (marked with arrow on Fig 3.8).

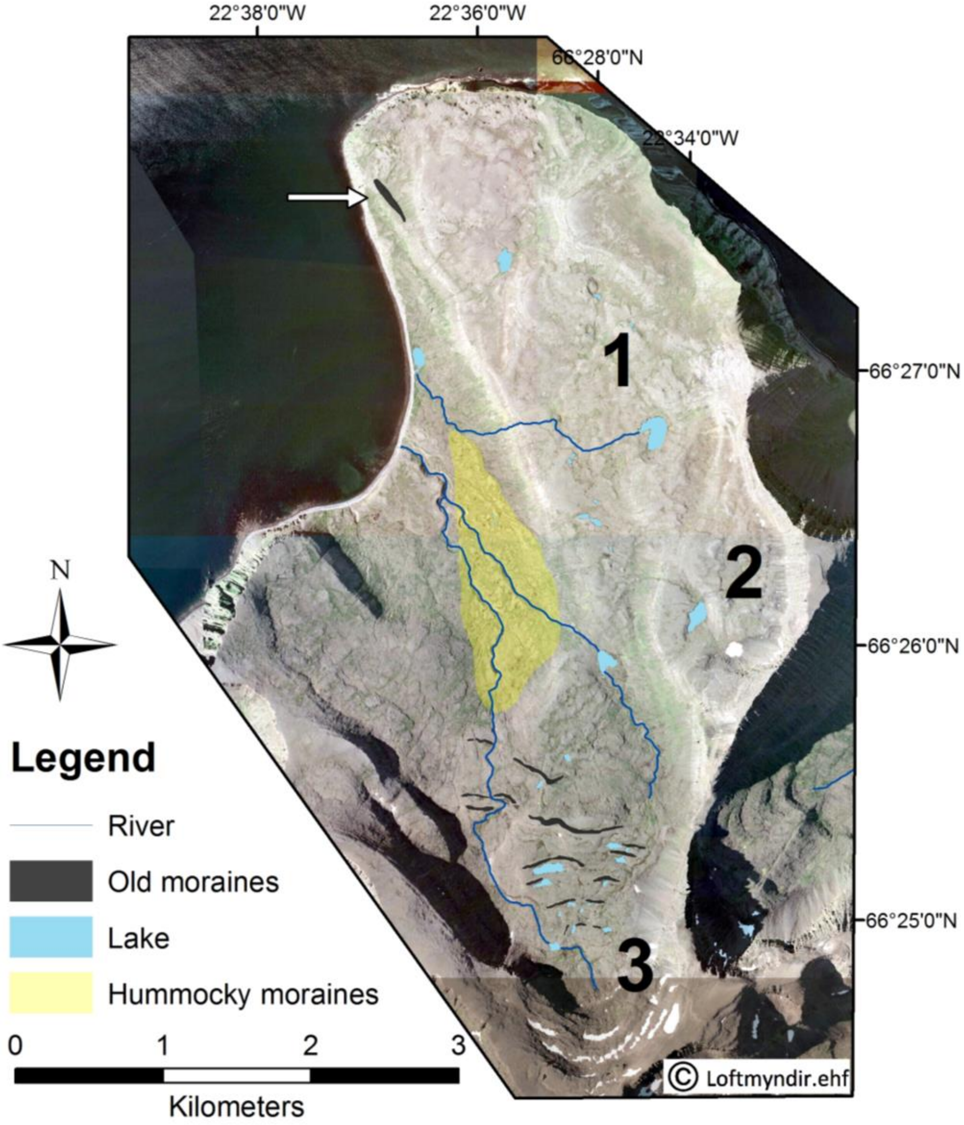


Fig. 3.8: A glacial geomorphology map of Hælavík.

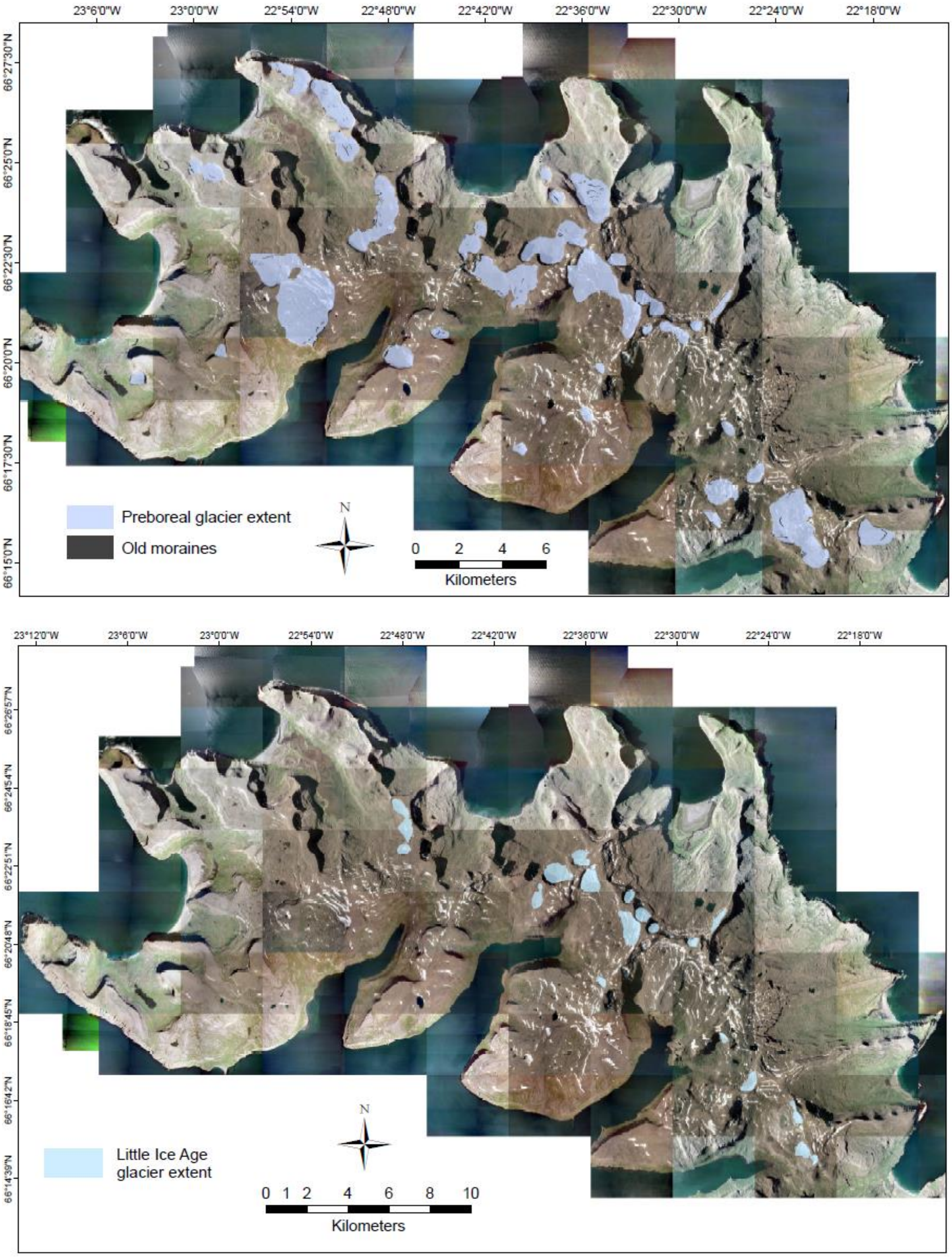


Fig. 3.9A: Estimated glacier extent on Hornstrandir during Preboreal time. The reconstruction is based on mapped terminal moraines mapped as *Old moraines*. **B:** LIA glacier extent on Hornstrandir. Reconstruction is based on terminal moraines mapped as *LIA moraines*.

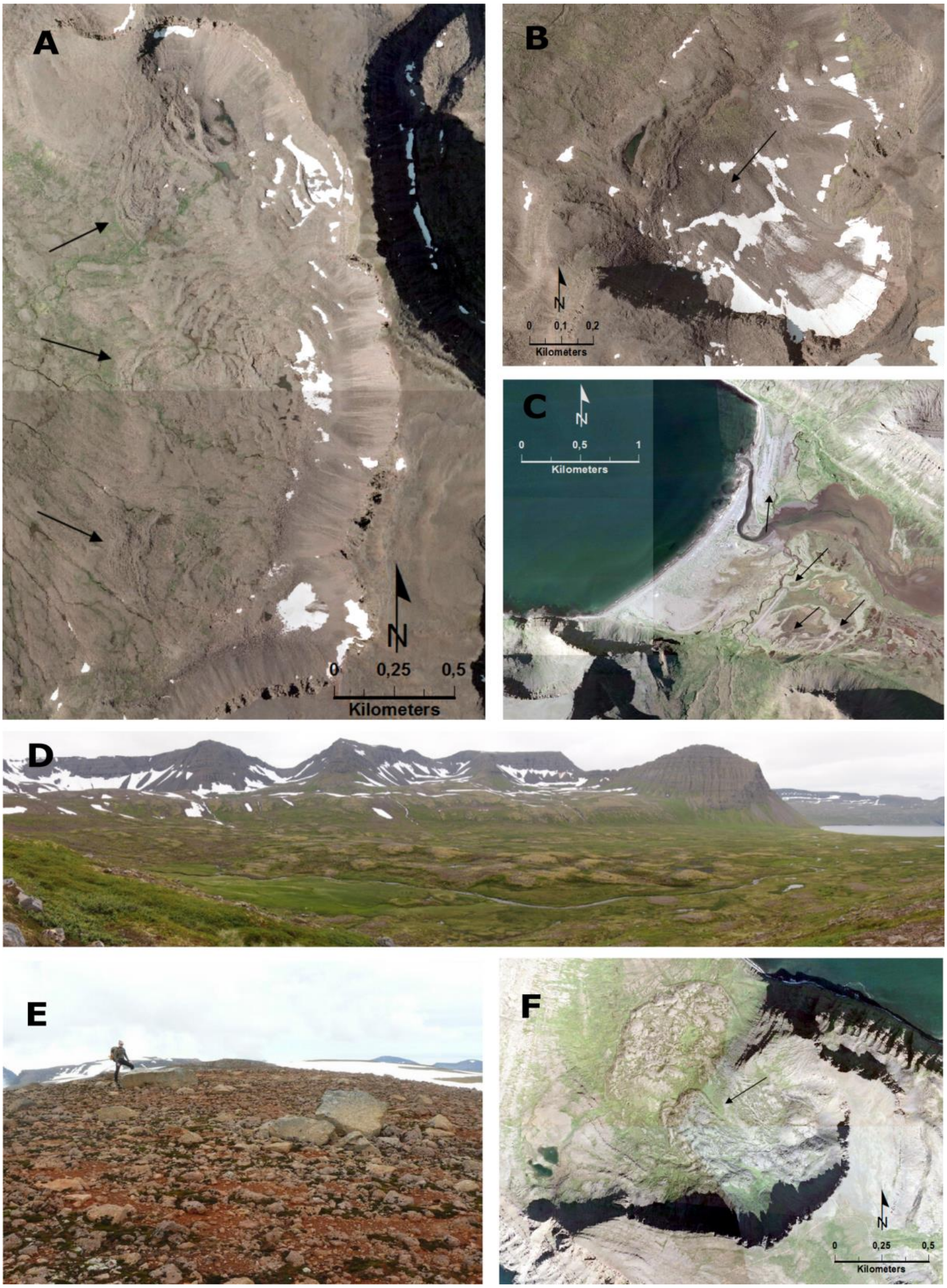


Fig. 3.10A: Moraines in Fljótavík. **B:** Fluted surface located within the LIA moraines in cirque 3 in Hlöðuvík. **C:** Raised beaches in Fljótavík. **D:** Hummocky moraines in Hlöðuvík. **E:** Erratic boulder sitting on a diamict surface upon the plateau. **F:** Rock glacier in Mannadalur.

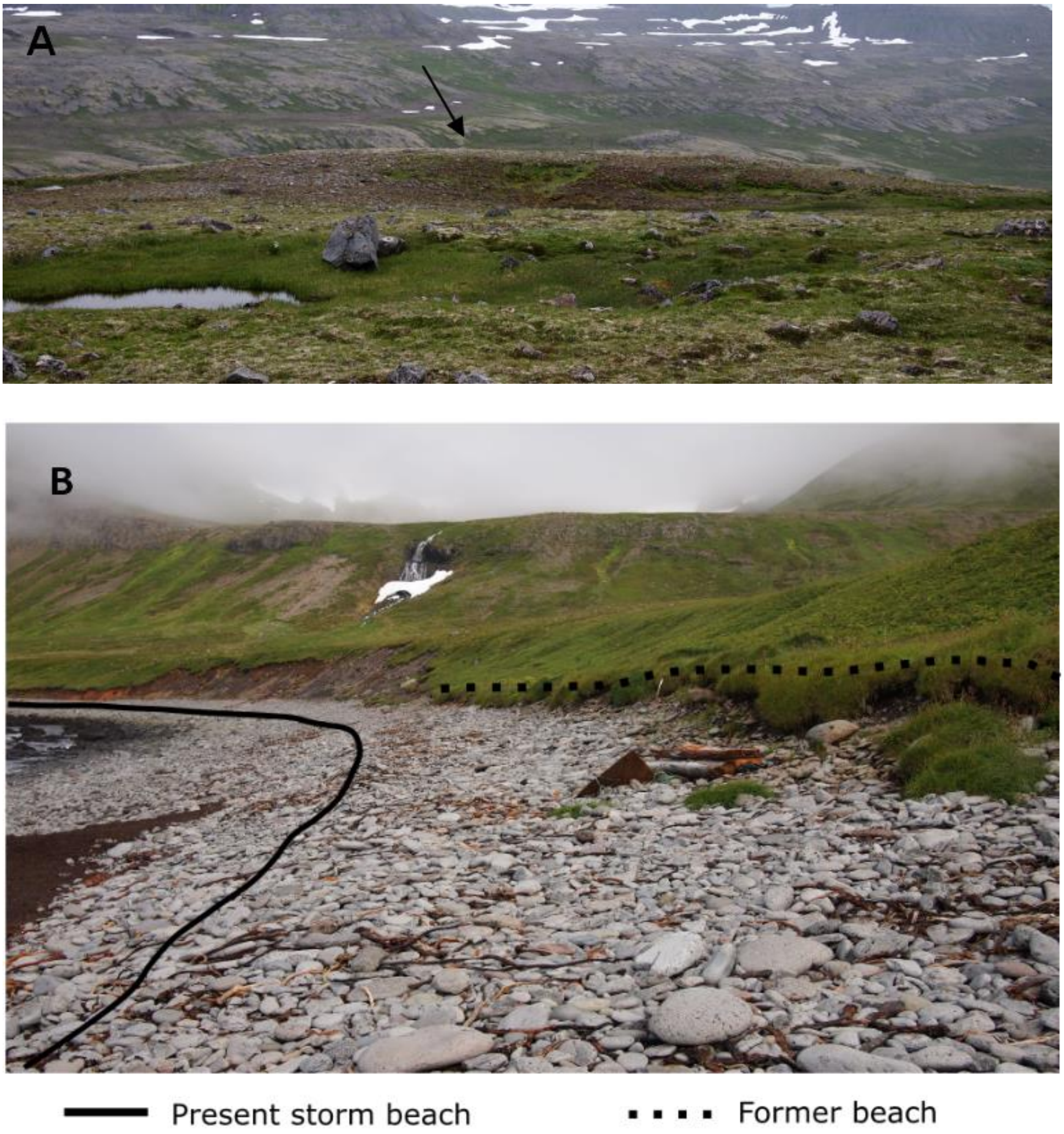


Fig. 3.11A: Old moraine located in cirque 1 in Kjaransvík. **B:** Raised beach in Hlöðuvík. The raised beach is located about 2 m above the present storm beach.

3.5 Coastal sections – sediment descriptions

Seven coastal sections were described and logged in the field. Two sedimentological logs were made in Hlöðuvík and Kjaransvík, respectively, while three logs were made in Hælavík (Fig. 3.12). The legend for the sedimentological logs is shown in Figure 3.13.

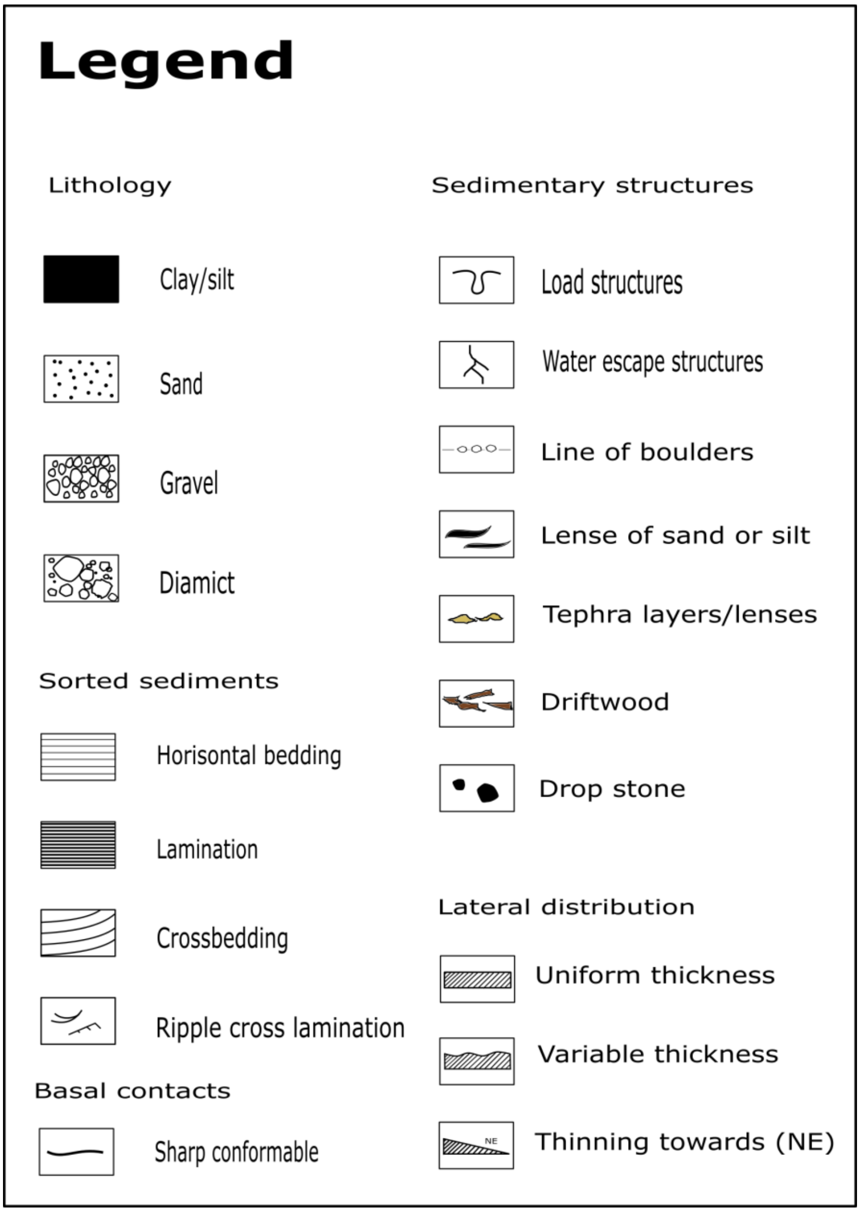


Fig. 3.12: Legend for the seven coastal sections logged in Hornstrandir during fieldwork. The legend is based on the data chart for field description of glacial diamicts and associated sediments, presented in Krüger and Kjær (1999).

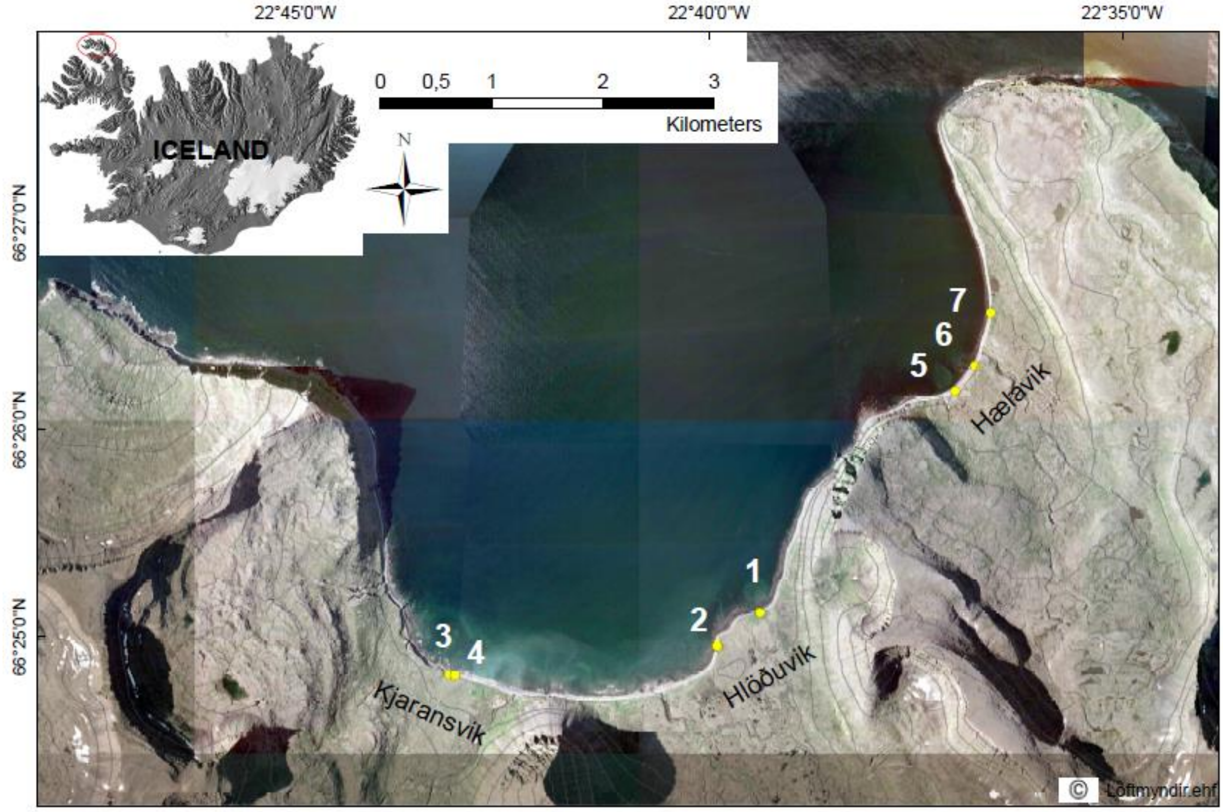


Fig. 3.13: Sedimentological logs were made at seven different locations at Hornstrandir.

Coastal section 1- Hlöðuvík

Position: N66° 25.382' W22° 38.812'

Observations

On the eastern side of Hlöðuvík, coastal erosion has exposed an approximately 110 m long coastal section. It is just over 10 m high and three distinctive units are represented in the section. The section is oriented in a NE-SW direction. The base of the section is located 2 m above the current storm beach. The lowermost unit is a 2 m thick diamict. The diamict is massive and homogenous with a coarse-grained matrix. The unit is matrix supported although it is very rich in clasts. The clasts are angular to subangular and there were no striations observed on them. The whole unit is very firm and difficult to excavate. The lateral distribution is uniform. Overlying the diamict is a 2.6 m thick sand layer that is horizontally bedded. The sand is silty to very fine, with some clay lenses in between. Soft sediment deformation structures are observed in some of the clay lenses. Some individual clasts are also observed in the unit, but they are few and far between. No striations are observed on these clasts. Several light-colored structures, consisting of clay and silt are percolating downwards through the unit (Fig. 3.21A). They are usually 1-10 mm thick and can be traced between 0.1 - 2 m. These structures are interpreted as water-escape structures. No fossils or mollusc shells are found in the unit. The silty-sand layer and the lowermost diamict are separated by a sharp conformable basal contact. A 5.5 m thick diamict concludes the units of this coastal section. The uppermost diamict is very similar to the lowermost. It is massive and has a coarse sand/gravel matrix. In contrast to the lowermost diamict, this unit is matrix supported and the clasts are sub-rounded to rounded. The unit is uniformly distributed laterally. No striations are found on the clasts and there are no traces of fossils. The sedimentological log representing coastal section 1 in Hlöðuvík is presented in Figure 3.14B.

Interpretation

The lowermost diamict unit is interpreted to be a subglacial till deposited by an overriding glacier. Indicators supporting this interpretation is the relatively uniform thickness of the unit, the high degree of compactness and the coarse grained matrix. The sand and silt unit above are interpreted as being deposited in a marine environment. The boulders and clasts found within the unit are interpreted as dropstones originating from calving glaciers further up valley. The diamict at the top of the section is interpreted as representing a new glacier advance, depositing a second subglacial till. The indicators are the uniform thickness and high degree of compactness. The water escape structures in the sand and silt layer were most likely formed when the uppermost till was deposited, forcing water to escape downwards through the unit.

The first coastal section in Hlöðuvík reflects a glacial event that deposited a subglacial till. When the glacier retreated, the sea-level stood at least 5 m higher than today, depositing the marine sand and silt unit. Finally a new glacial advance deposited the uppermost till.

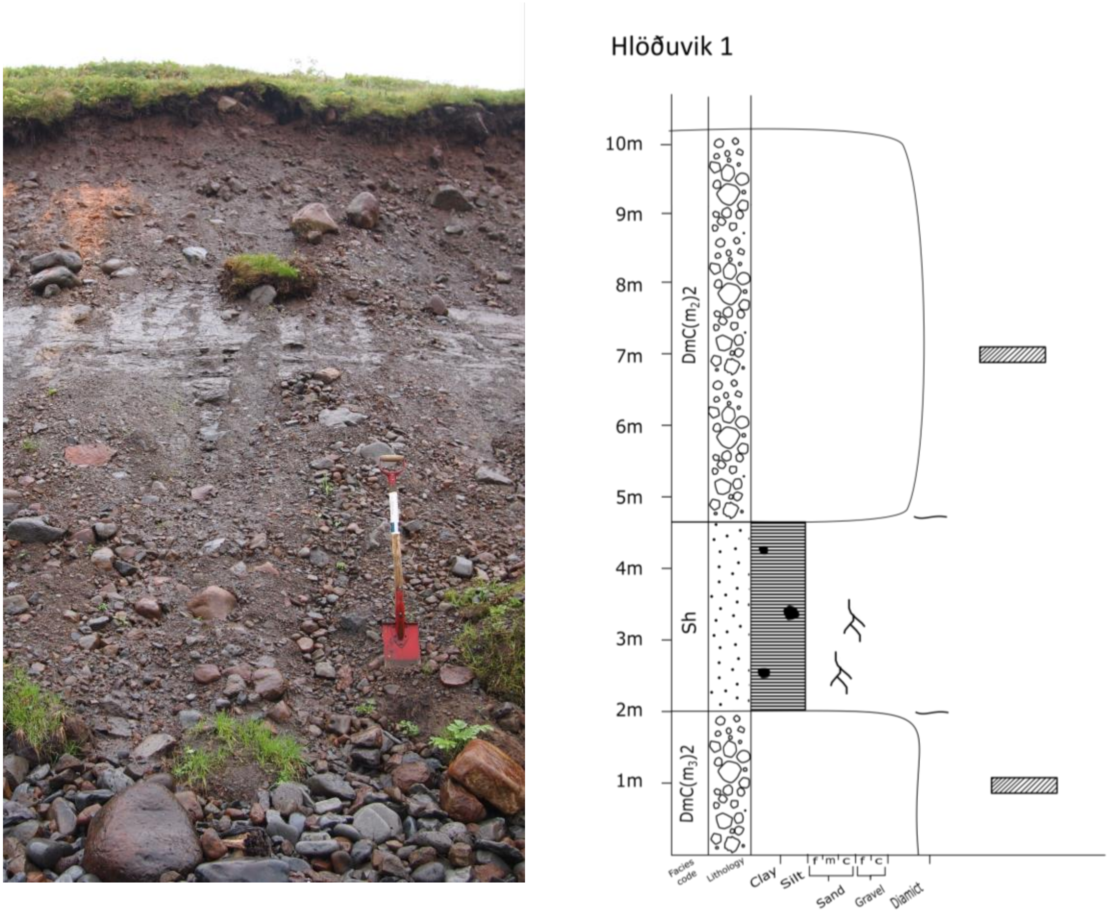


Fig. 3.14A: Photograph of coastal section 1 in Hloduvik. **B:** The sedimentological log representing coastal section 1 in Hloduvik.

Coastal section 2 – Hlöðuvík 2

Position: N66° 25.142' W22° 39.461'

Observations:

The second coastal section in Hlöðuvík is an approximately 40 m long section. The section is about 10 m high and located 1 - 2 m above the present storm beach. It is orientated in a NE-SW direction. The outcropping units are partly covered by debris, making description difficult. Two units have, however, been described from the section. The lowermost unit is a banded diamict. The matrix is fine grained, consisting of clay and silt. It is matrix-supported and very firm, making it hard to excavate. The unit has a uniform thickness laterally. The second unit is a matrix-supported massive diamict. The matrix is coarse and consists of sand

and gravel. The diamict is very firm. Parts of the unit are covered by debris. The two units are separated by a sharp conformable contact and they are both uniform distributed laterally. The sediment log representing coastal section 2 in Hlöðuvík is presented in Figure 3.15B.

Interpretation

Both units in this section are interpreted as being subglacial tills, deposited by an overriding glacier. Indicators supporting this are the uniform lateral distribution and the very high degree of compactness of the tills. The banded appearance of the lowermost diamict suggests that the unit have undergone high cumulative strains. This deformation probably happened during the deposition of the upper till. The second coastal section in Hlöðuvík therefore reflects two different glacial advances.

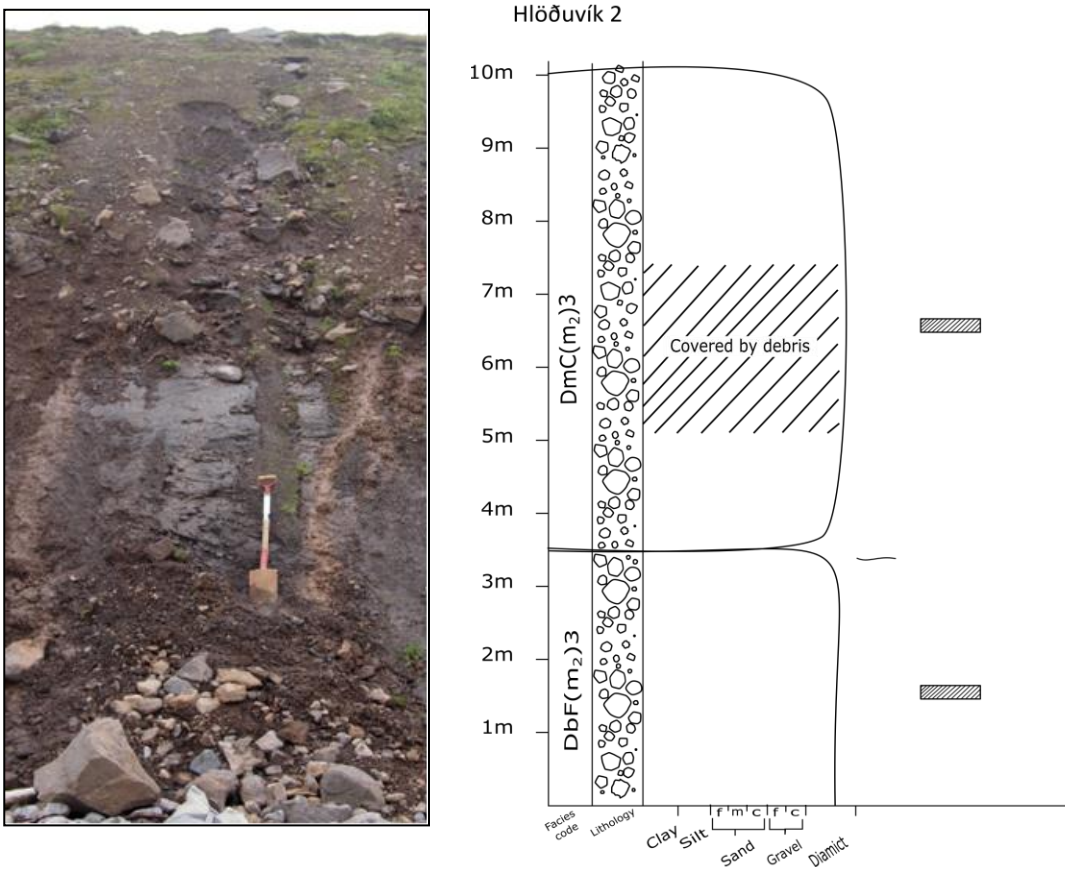


Fig. 3.15A: Photograph of coastal section 2 in Hlöðuvík. **B:** The sedimentological log representing coastal section 2 in Hlöðuvík.

Coastal section 3 – Kjaransvík 1

Position: N66° 24.934' W22° 42.686'

Observations:

The first cliff in Kjaransvík is a 2.8 m high and 10 m long coastal cliff. It is oriented in a NW-SE direction and has three distinct units. The bottom unit is 20 cm of imbricated boulders. The boulders are elongated and sub-rounded to rounded. The grain size varies from 2 - 20 cm in diameter. Fine silt and sand are situated in between the boulders. The unit above is a 1 m thick, horizontally bedded sand unit. The sand is from fine to medium grained. The unit contains large amounts of driftwood in the lower part. The upper part of the sand unit contains several small lenses of light coloured tephra. Samples of both driftwood (UA-49595, UA-49596) and tephra (Kjaran) were sampled from this coastal section. Above is a 70 cm thick and poorly sorted gravel unit. The gravel unit has a clear orange colour. Clasts are sub-angular. At the boundary between the sand and the gravel, a thin layer of organic material was observed. The uppermost part of the section is covered by peat. All of the three units seem to be uniform distributed laterally. The sedimentological log representing coastal section 3 in Kjaransvík is presented in Figure 3.16B.

Interpretation

Based on the rounded clasts and imbricated structure, the bottom boulder unit is interpreted as a beach sediment. The coarse grains suggest that the sediment was deposited on a high-energy beach. The sand unit above suggests calmer conditions and the horizontal bedding and occurrence of tephra suggests that the sand was deposited in water. It is interpreted that the sand could have been deposited in a lagoon or a small lake situated just inside the berm crest. The driftwood could have been deposited during a storm that carried the driftwood over the crest and into the lagoon. Both the driftwood and the ash layer have been dated. The driftwood yield ages of 1930 cal. yr BP and 2075 cal. yr BP. The tephra has been identified as being formed during the Sn-1 eruption (Snæfellsjökull volcano) at 1855 cal. yr BP. This means that the stratigraphy of the sand unit is correct. Although the uppermost unit looks like it is glacially derived, the age of the underlying sand does not allow for a glacial interpretation. The uppermost gravel is therefore interpreted as a new beach deposit.

The whole section reflects an initial regressional event, where the beach consisting of boulders, was covered by a lagoon or small lake. At that time, the coastline was situated further out than present. At some point after 1855 cal. yr BP, a transgression started and deposited new beach sediments on top of the sandy unit.

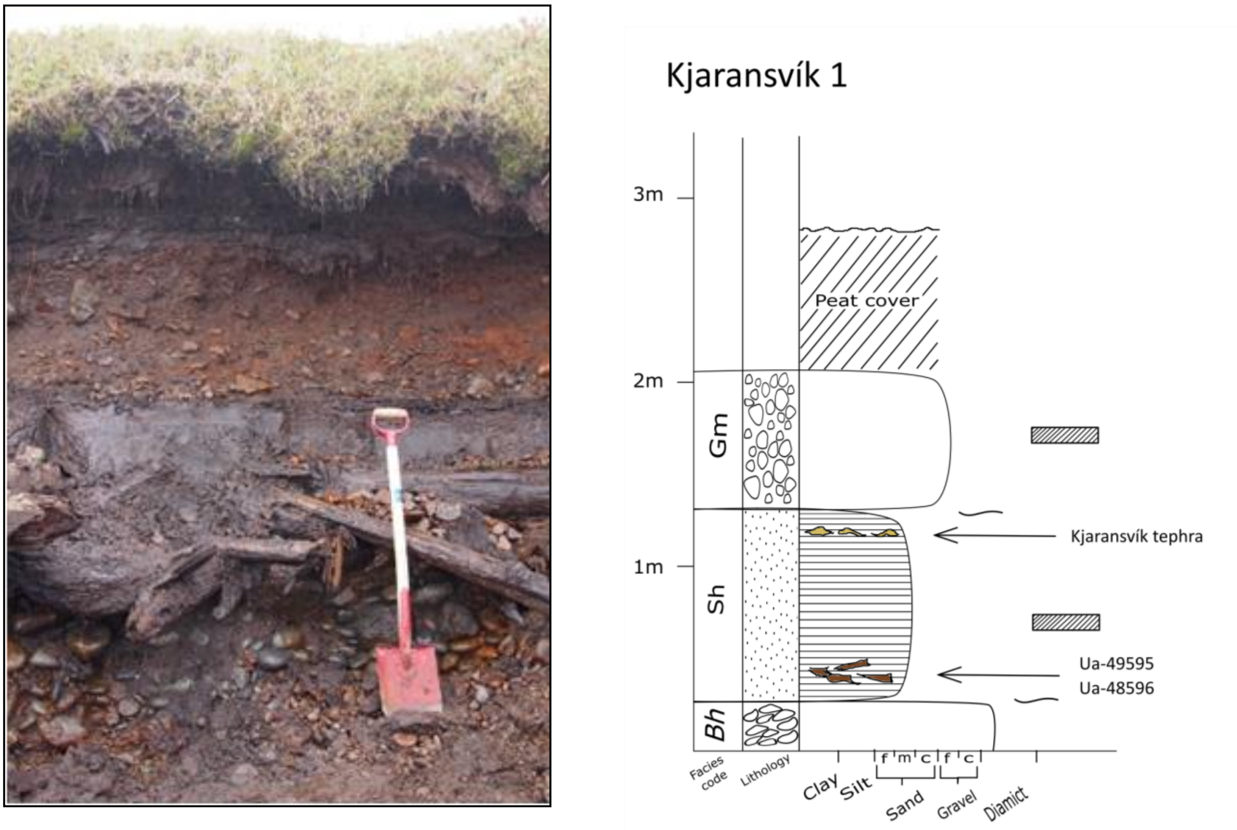


Fig. 3.16A: Photograph of coastal section 3 in Kjaransvík. **B:** The sedimentological log representing coastal section 3 in Kjaransvík.

Coastal section 4 – Kjaransvík 2

Position: N66° 24.931' W22° 42.615'

Observations:

The second cliff that that was logged in Kjaransvík is a 2.6 m high and approximately 10 m long section. The section contains several small units that had to be excavated before logging. The cliff is oriented in a NW-SE direction. The bottom unit is a 1 m thick sequence with imbricated boulders. The boulders are elongated and sub-rounded to rounded. The grain size varies from 2-20 cm in diameter. Fine silt and sand are situated in between the boulders. The next unit is a 25 cm thick sand layer. The sand is massive and medium grained. Above sits a 10 cm thick, horizontally bedded fine grained sand layer. The unit above is a 25 cm thick, matrix-supported firm diamict. It is massive with a silty matrix. Above is a 15 cm thick sand unit. The sand is horizontally bedded and the grain size is fine. The uppermost unit of the section is a 70 cm thick diamict. It is stratified with a coarse grained matrix. It is very clast rich and firm. All the basal contacts in the section seem to be sharp and conformable. The lateral distribution could not be identified. The sedimentological log representing this coastal section in Kjaransvík is presented in Figure 3.17B.

Interpretation

Based on the imbricated structure, coarse and rounded clasts is the bottom boulder unit interpreted to be a high-energy beach sediment. Due to the proximity to coastal section 3 (about 30 m), the same interpretations can be made for this section. It is also likely that the ages of this coastal section resembles the ages obtained from the previously section. The sand units indicate calmer conditions, while the diamicts are indicators for sediments deposited at the beach during storms.

The coastal section records small transgressional and regressional events. The initial boulder beach was first covered by sand during a transgression and rise in sea-level. Then followed a small regression event where a new storm beach was deposited over the sand. The same transgression-regression cycle occurred, with the deposition of the next sand and diamict units.

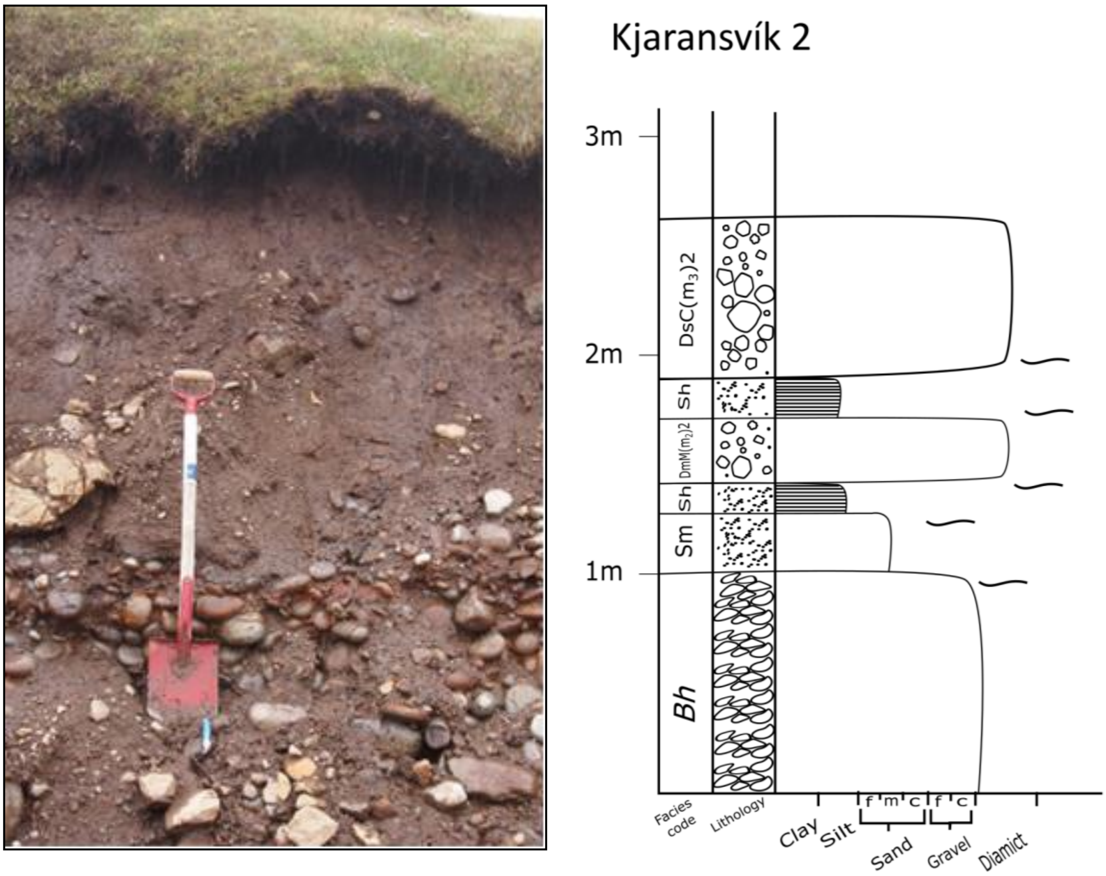


Fig. 3.17A: Photograph of coastal section 4 in Kjaransvík. **B:** The sedimentological log representing coastal section 4 in Kjaransvík.

Coastal section 5 – Hælavík 1

Position: N66° 26.446' W22° 36.771'

Observations

The first section logged in Hælavík is a 2 m high cliff. It is a 20 m broad section, oriented in a NE-SW direction. The base of the section is situated 4 m above the present storm beach. The lower unit is a 1.4 m thick diamict. The diamict is coarse, massive and clast supported. It is firmable and easy to excavate. In the lower part of the unit, boulder lenses are observed. Driftwood was found about 50 cm up in the unit and sampled for radiocarbon dating (Sample number Ua-49593 and Ua-49594). In the upper part of the unit, lenses of silt and clay were found at various heights. The upper unit is a new diamict. It is a 60 cm thick, massive, firm and matrix-supported diamict. The matrix is medium grained sand. The boundary between the two units is sharp and conformable. Both units have a uniform lateral distribution. The sedimentological log representing the coastal section in Hælavík 1 is presented in Figure 3.18B.

Interpretation

The bottom unit is coarse, firmable and lacks any traces of clay and silt, except for scattered lenses in the upper part. The diamict is therefore interpreted to be a beach deposit. The driftwood is a significant indicator supporting this interpretation. The upper unit are also interpreted to be a beach deposit, based on the sand matrix, with very little content of clay and silt.

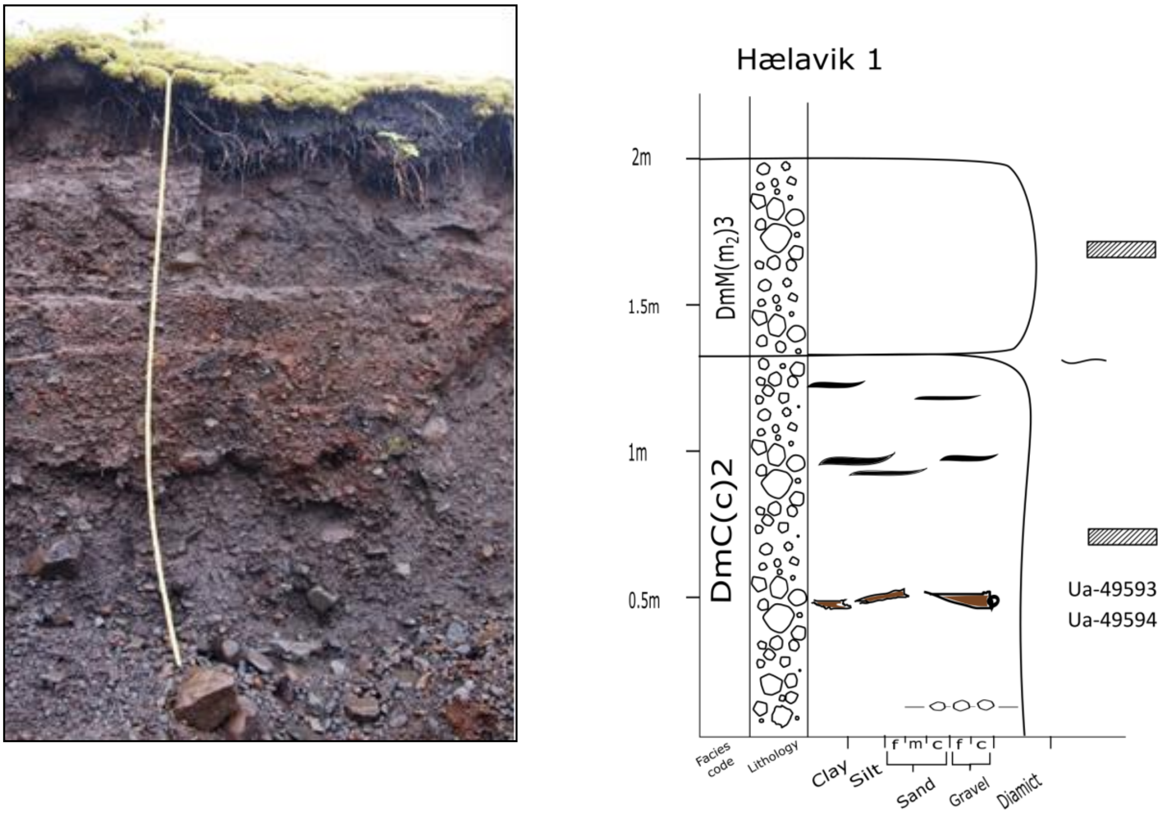


Fig. 3.18A: Photograph of coastal section 5 in Hælavík. **B:** The sedimentological log representing coastal section 4 in Hælavík.

Coastal section 6 – Hælavík 2

Position: N66° 26.573' W22° 36.555'

Observations

The second cliff in Hælavík is approximately 100 m long and is oriented in a NE-SW direction. The 14 m high section contains three distinct units and bears similar characteristics as the Hlöðuvík 1 section. The lower part of the section consists of a 5 m thick diamict. The diamict has a silty matrix and is extremely firm. It is clast rich and the clasts seem to be concentrated in the upper part of the unit. The clasts are sub-angular to angular and no striations of the clasts were observed. Water escape structures are spread evenly out in the unit (Fig. 3.21A). Over the diamict lies a 3 m thick silty/fine sand unit. The sand is horizontally bedded and contains a few clasts spread out evenly. Several sets of water escape structures are also seen in this unit. The unit contains no traces of mollusc shells or other fossils. The contact between the two units is sharp and conformable. However the thickness varies laterally. The uppermost unit is a new diamict. It is very similar to the lowermost diamict, but this one is more coarse grained and is not as firm and therefore easier to excavate. The contact to the underlying sand is sharp and conformable. The sedimentological log representing the coastal section in Hælavík is presented in Figure 3.19B.

Interpretation

This section bears resemblance with the Hlöðuvík 1 coastal section and several of the same interpretations can be made for this section. The lowermost diamict unit is interpreted to be a subglacial till deposited in a subglacial environment. Indicators supporting this interpretation is the relatively uniform thickness of the unit and the high degree of compactness. The sand and silt unit above are interpreted as being deposited in a marine environment. The boulders and clasts found within the unit are interpreted as drop stones, transported out by ice rafted debris, originating from calving glaciers further up valley. The diamict at the top of the section is interpreted as representing a new glacier advance, depositing a second subglacial till. The indicators are the uniform thickness and high degree of compactness. The water escape structures observed within the sand and silt layer and the lowermost till were most likely formed when the uppermost till was deposited, forcing water to escape downwards through the section.

As the first section in Hlöðuvík, this coastal section represents an initial glacial advance. Then as the glacier retreated, the sea-level stood at least 9 m higher than today, depositing the marine sand and silt unit. Finally a new glacial advance deposited the uppermost till.

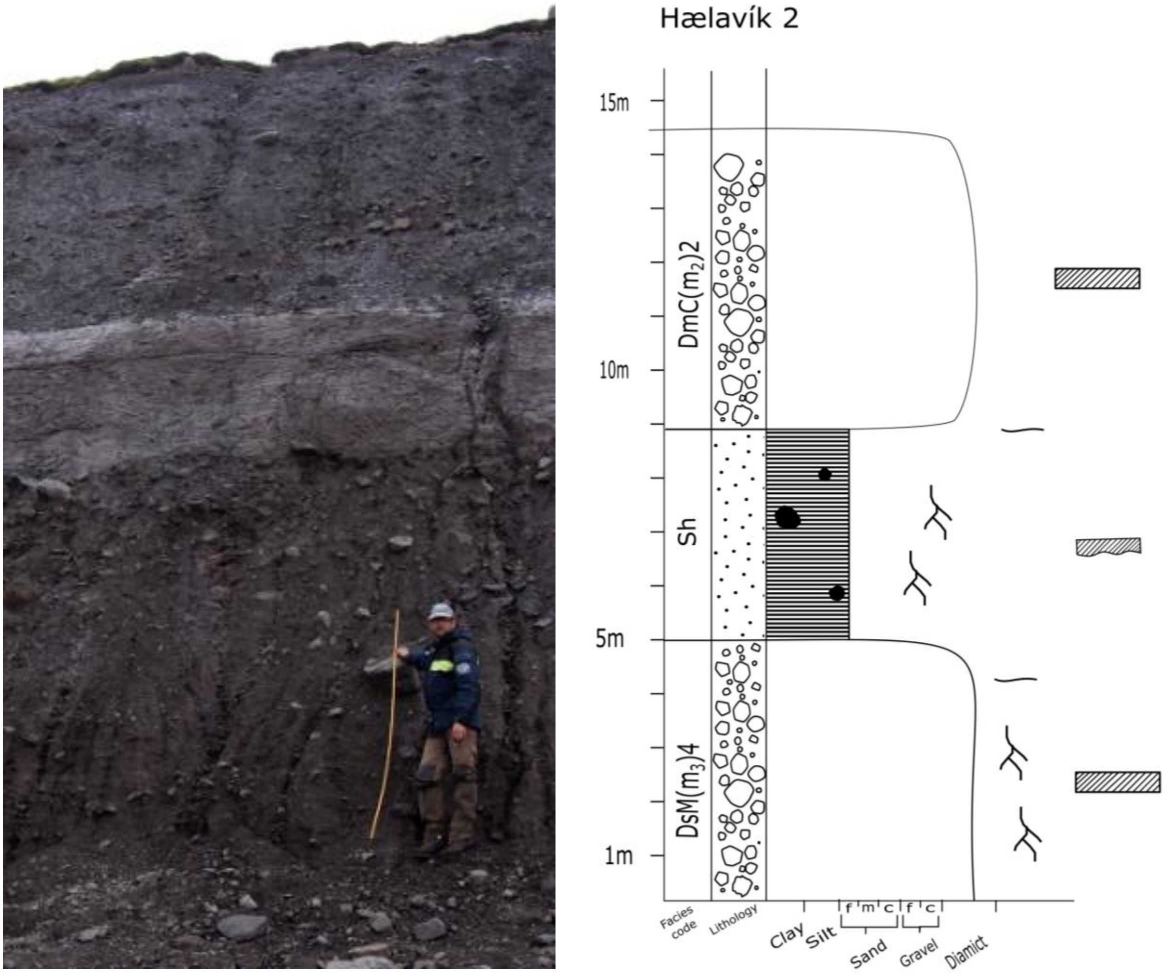


Fig. 3. 19A: Photograph of coastal section 6 in Hælavík (Photo: Skafti Brynjólfsson). **B:** The sedimentological log representing coastal section 6 in Hælavík.

Coastal section 7 – Hælavík 3

Position: N66° 26.831' W22° 36.397'

Observations

The third section in Hælavík is an approximately 50 m long cliff, containing four distinct sedimentary units. The section is 4 m high. The lowermost unit is horizontally laminated yellow clay. A fold or a load structure is observed in the unit. Above the clay, lies a 1.1 m thick sand layer. The bottom of the unit is dark black and it gets gradually more light coloured upwards in the unit (Fig. 3.21B). The sandy grain size and black colour suggests that the whole unit is a tephra. The unit is ripple cross laminated although the structure is most apparent in the lower part than in the upper. The top and bottom contacts are sharp and conformable. Above the sand/tephra unit, lies a new yellow clay layer. It is horizontally laminated and very similar to the lowermost one. However, no other structures were observed in the sediment. Over the clay lies an orange/yellow sand layer. The sand is cross bedded throughout the unit. The basal contacts are sharp and conformable. At the top lies a humus layer containing large elongated boulders. The sedimentological log representing the coastal section in Hælavík is presented in Figure 3.20B.

Interpretation

The grain size and laminated structure indicates that the bottom unit was deposited under very calm conditions, possibly in a lacustrine setting. The unit above is a result of a very heavy influx of tephra being deposited in the lacustrine environment. The load structure in the clay layer below, was probably formed when the heavy tephra influx appeared. The clay and silt unit above the tephra indicates that the tephra influx stopped and the calm conditions continued. The uppermost sand is interpreted as being an aeolian deposit. Indicators are the fine grain size and good sorting, cross bedded structure and orange colour. The boulders located at the top of the section were only found inside remains of old farm houses. They are therefore thought to be manmade and not relevant to the stratigraphy of the section.

The third coastal section in Hælavík represents a lacustrine environment where fine material was deposited. The hummocky terrain just inside the coast suggests that the section reflects sedimentation in small lake in between the hummocky moraines. After the heavy tephra influx, sedimentation in the lake continued until the lake dried out and aeolian sand was deposited at the top as dunes.

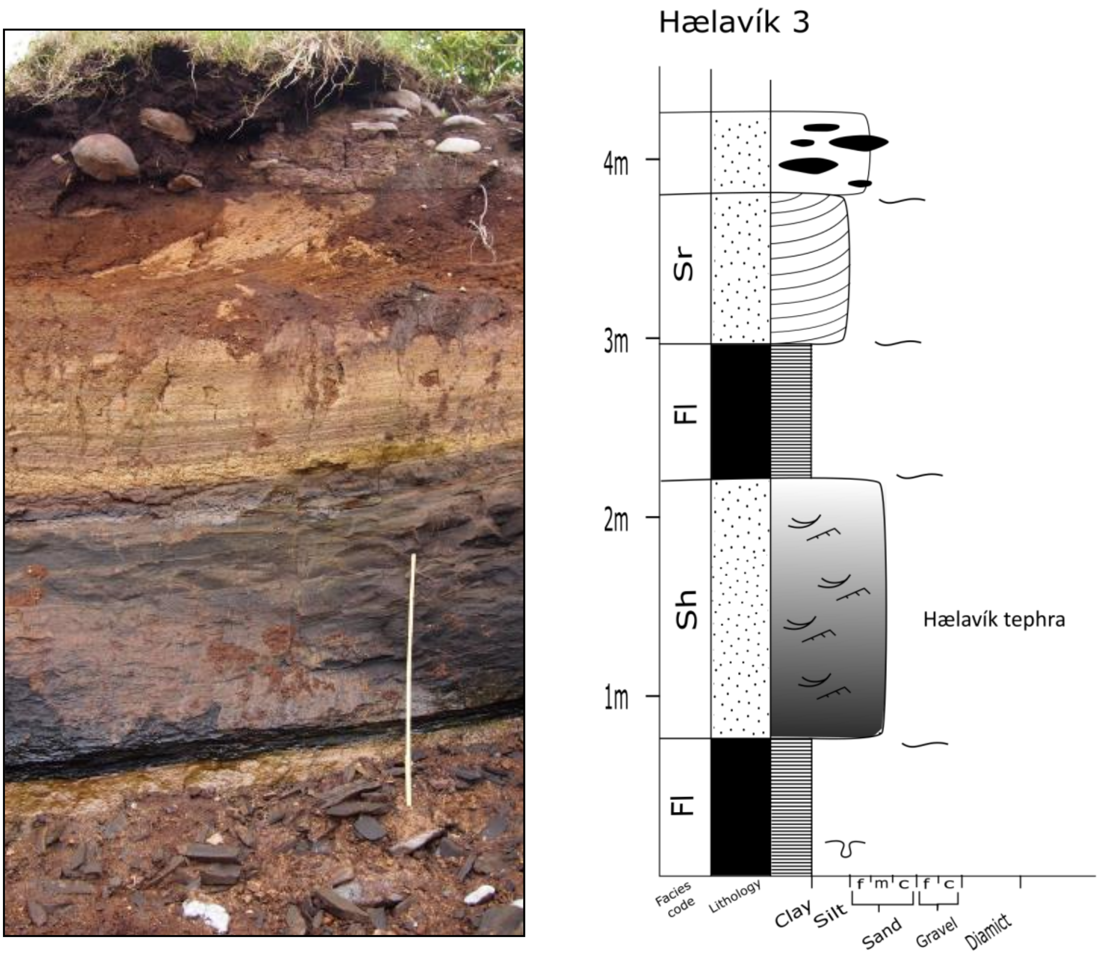


Fig. 3.20A: Photograph of coastal section 7 in Hælavík. **B:** The sedimentological log representing coastal section 7 in Hælavík.

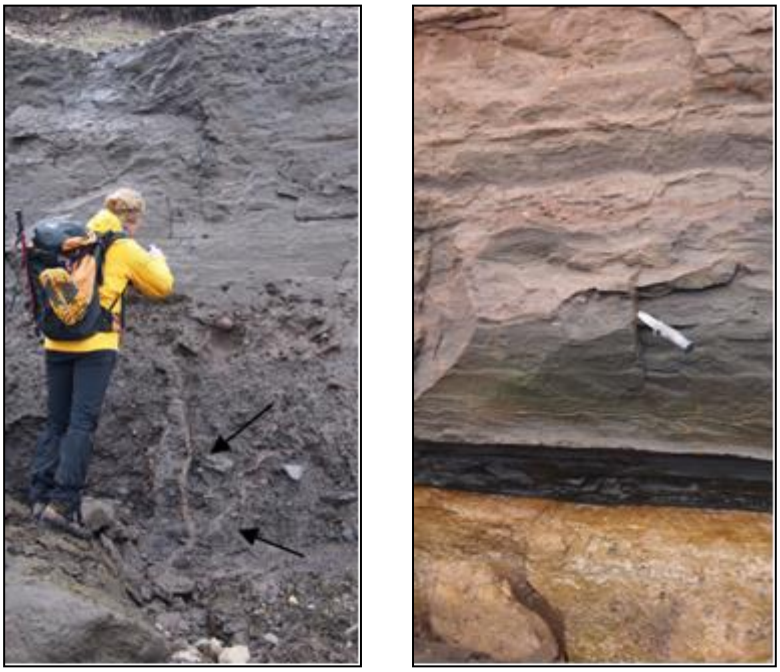


Fig. 3.21A: Photograph of water escape structures in the lowermost till in Hælavík.

B: Photograph of the base of the tephra sampled at coastal section 7 in Hælavík.

3.6 ^{14}C dating

Organic material was sampled from driftwood that is eroding out from two coastal sections at present, coastal section 5 in Hælavík and coastal section 3 in Kjaransvík (Fig. 3.12). The samples were radiocarbon dated at The Ångström Laboratory, Uppsala University (Table 1), and were dated to; Ua-49593 1335 ± 90 cal. yr BP, Ua-49594 1475 ± 170 cal. yr BP, Ua-49595 2075 ± 170 cal. yr BP and Ua-48596 1930 ± 140 yr BP. The samples Hæla 2 and Hæla 3 are taken from driftwood in Hælavík, while the samples Kjar 2 and Kjar 3 are from Kjaransvík.

Table 1: Radiocarbon ages from sampled driftwood. The dating was done by The Ångström Laboratory, Uppsala University. (BP = Before present, Present = 1950 AD)

LAB NUMBER	**SAMPLE**		**Δ^{13}C‰VPBD**	**CAL. YR BP**
UA-49593	*Hæla 2*		*-25,3*	*1335 ± 90*
UA-49594	*Hæla 3*		*-27,6*	*1475 ± 170*
UA-49595	*Kjar 2*		*-28,0*	*2075 ± 170*
UA-49596	*Kjar 3*		*-26,3*	*1930 ± 140*

Fig. 3.22A: Driftwood from coastal section 3 in Kjaransvík was sampled for 14C dating. **B:** Sampling of a driftwood log from coastal section 5 in Hælavík (Photo: Skafti Brynjólfsson, 2014).

3.7 Tephra analyses

Tephra was sampled at three different sites at Hornstrandir. Two tephras were found in coastal sections in Hælavík and Kjaransvík, while one was found in a till plain, dissected by meltwater streams in Hlöðuvík (Fig. 3.23). The geochemical composition of the tephras from Hornstrandir is presented in Table 2. Plots comparing the tephras from this study with other studies and tephra databases are shown in Figures 3.24, 3.25 and 3.26.

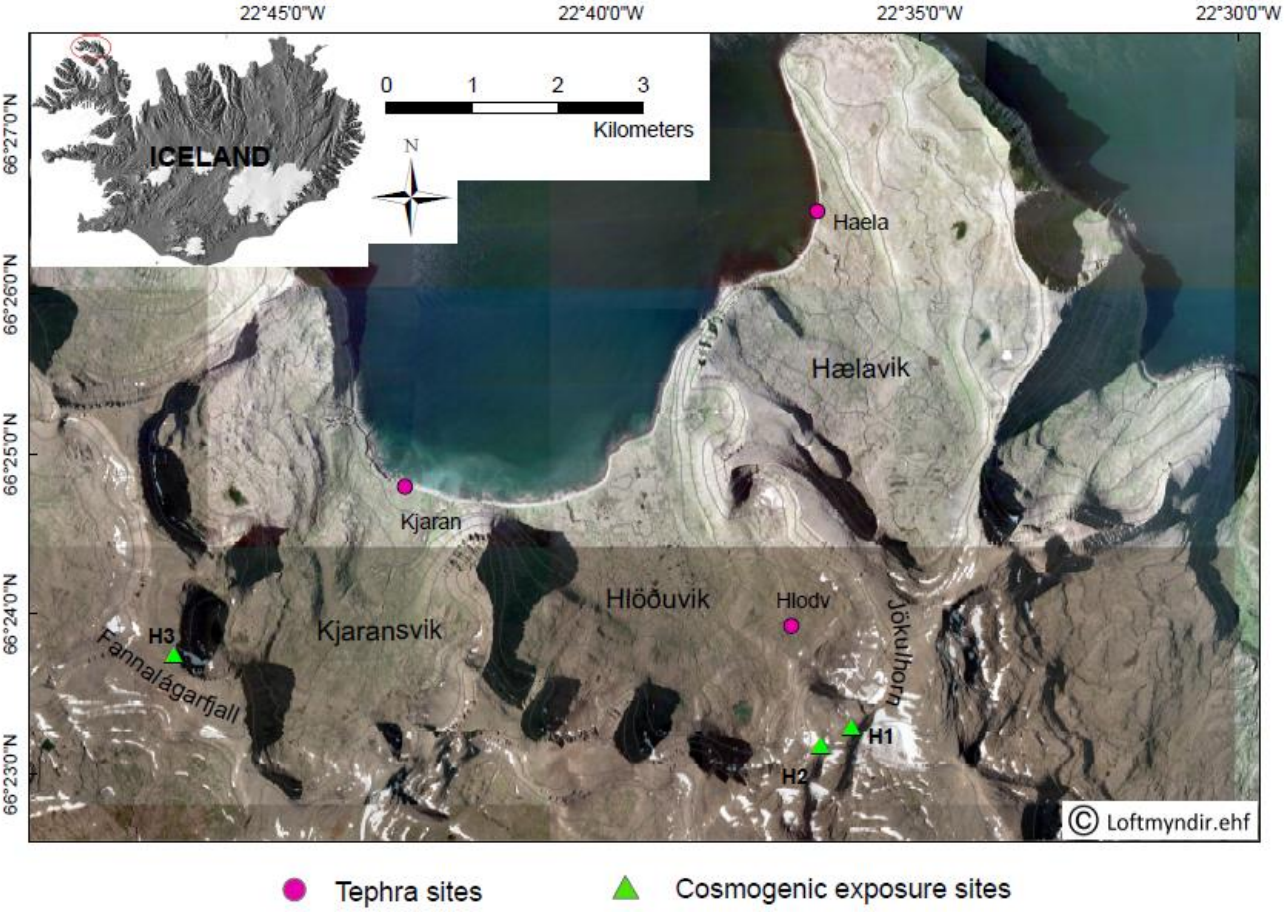


Fig. 3.23: Map presenting the locations where tephras and rock samples for cosmogenic exposure dating were sampled.

Hælavík tephra:

Position: N66° 26.831' W22° 36.397'

The tephra was sampled from the coastal section *Hælavík 3*, where it appeared as a 1.1 m thick black tephra (Fig. 3.27B). The geochemical composition of the tephra is identical with the Saksunarvatn tephra (Fig. 3.24). The Saksunarvatn tephra is thought to have originated from the Grímsvötn volcanic system and is dated to 10180 ± 60 cal. yr BP (Birks et al., 1996; Andrews et al., 2002a).

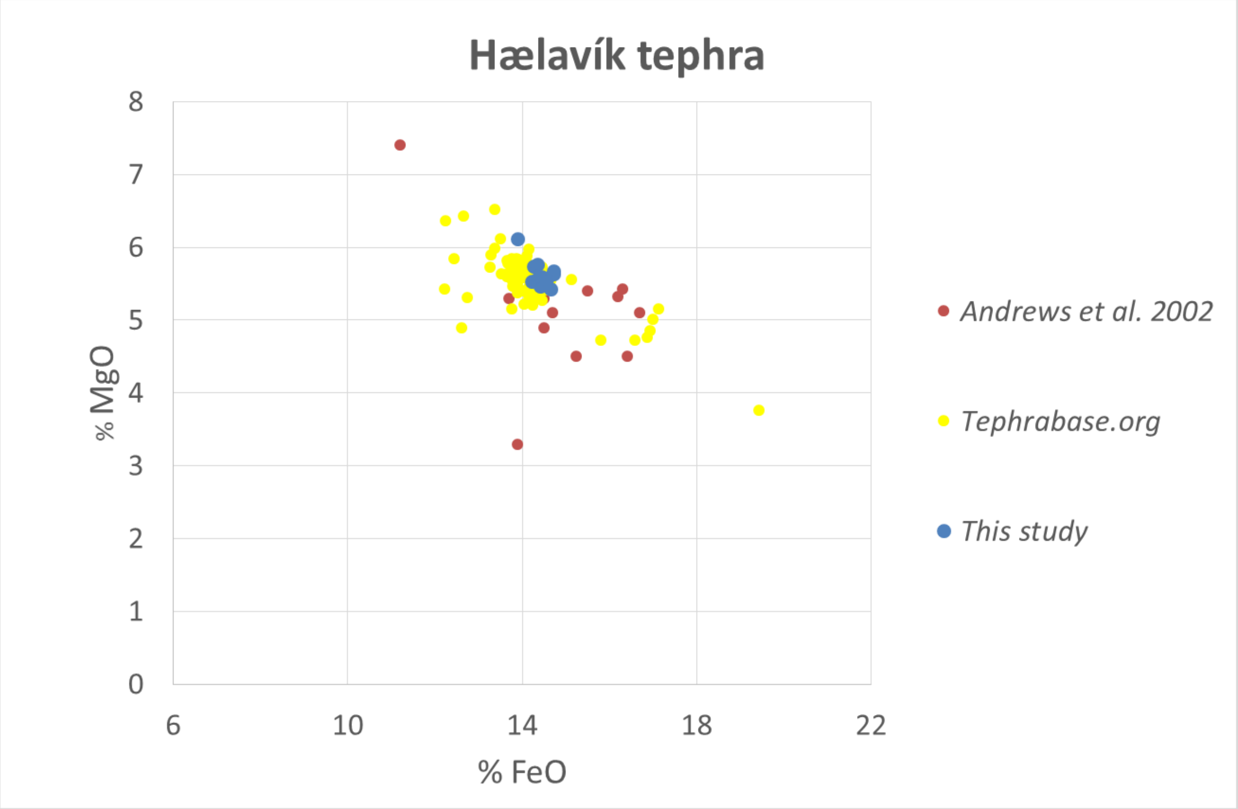


Fig. 3.24: Plot showing a comparison of the geochemical composition between the tephra found in Hælavík and Saksunarvatn tephra from other studies.

Hlöðuvík tephra:

Position: N66° 24.120' W22° 36.293'

The tephra was sampled from a dissected till plain in Hlöðuvík. The tephra appeared as a black horizon in the dissected section. The geochemical composition in the Hlöðuvík tephra is identical with the Saksunarvatn tephra (Fig. 3.25).

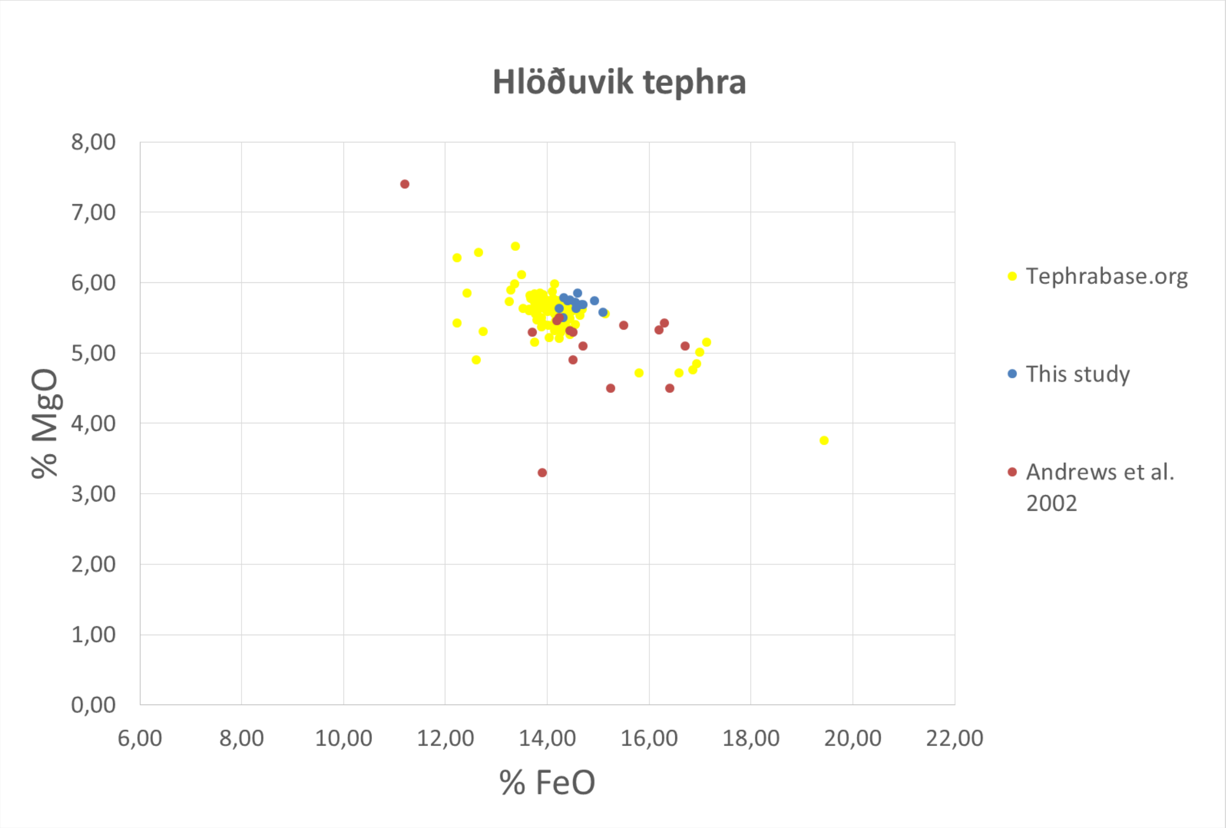


Fig. 3.25: Plot showing a comparison of the geochemical composition between the tephra found in Hlöðuvík and tephra from other studies.

Kjaransvík tephra:

Position: N66° 24.934' W22° 42.686'

The tephra was sampled in the coastal section *Kjaransvík 1*. It appeared as small white lenses varying in thickness from 0.1-2 cm and length from 5-15 cm (Fig. 3.27A). The tephra has a geochemical composition that resembles the Sn-1 tephra (Fig. 3.26). The Sn-1 tephra was produced during an eruption of the Snæfellsjökull volcano and has been dated to 1855 ± 25 cal. yr BP (Larsen et al., 2002; Eiríksson et al., 2011).

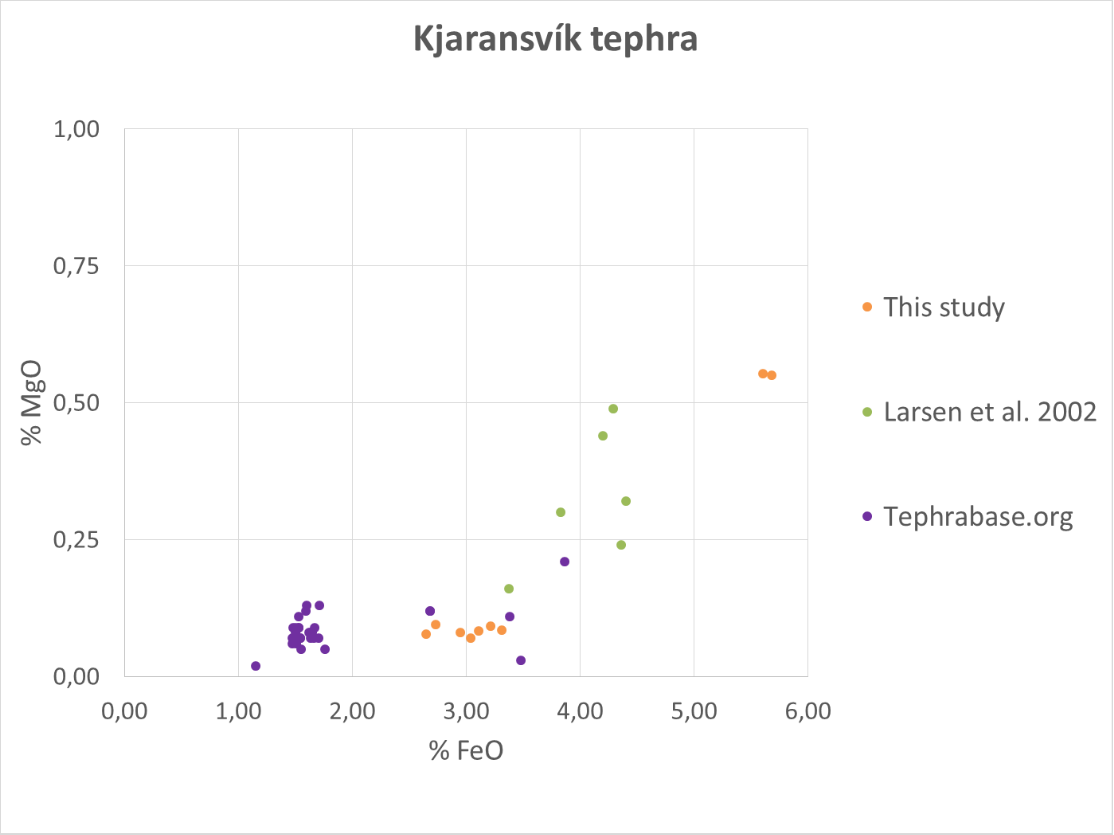


Fig. 3.26: Plot showing a comparison of the geochemical composition between the tephra found in Kjaransvík and tephra from other studies.

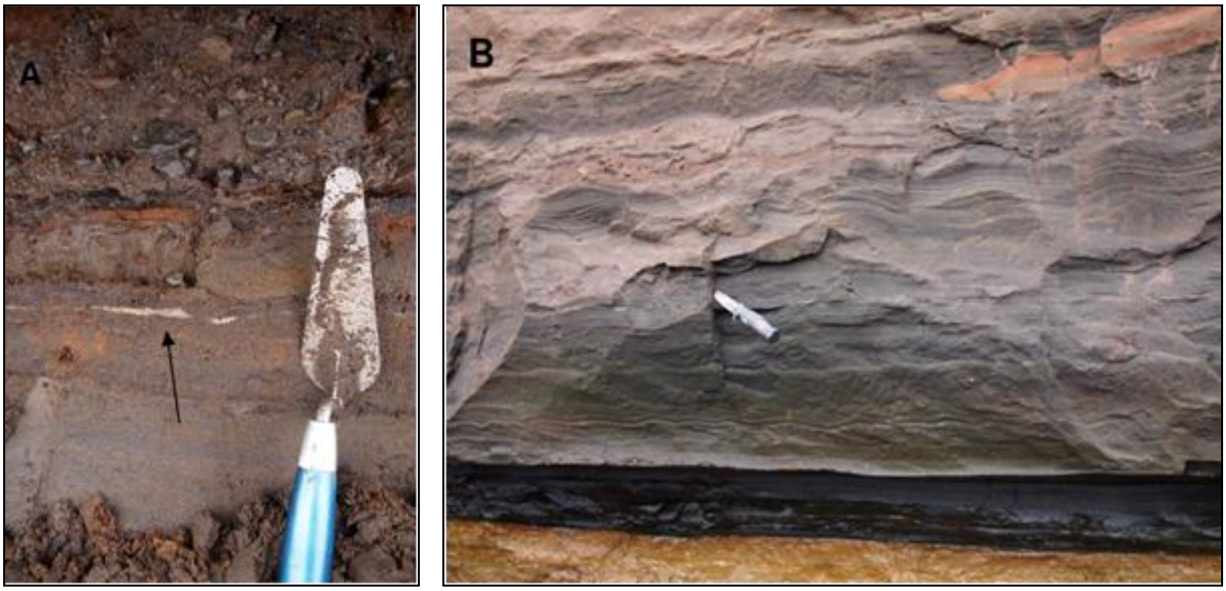


Fig. 3.27A: Picture of the tephra sampled at Kjaransvík. **B:** Picture of the tephra sampled at Hælavík.

No.	Comment	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Cr2O3	F	Total	Grímsvötn
37	Haela_7	49,70	3,33	13,05	14,56	0,16	5,57	9,88	3,10	0,45	0,26	0,00	0,00	100,06	
46	Haela_16	49,47	3,24	12,83	14,64	0,25	5,43	9,90	2,91	0,40	0,35	0,04	0,10	99,55	
47	Haela_17	49,13	3,22	12,61	14,41	0,21	5,47	9,72	2,82	0,48	0,43	0,04	0,02	98,57	
31	Haela_1	49,10	3,18	12,72	14,54	0,26	5,57	9,97	2,91	0,44	0,34	0,00	0,09	99,11	
39	Haela_9	48,07	3,17	12,88	14,22	0,23	5,53	10,02	2,81	0,45	0,28	0,00	0,00	97,65	
34	Haela_4	49,77	3,16	12,90	14,71	0,23	5,63	9,79	3,01	0,43	0,35	0,00	0,02	100,00	
44	Haela_14	49,35	3,14	13,00	14,47	0,28	5,59	9,75	2,81	0,43	0,33	0,02	0,00	99,17	
33	Haela_3	49,33	3,12	13,00	14,37	0,26	5,58	9,96	2,83	0,41	0,33	0,00	0,00	99,19	
32	Haela_2	50,17	3,08	13,28	13,88	0,29	6,12	10,66	2,77	0,47	0,30	0,05	0,00	101,06	
41	Haela_11	49,83	3,08	12,98	14,71	0,26	5,67	9,89	2,74	0,44	0,38	0,02	0,00	100,00	
42	Haela_12	48,71	3,08	12,86	14,25	0,19	5,74	10,06	2,75	0,37	0,29	0,03	0,05	98,38	
36	Haela_6	49,76	3,03	12,99	14,35	0,24	5,77	9,99	2,83	0,42	0,24	0,00	0,01	99,63	
45	Haela_15	49,41	3,00	12,83	14,44	0,26	5,60	9,88	2,89	0,44	0,34	0,00	0,05	99,14	

No.	Comment	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Cr2O3	F	Total	Grímsvötn
53	Hlodv6	50,91	3,73	12,73	14,72	0,29	4,54	8,36	3,07	0,65	0,49	0,00	0,04	99,53	
57	Hlodv10_mikrolitar	50,35	3,36	12,95	*15,09*	0,20	5,58	10,09	2,57	0,53	0,41	0,05	0,02	*101,20*	
50	Hlodv3	49,70	3,17	12,90	14,70	0,29	5,69	9,91	2,93	0,49	0,36	0,00	0,00	100,15	
58	Hlodv11	49,40	3,15	13,09	14,93	0,22	5,75	9,97	3,01	0,46	0,38	0,00	0,04	100,40	
52	Hlodv5	49,27	3,14	13,22	14,23	0,25	5,64	9,85	2,95	0,46	0,33	0,07	0,08	99,48	
55	Hlodv8	49,68	3,14	12,83	14,31	0,22	5,51	9,91	2,95	0,50	0,33	0,00	0,00	99,38	
62	Hlodv15	49,92	3,12	12,95	14,45	0,25	5,76	10,10	2,88	0,45	0,38	0,03	0,00	100,28	
48	Hlodv1	49,66	3,11	12,72	14,67	0,24	5,69	10,01	2,89	0,44	0,43	0,02	0,04	99,91	
61	Hlodv14	50,41	3,11	13,38	14,60	0,30	5,85	9,99	2,42	0,43	0,31	0,01	0,00	100,80	
54	Hlodv7	49,65	3,06	13,13	14,40	0,23	5,75	9,93	2,82	0,42	0,35	0,00	0,05	99,78	
59	Hlodv12	49,49	3,05	12,94	14,56	0,23	5,64	9,86	2,95	0,40	0,35	0,00	0,01	99,49	
56	Hlodv9	49,50	3,00	13,01	14,33	0,23	5,79	10,04	2,85	0,38	0,37	0,00	0,00	99,50	
60	Hlodv13	49,71	2,94	12,84	14,55	0,26	5,72	9,96	2,83	0,46	0,39	0,01	0,00	99,67	

No.	Comment	SiO2	TiO2	Al2O3	FeO	MnO	MgO	CaO	Na2O	K2O	P2O5	Cr2O3	F	Total	Snæfellsjökul
65	Kjaran3	70,75	0,28	14,70	2,73	0,08	0,10	1,06	4,76	4,59	0,00	0,00	0,08	99,12	
71	Kjaran9	70,66	0,20	15,06	3,31	0,12	0,09	1,14	4,84	4,77	0,03	0,00	0,17	100,39	
73	Kjaran11	70,39	0,18	14,92	2,65	0,15	0,08	1,04	4,64	4,64	0,00	0,03	0,16	98,87	
75	Kjaran13	70,30	0,26	15,04	3,21	0,15	0,09	1,08	4,66	4,67	0,00	0,00	0,14	99,60	
72	Kjaran10	70,24	0,21	14,97	3,11	0,15	0,08	1,11	4,61	4,64	0,05	0,00	0,12	99,30	
63	Kjaran1	70,21	0,27	15,06	3,04	0,13	0,07	1,08	4,88	4,80	0,01	0,00	0,08	99,64	
70	Kjaran8	69,69	0,25	15,08	2,95	0,11	0,08	1,07	4,78	4,48	0,07	0,00	0,08	98,64	
74	Kjaran12	65,24	0,64	15,98	5,60	0,18	0,55	2,53	5,05	3,85	0,14	0,00	0,20	99,96	
69	Kjaran7_vikur	65,19	0,60	15,84	5,68	0,25	0,55	2,62	4,21	3,62	0,12	0,00	0,18	98,86	

Table 2: Results from the geochemical analysis of the three sampled tephras.

3.8 Cosmogenic exposure dating (^{36}Cl)

Three rock samples were collected for cosmogenic exposure dating. Two samples were sampled on Jökulhorn while one weas sampled on Fannalágarfjall. See figure 3.22 for the locations of the samples- Sample H1 was sampled from a tor surface, while H2 and H3 were sampled from erratic boulders (Fig. 3.28). The rock samples were processed at the PRIME-Lab, Purude University in USA and dated to; H1 41.6 kyr BP, H2 17.9 kyr BP and H3 14.0 kyr BP. Ages are based on the production rate of Licciardi et al. (2008) and erosion rates are estimated to e = 0,5cm/kyr.

Table 3: ^{36}Cl cosmogenic surface exposure dates obtained from the plateaux on Hornstrandir. Ages are based on the production rate of Licciardi et al. (2008).

Sample number	Location	Elevation (m a.s.l.)	Position	Type	Age (kyr)	AMS error (± year)
H1	Jökulhorn	675	7364650 N 0428914 W	Bedrock	**41,6**	1124
H2	Jökulhorn	630	7364425 N 0428559 W	Erratic	**17,9**	465
H3	Fannalágarfjall	585	7365235 N 0420978 W	Erratic	**14,0**	392

Fig. 3.28: Sampling rock samples for cosmogenic exposure dating from Fannalágarfjall (Photo: Skafti Brynjólfsson, 2014).

4. Discussion: Late Quaternary glacial history of Hornstrandir

Results from the present study and relevant literature of the glacial history of Hornstrandir are discussed below. A map featuring the geographical names which are used in the discussion are presented in figure 4.1.

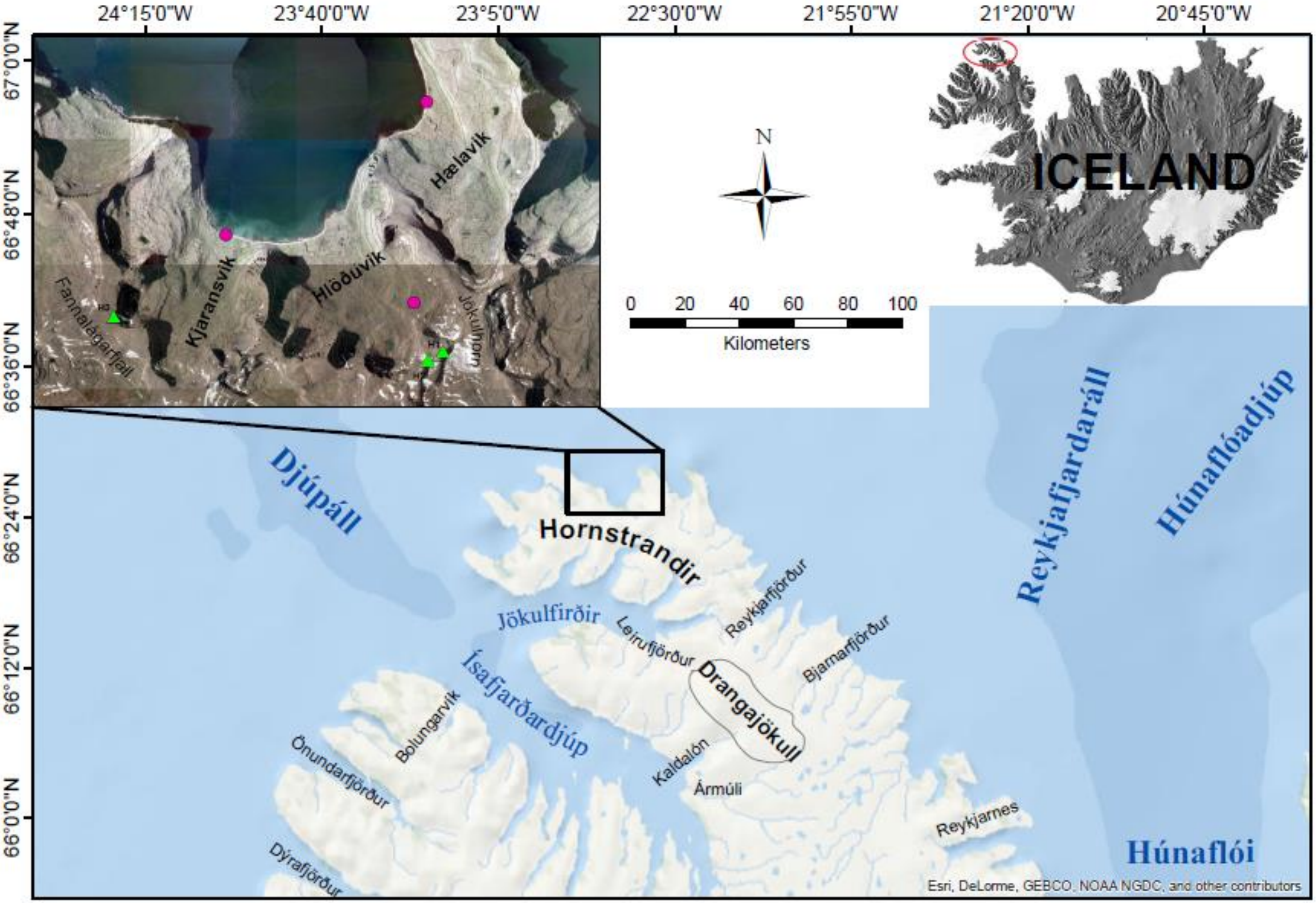


Fig. 4.1: Map over the area which are featured in the discussion. In the insert map are purple dots and green triangles showing the locations of tephra sites and cosmogenic exposure dating sites, respectively.

4.1 Late glacial maximum (LGM)

The ice extent and thickness over Iceland during the LGM has been a much discussed topic over the years. Reconstructions range from an extensive ice cover with no ice free areas (Larusson, 1983; Buckland and Dugmore, 1991) to a refugia model with ice free areas on the high plateaux and nunataks (Hoppe 1982; Einarsson and Albertsson, 1988; Ingólfsson, 1991). It is also believed that Vestfirðir hosted an ice sheet independant from the mainland ice sheet during the LGM (Ingolfsson and Norðdahl, 2001).

From Vestfirðir, Geirsdóttir et al. (2002) studied marine cores from Djúpáll and recognised that IRD was absent from the cores from ca. 22 to 19 kyr, indicating that an extensive land fast ice cover was present over Vestfirðir at that time. Principato et al. (2006) showed that bedrock surfaces at an elevation of 370 m a.s.l. were ice free in Vestfirðir by 20.4 kyr. Erratic boulders dated to 20 -30 kyr BP has also shown that at least some coastal capes and plateaux above Leirufjörður were ice-free during the LGM (Brynjólfsson et al., 2015). It has been suggested that ice filled Ísafjarðardjúp and extended to the north/northeast to the Djupall trough where the ice grounded close to the shelf edge, 100-150 km off the present coast (Principato et al., 2006). 80 – 120 km to the northeast of Vestfirðir, three marine cores have penetrated into late glacial diamict units, suggesting that ice also extended out to the Reykjafjardarál – Húnaflóadjúp trough system during the LGM (Fig. 4.1) (Andrews and Principato, 2002; Principato et al., 2006).

Evidence of the LGM ice sheet on Hornstrandir:

Both the coastal sections 1 and 2 in Hlöðuvík and coastal section 6 in Hælavík show signs of an initial glacial advance, followed by deglaciation and significant sea level rise, then a new glacial advance. The age of the lowermost tills in the three coastal sections have not been established in the present study, but it is likely that the tills were deposited sometime during the LGM. With a substantial ice load at these positions is it likely that the valleys and coastal lowlands in Hornstrandir were fully covered by ice during the LGM. This supports the consensus that Vestfirðir was covered by an extensive ice sheet at this point. At the northern side of Hornstrandir, cirque glaciers are believed to have coalesced to form valley glaciers that flowed northwards (Fig. 4.3). It is not known where the ice margin outside Hornstrandir was situated. Hjort et al. (1985) estimated that the ice terminated 6 – 10 km off the present coast, while other researchers have argued that the ice reached out to the shelf break (e.g. Andrews and Principato, 2002; Principato et al., 2006). Spagnolo and Clark (2009) who produced geomorphological maps based on bathymetric data observed that several glacial troughs were situated on the Icelandic shelf. These troughs mark the presence of former ice streams (Spagnolo and Clark, 2009). Outside Hornstrandir, two glacial troughs extend in a NW direction from Hornvík and the Strandir coast. They reach about 20 km outside the present coast and suggest that ice streams were flowing from Hornstrandir and that they at least reached this position during the LGM (Fig. 4.2). At the south side of Hornstrandir are cirque and valley glaciers thought to have coalesced and flowed into to the ice streams draining through Jökulfirðir and Ísafjarðardjúp (Fig. 4.3).

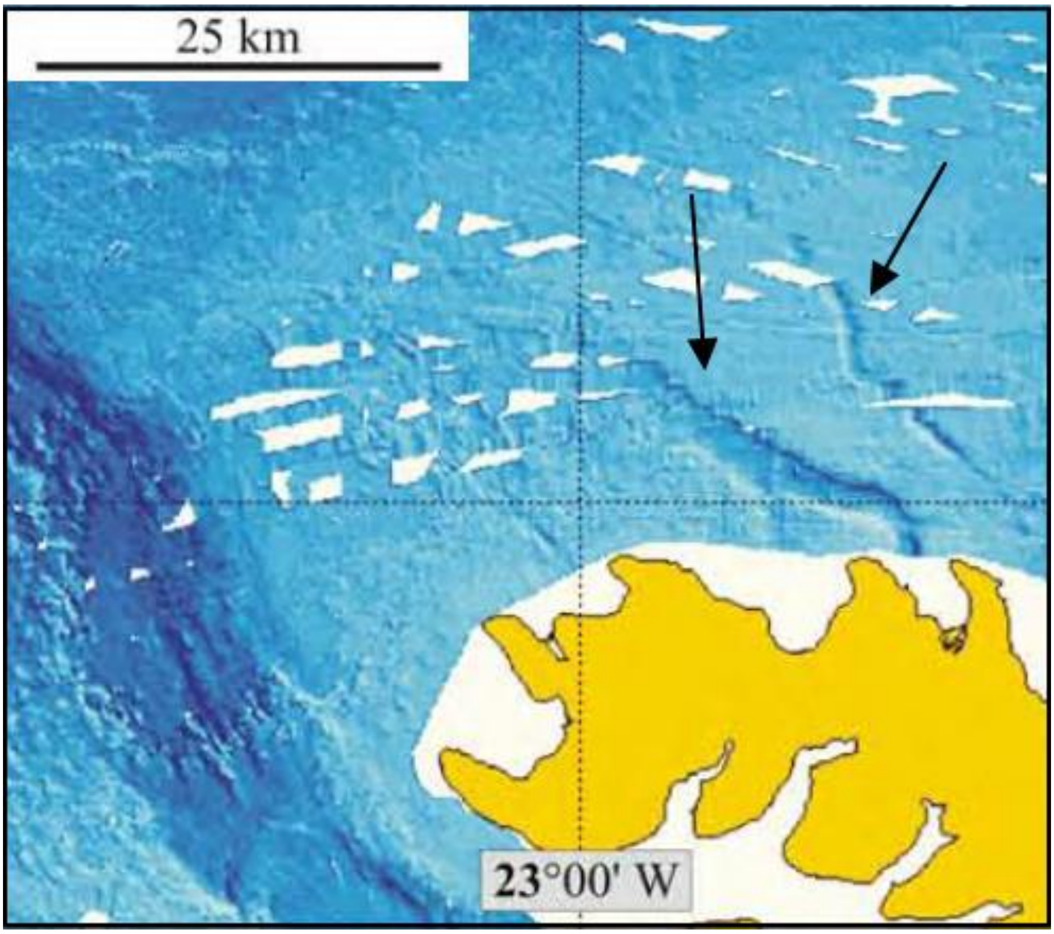


Fig. 4.2: Glacial troughs located outside the coast of Hornstrandir. The seabed is presented as a shaded image with blue colours representing depth. Light blue indicates shallow depths, while dark blue represents deep depths (Spagnolo and Clark, 2009).

Several researchers have proposed that ice free plateaux and nutataks existed in Iceland during the LGM. Hornstrandir has been considered a likely candidate for such conditions (e.g.

Hoppe, 1982; Einarsson and Albertsson, 1988; Ingólfsson, 1991). Principato and Geirsdottir (2002) argued that the geomorphology of the Strandir coast is the result of alpine style glaciation and it is unlikely that ice covered the entire area. They concluded that the topographic features such as bedrock spires, cirques, horns and arêtes, were nunataks during the LGM. The glaciers could have been cold based, but it is unlikely that these features would survive a thick ice cover (Principato and Geirsdóttir, 2002). The plateaux on Hornstrandir are covered with periglacial features such as polygons, block fields and tors which could indicate that the high plateaux weren't covered by active glaciers. Commonly has it been accepted that highly weathered surfaces such as this, took a long time to form and that they therefore must have escaped any recent glaciation. Thus have also highly weathered mountain tops been unglaciated and possibly served as biologic refugia throughout the Quaternary (Briner et al., 2003). Hjort et al. (1985) also recognized that the plateaux showed little signs of being covered by active glaciers and estimated the maximum glacier height to the altitude of these plateau surfaces. However, recent work have concluded that not all highly weathered surfaces can be used as an argument for the absence of LGM ice (Briner et al., 2003). Briner et al. (2005) suggested that difference in weathering zones represent the differential thermal regimes, where the highly weathered uplands were less modified by frozen-bedded ice than the valleys which are highly modified by sliding basal conditions.

The bedrock sample from Jökulhorn (H1) have been dated to 41,6 kyr, suggesting that the bedrock on Jökulhorn has been exposed to cosmic radiation for the last 41,6 kyr and thus ice free during the LGM. The surface is also a highly weathered blockfield with little or no signs of active glaciers. However, due to the "young" erratic (H2) situated nearby isn't the exposure age considered to represent the time of deglaciation of the bedrock. The weathered bedrock is interpreted to contain isotopic inheritance which gives an older exposure age than it actually has. This implies that the periglacial plateau surface at Jökulhorn was covered by cold based ice which preserved the periglacial surface beneath. The erratic boulders that are located on the plateaux must therefore been transported by the deformation of the ice internally, instead of basal sliding. The highest mountain tops on Hornstrandir reach about 700 m a.s.l., no more than ~50 m above the bedrock sample. It is therefore suggested that both lowlands and uplands on Hornstrandir were fully covered by ice during the LGM, but that the ice was differentially erosive as a function of its spatially basal thermal regime. Cold based glaciation of the plateaux was contemporaneous with warm-based glaciation in the valley and fjords. The reason for this could be as Briner et al. (2003) speculated, that the uplands ice was cold based because it was relatively thin and flowed over crystalline bedrock, whereas the ice flowing through the fjords was thick, constrained and flowed over water-saturated unconsolidated sediments. However, due to a little selection of samples scattered over a relatively small area, one cannot say for certain that ice free nunataks at the outermost coast didn’t exist during the LGM.

The two erratic boulders situated on the plateau at Jökulhorn and Fannalágarfjall have yielded ^{36}Cl exposure ages as 17,9 kyr and 14,0 kyr respectively. Both boulders were situated upon a weathered blockfield and could only have been deposited by an ice sheet covering the plateaux. Both erratics rest directly on stable plateau surfaces, hence they have experienced minimal post-depositional shielding or movement. The ages obtained from cosmogenic exposure dating are therefore assumed to date deglaciation of the upland plateaux. The 17,9 kyr Jökulhorn erratic is located 45 m above the 14,0 kyr Fannalágarfjall erratic, indicating that the it took about 4 kyr for the glacier to deglaciate 45 m. The ^{36}Cl cosmogenic exposure dates of erratic boulders from the ~600 m high plateau above Leirufjörður, have shown that the the plateaux were ice free by 20 – 30 kyr. However it should be mentioned that the 20-30 kyr old erratics from Leirufjörður could also be older rocks preserved under less active or even cold based ice, as it is shown in Hornstrandir (Brynjólfsson et al., 2015b). Principato et al. (2006) also showed that ice free areas existed at 370 m a.s.l. in Ármuli by 20.4 cal. kyr BP, indicating that the plateaux at Hornstrandir deglaciated ~2 – 6 kyr later than the plateaux around Drangajökull.

A figure demonstrating a reconstruction of the glacial situation on Hornstrandir during the Last Glacial Maximum is presented in figure 4.3.

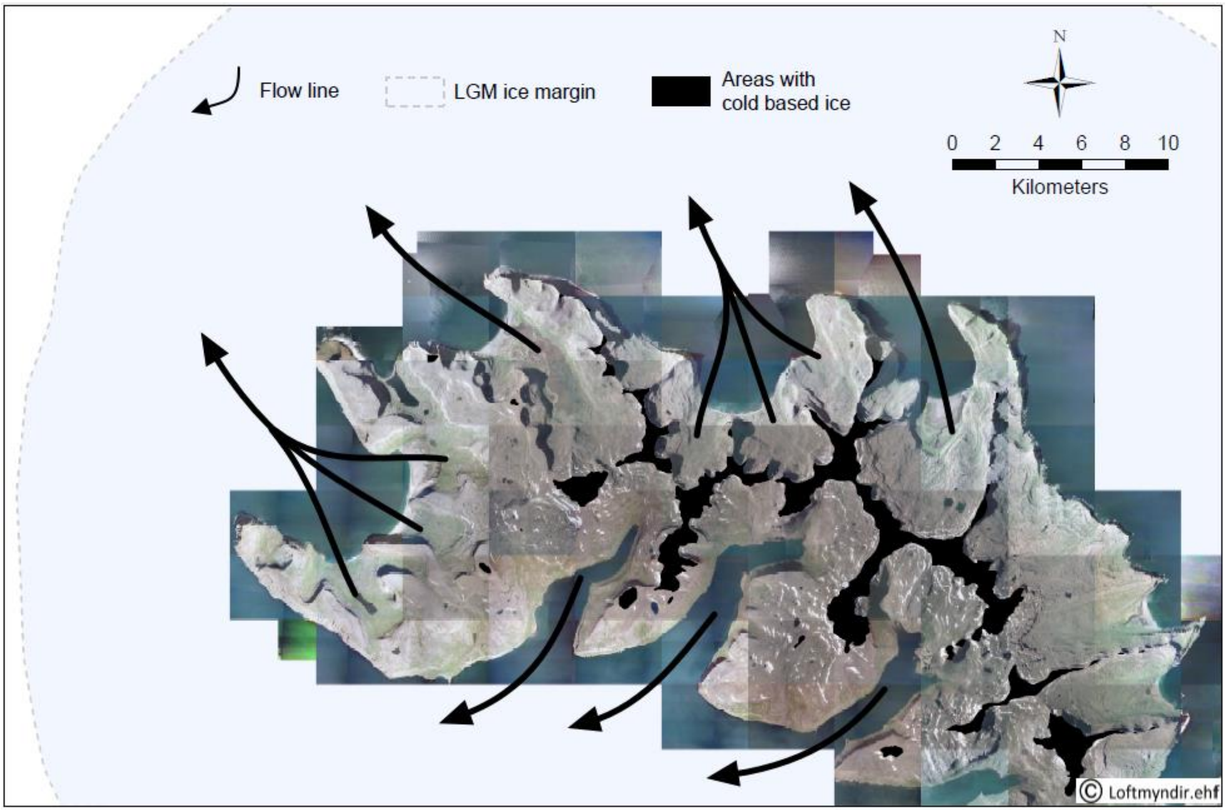


Fig. 4.3: Ice cover on Hornstrandir during the LGM. Based on literature and observations from this study.

4.2 The Bølling Interstadial

Data from the west Iceland shelf suggest that the ice sheet was grounded close to the shelf edge, 100 – 150 km off the present coast, around 15 cal. kyr BP (Jennings et al., 2000; Ingólfsson and Norddahl, 2001; Geirsdóttir et al., 2002). By 14.6 kyr the marine based part of the ice sheet started to collapse and retreated towards present day dry land (Geirsdóttir et al., 2002). This led to greatly elevated shorelines after the deglaciation of the LGM ice sheet (Rundgren et al., 1997). At Reykjarnes on the Strandir coast is a raised beach situated 48 m a.s.l marking the marine limit on eastern Vestfirðir. Along the Ísafjarðardjúp coastline is the marine limit approximately 30 m near Kaldalón, while the marine limit is 14 m near the mouth of Jökulfirðir (Principato, 2008).

Evidence of the Bølling Interstadial on Hornstrandir:

The sand and silt units found in coastal section 1 in Hlöðuvík and coastal section 6 in Hælavík are interpreted to represent the sea level rise during the Bølling Interstadial. The sections suggest that the sea level stood at least 5 - 9 m higher than today. Hjort et al. (1985) argued that an abrasion terrace marked the marine limit in Hælavík at 26-27 m above present sea level. The boulders and clasts found within the unit are interpreted to have been derived from ice rafted debris, originating from calving glaciers. This could suggest that a calving margin was situated further up valley in Hælavík and Hlöðuvík during the Bølling Interstadial. However, the IRD could also have originated from calving margins elsewhere, such as the calving margin situated at the mouth of Ísafjarðardjúp at 15 – 12 cal. kyr BP (Geirsdóttir et al., 2002). The cosmogenic exposure dates of the erratic boulders have also shown that the plateaux were ice free by The Bølling Interstadial time.

4.3 Younger Dryas (YD)

Between 13.9 and 11.5 cal. kyr BP a climatic deterioration induced positive mass balance and increase in ice volume on Iceland. Glaciers extended and the period culminated in Younger Dryas time at about 12 cal. kyr BP (Ingólfsson et al., 2010). Between 13 – 12 kyr the ice sheet reached close to the present coastline. In Vestfirðir were the inlet fjords more or less filled with glaciers from the Vestfirðir Peninsula ice cap that coalesced into the main Ísafjarðardjúp (Geirsdottir et al., 2002).

In Hornstrandir, the uppermost diamicts in the three coastal sections (Nr. 1, 2, and 6) in Hlöðuvík and Hælavík are interpreted to represent a new glacial advance. This glacier advance is suggested to correspond to the Younger Dryas, which would mean that the cirque glaciers on the northern coast of Hornstrandir coalesced to form valley glaciers that reached at least out to the present coast. At Hælavík, the glacier had a thickness of 55 m marked by the lateral moraine mapped 500 m within Hælavíkurbjarg (Fig. 3.8). Several headlands that are situated in the fjords on the southern side of Hornstrandir are interpreted to be remains of moraines (Fig. 4.4). It is believed that these moraines marks the location were calving glacier margins were present during deglaciation of the Younger Dryas ice sheet. IRD found in cores from the shelf and fjord record, suggests the presence of actively calving glacier margins in Jökulfirðir and Ísafjarðardjúp at 12 – 11 cal. kyr BP (Geirsdottir et al., 2002). The moraines situated in the southern fjords in Hornstrandir could represent some of these calving margins (Fig. 4.4). The Vedde ash is dated to 12.0 ± 0.8 cal. kyr BP and has proven to be an excellent marker for the Younger Dryas ice extent (Grönvold et al., 1995). The ash was transported on sea ice and was deposited when the sea ice melted, making it widespread across large parts of the North Atlantic. The Vedde Ash is therefore often used as a proxy for ice free conditions during the Younger Dryas (Birks et al., 1996). A seismic reflector in Jökulfirdir suggests the presence of the Vedde ash, which would mean that the outer part of Jökulfirdir was ice free at that time (Johannsdottir, 2003). The Vedde ash lacks terrestrial locations in Hornstrandir, suggesting that most of the presently dry land on Hornstrandir was covered by ice at 12 kyr. However, ice free nunataks or areas of cold-based ice are likely to have existed on the plateaux and mountain tops on Hornstrandir.

Hjort et al. (1985) recognised a moraine bank outside of Aðalvík and suggested it to have marked the maximum extent of the LGM. The maximum extent of the LGM has later been estimated to have reached out to the shelf (Principato et al., 2006). It is therefore proposed that the shallow banks outside Aðalvík instead represent the Younger Dryas glacier extent.

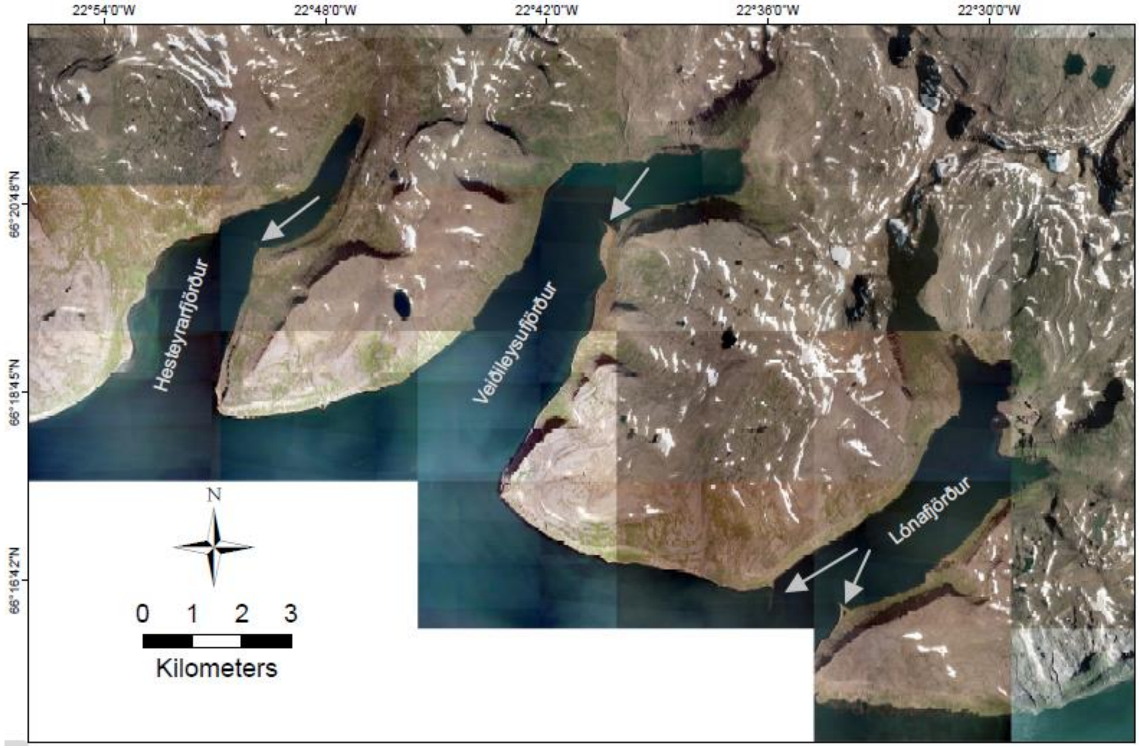


Fig. 4.4: Several headlands interpreted as remains of terminal moraines are situated in the southern fjords on Hornstrandir.

4.4 Preboreal

Ice free conditions in Preboreal time are constrained by the presence of the Saksunarvatn Ash which is dated to 10180 cal. yr BP (Grönvold et al., 1995). The tephra is present in several marine cores from Jökulfirðir and Ísafjarðardjúp, suggesting that the fjords were ice free at the time (Fig. 4.5) (Andrews et al., 2002b).

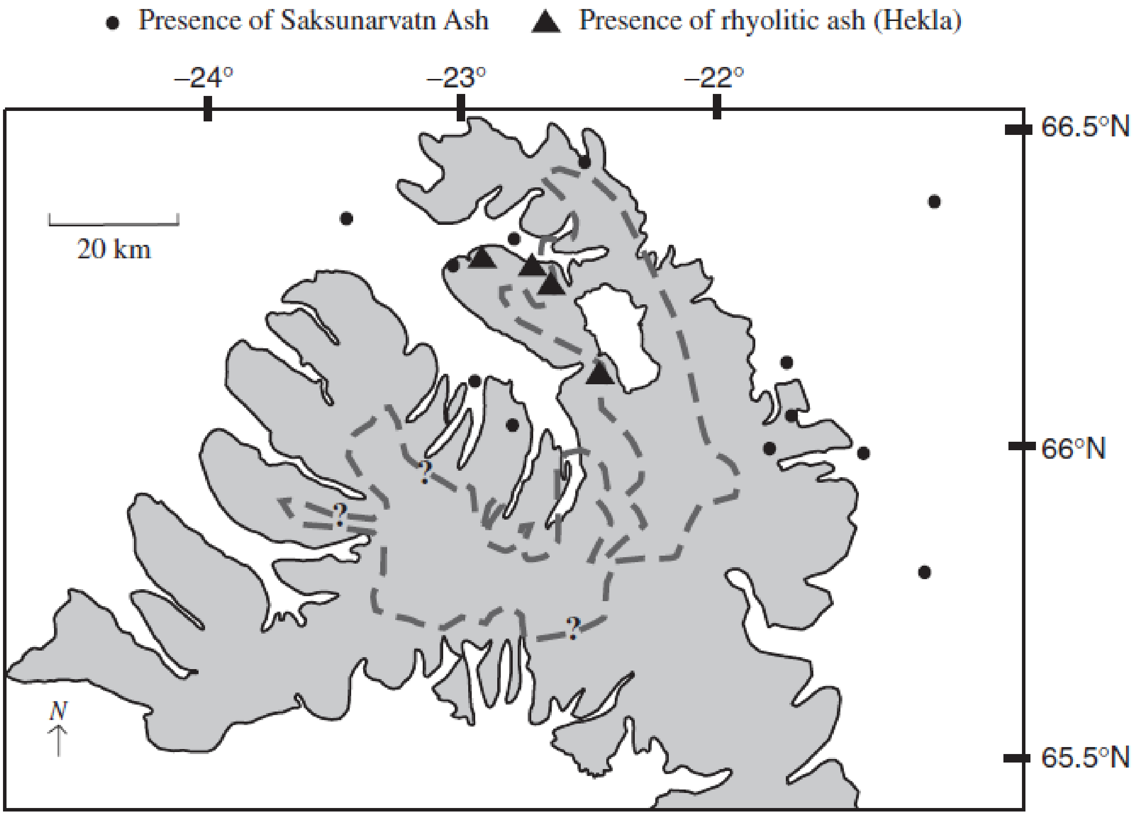


Fig. 4.5: Distribution of the Saksunarvatn Ash and rhyolitic Hekla Ash. The dotted line represents the inferred Preboral ice extent from Principato (2008).

The black tephra named "The Hælavík Tephra", was suggested to be the Saksunarvatn Ash by Hjort et al. (1985). This suggestion has been tested in this study and confirmed. It is believed that the tephra found in coastal section 7 in Hælavík is the same tephra which is referred to as "the Hælavík tephra" in Hjort et al. (1985). The presence of the Saksunarvatn tephra in Hælavík suggests that the valley had ice free conditions at that time. The tephra was deposited in a lacustrine setting, possibly in a kettle hole or a small lake in connection with the hummocky moraines situated just inside of the present coast. With hummocky moraines in the valley lowlands at that time, the glacier margin in Hælavík must have been situated much further up in the valley. The glacier margin in Hælavík is probably marked by the moraines which have been mapped at the head of the valley (Fig. 3.8). The tephra found in Hlöðuvík, has also chemical characteristics linking it to the Saksunarvatn Ash. The tephra was found within the outermost moraines situated about 2 km up in the valley inside Hlöðuvík (Fig. 3.22). This suggests that most of Hlöðuvík was ice free at the time. If both Hælavík and Hlöðuvík were more or less ice free at 10.2 cal. kyr BP is it likely that the rest of the northern part of Hornstrandir experienced the same kind of restricted glacier cover.

On the southern part of Hornstrandir, several of the valleys and cirques host well developed moraines, mapped as “old moraines” (Fig. 3.2, 3.3, 3.4, 3.5). None of the moraines are dated, but due to their morphology and general appearance, they are interpreted to be older than the Little Ice Age. IRD are found in marine cores from Jökulfirdir between 12 – 11 kyr but is absent from the fjord record by 10 kyr. This suggests that glaciers in Jökulfirdir had retreated up on presently dry land by that time (Geirsdóttir et al., 2002). The old moraines mapped in Hornstrandir are therefore likely to have formed sometime around or shortly after 10 kyr. The outermost lateral and terminal moraines in Leirufjörður is dated to 9.2 kyr BP (Brynjólfsson et al., 2015). With moraines forming in Leirufjörður could moraines also have formed on Hornstrandir around the same time. Several researchers have also reported that a glacier advance or stillstand occurred in Iceland around 9.8 – 9.6 kyr BP, supporting that the morines on Hornstrandir formed in the early Preboreal (e.g. Ingolfsson, 1991). Glaciers in Iceland are considered to have retreated to their minimum extent during the Holocene Thermal Maximum (HTM) at 5.0 cal kyr BP (Flowers et al., 2008; Ingólfsson et al., 2010). The Neoglaciation began shortly after the HTM, marked with glacier advances and ice cap growth (Stotter et al., 1999). However, in most places in Iceland, the LIA advances were the most extensive during the Holocene. The old moraines mapped at Hornstrandir are located outside of the LIA moraines and they are therefore considered to have been formed sometime prior to the LIA. The old moraines must therefore at least yield an age sometime between 10 - 5 kyr. However, it is most likely that the moraines formed during a small readvance or stillstand during the general deglaciation of the Vestfirðir ice cap around 10 - 9 kyr.

The outermost old moraines in several valleys have been used to create a map, estimating the glaciated area on Hornstrandir sometime around 10 kyr (Fig. 3.9A). The total glaciated area has been estimated to 44 km^2. This figure, which is solely based on mapped terminal moraines, is recognized as a minimum case scenario. It is likely that several valleys and cirques that were seemingly deglaciated, contained cold based glacier that did not leave a geomorphological fingerprint on the landscape. The total glaciated area was therefore probably more extensive than the terminal moraines indicate.

4.5 Neoglacial period

Neoglaciation began after the HTM at 5.0 cal. kyr BP and was marked by growth of glaciers and ice caps all over Iceland. The advances appeared in clusters in two intervals: The Sub-Atlantic period (2.6 – 2.0 cal. kyr BP) and during the Little Ice Age (Björnsson and Pálsson, 2008; Ingólfsson et al., 2010). In Vestfirðir Principato (2008) mapped raised beaches parallel to the coastlines of Jökulfirðir and Ísafjarðardjúp at an elevation of approximately 5 m a.s.l. The raised beaches range in age from ~ 3000 to 123 ± 46 cal. yr BP, suggesting several minor transgression events, where the younger dates suggests that beaches at the same elevation were reoccupied several times (Principato, 2008).

On Northern Hornstrandir, three coastal sections (Kjaransvík 1, Kjaransvík 2 and Hælavík 1) were described and interpreted as beach deposits, indicating a sea-level 2 – 3 m higher than today. In Kjaransvík the dated driftwood and tephra yielded ages around 2000 cal. yr BP and 1900 cal. yr BP respectively. In Hælavík, the sampled driftwood was dated to about 1400 cal. yr BP. All these coastal sections suggest that a minor transgression event occurred between 1400 and 2000 cal. yr BP. It is believed that the transgression recorded by the coastal sections in Hornstrandir coincides with some of the transgression events described by Principato (2008). The cause of this transgression probably relates to the lithospheric depression following the Sub-Atlantic expansion of glaciers. Unlike most regions in Iceland, the Neoglacial moraines, and not the LIA moraines, mark the most extensive Holocene glacier advance on eastern Vestfirðir (Principato, 2008). At the nearby Drangajökull ice cap, did the Reykjarfjörður and Kaldalón outlet glaciers reach their Holocene maximum during Neoglaciation, while the third outlet glacier, Leirufjörður, did not reach its maximum until the LIA (Brynjólfsson et al., 2015). Whether this is the case for Hornstrandir is not known, but it is likely that several cirques were reoccupied throughout the Neoglaciation to a larger extent than during the LIA.

4.6 Little Ice Age (LIA)

The most extensive glacier advances in Iceland during the Holocene occurred during the Little Ice Age (Gudmundsson, 1997; Ingólfsson et al., 2010). Small valley and outlet glaciers reached their maximum around AD 1750 (Björnsson and Pálsson, 2008). The three outlet glaciers of the Drangajökull ice cap (Fig. 4.1) reached their LIA maximum asynchronously during surges in the period AD ~ 1700 – 1846 (Brynjólfsson et al., 2015a). Hjort et al. (1985) recorded that the LIA glaciers in Hornstrandir had their maximum extent by AD 1860 and that most glaciers had disappeared by AD 1920.

Evidence of the Little Ice Age on Hornstrandir are as follows:

Moraines interpreted to be LIA moraines are mapped at several locations on Hornstrandir (Fig. 3.2, 3.3, 3.4, 3.5). In Hlöðuvík two out of the seven cirques contain LIA moraines in front of them. Thoroddsen (1982a; 1982b) recognised that the moraines situated at the head of the Hlöðuvík valley were formed during the Little Ice Age. The presence of a well preserved fluted surface within the LIA moraines in Hlöðuvík supports that the moraines have been formed recently. Old local names for cirques and valleys on Hornstrandir also indicate that at least perennial snow fields or glaciers were present during the Little Ice Age. The valley inside Hlöðuvík is for instance called "Jökladalur", meaning "Glacier valley", suggesting that the valley contained larger glaciers at that time than it is today.

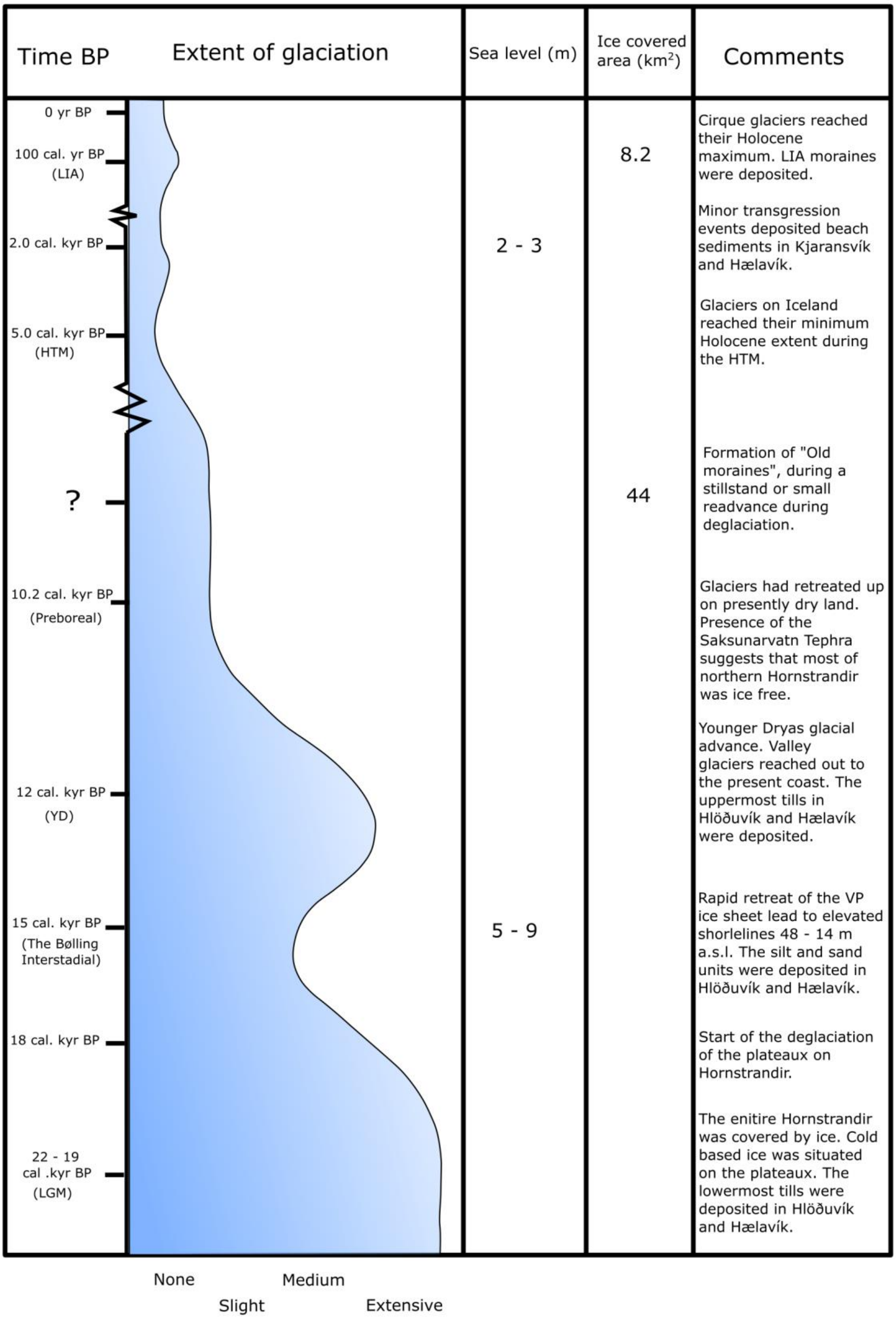
On Hornstrandir the LIA glacier extent has been constrained by the LIA moraines. The terminal moraines occur in front of cirques and valley sides and mark the maximum extent of LIA glaciation. The LIA moraines occur in front of 16 cirques, where nine of the cirques still contain glacier ice. None of the LIA moraines have been dated so their age is based on interpretation of their geomorphological characteristics, vegetation cover and comparison to older moraines. For a more accurate estimate, more fieldwork should be carried out with the purpose of dating the moraines. The LIA in Iceland was characterized by a cool climate with temperature depressions of 1 – 2 °C compared to the AD 1961 – 1990 average (Geirsdottir et al., 2009). Cirques that presently host glacier ice, but lack any geomorphological fingerprint are therefore also considered to have been glaciated during the LIA. However, the maximum extent of these cirque glaciers is unknown. Figure 3.9B presents a reconstruction of the glacier extent on Hornstrandir during the LIA. The extent of LIA glaciers has been drawn to the outermost LIA moraines. In glaciated cirques without any moraines, only the present glacier ice is mapped. It has been estimated that 21 cirques were glaciated during the LIA. Together, the total glaciated area during the LIA has been calculated to 8.2 km^2. Hjort et al. (1985) calculated the total LIA glacier extent to be 8 – 10 km^2, which fits well the estimate from the present study.

Hjort et al. (1985) also concluded that cirques in Kjaransvík, Hlöðuvík and Hælavík were glaciated during the LIA. In this study, only Hlöðuvík has been considered to have been glaciated. In Kjaransvík and Hælavík no signs of LIA glaciation were recognised during fieldwork. From aerial photographs, moraines have been mapped in both Kjaransvík and Hælavík, but their appearance does not suggest any recent glaciation as the LIA moraines in Hlöðuvík do. While Hjort et al. (1985) only mapped glacial landforms at the western and northern part of Hornstrandir, this study has mapped LIA glaciers extent throughout the entire Hornstrandir. Taking in account the difference in study area, the results from this study indicate a more limited LIA extent than suggested by Hjort et al. (1985).

Most of the LIA moraines are located in front of cirques that are facing an S-SW direction. These cirques face the lee side of the main wind direction (main wind direction is from NE (Einarsson, 1976)) suggesting that wind transported snow was the main reason for glacier growth during the LIA. Similar conclusions have been made for the perennial snow fields in the area surrounding the Drangajökull ice cap (Brynjólfsson et al., 2014).

5. Conclusions

- This thesis has presented detailed geomorphological maps of the Hornstrandir peninsula in Iceland. Landforms such as terminal moraines, hummocky moraines, flutes, raised beaches and rock glaciers were mapped.
- The Saksunarvatn Ash has been sampled in both Hlöðuvík and Hælavík, while the Snæfellsjökull-1 tephra has been sampled in Kjaransvík.
- Cosmogenic exposure dating from the plateaux have revealed that the entire Hornstrandir were probably covered by ice during the LGM.
- Moraines mapped as LIA moraines and "*Old moraines*" have been used to reconstruct the glacier extent on Hornstrandir during the LIA and during Preboreal time.
- The glacial history on Hornstrandir has been interpreted as follows:
    - During the LGM, the entire Hornstrandir was covered by ice. Cirques glaciers coalesced to form valley glaciers that flowed northwards towards the shelf break. These glaciers deposited the subglacial tills in Hlöðuvík and Hælavík. The upland plateaux were covered by cold based ice which preserved the periglacial surface beneath. The plateaux weren't deglaciated until 18 – 14 kyr BP.
    - By the Bølling Interstadial, glaciers had retreated further back than the present coastline. Fine sand and silt units in Hlöðuvík and Hælavík indicate that the sea-level stood at least 5 – 9 m higher than today.
    - The glacier advance during the Younger Dryas reached at least out to the present coast. Subglacial tills were deposited in Hlöðuvík and Hæalvik.
    - By Preboreal time, most of Hornstrandir was deglaciated as indicated by the Saksunarvatn Ash.
    - During Neoglaciation, small transgression events occurred as seen from raised shorelines in Kjarnasvík and Hælavík.
    - By the LIA, 21 cirques on Hornstrandir were glaciated, with a total area of 8,2 km^2.
- A summary of the glacial history of Hornstrandir is presented in Figure 5.1.



Time BP	Sea level (m)	Ice covered area (km^2)	Comments
0 yr BP			
100 cal. yr BP (LIA)		8.2	Cirque glaciers reached their Holocene maximum. LIA moraines were deposited.
2.0 cal. kyr BP	2 - 3		Minor transgression events deposited beach sediments in Kjaransvík and Hælavík.
5.0 cal. kyr BP (HTM)			Glaciers on Iceland reached their minimum Holocene extent during the HTM.
?		44	Formation of "Old moraines", during a stillstand or small readvance during deglaciation.
10.2 cal. kyr BP (Preboreal)			Glaciers had retreated up on presently dry land. Presence of the Saksunarvatn Tephra suggests that most of northern Hornstrandir was ice free.
12 cal. kyr BP (YD)			Younger Dryas glacial advance. Valley glaciers reached out to the present coast. The uppermost tills in Hlöðuvík and Hælavík were deposited.
15 cal. kyr BP (The Bølling Interstadial)	5 - 9		Rapid retreat of the VP ice sheet lead to elevated shorlelines 48 - 14 m a.s.l. The silt and sand units were deposited in Hlöðuvík and Hælavík.
18 cal. kyr BP			Start of the deglaciation of the plateaux on Hornstrandir.
22 - 19 cal .kyr BP (LGM)			The enitire Hornstrandir was covered by ice. Cold based ice was situated on the plateaux. The lowermost tills were deposited in Hlöðuvík and Hælavík.

Fig. 5.1: Summary of the glacial history on Hornstrandir. Based on literature and observations from this study.

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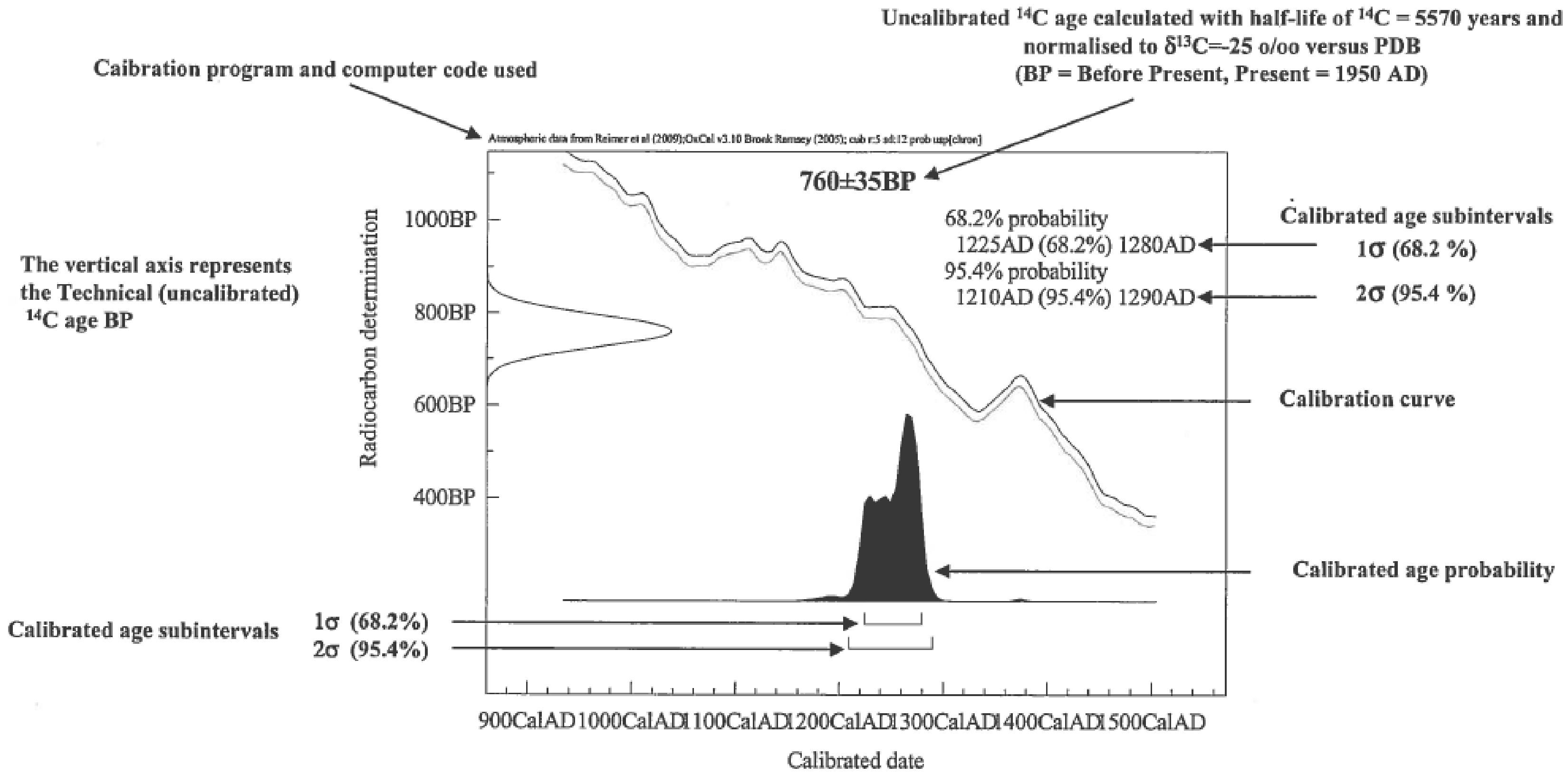
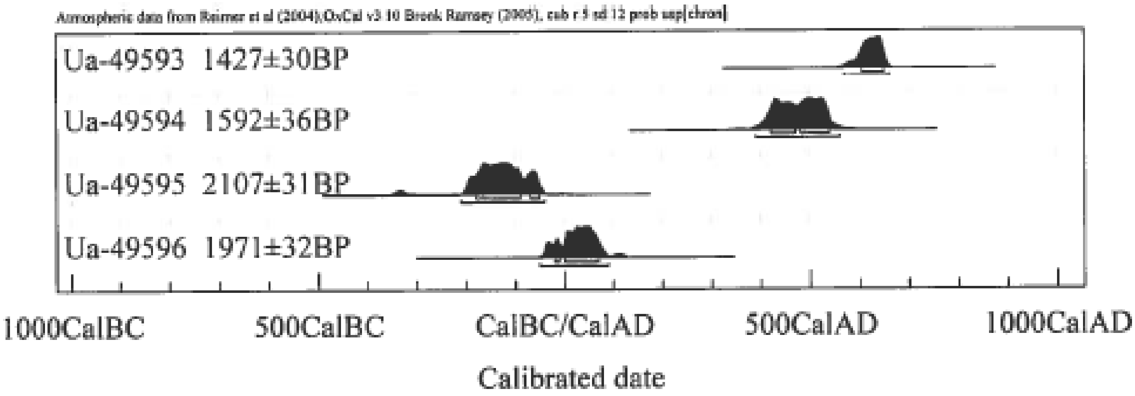
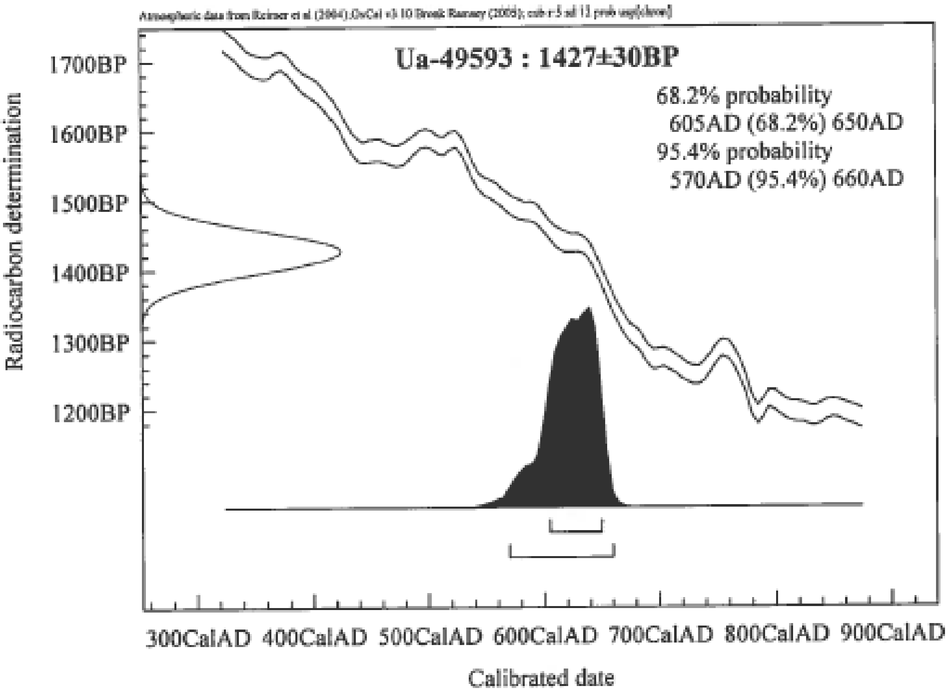
7. Appendix

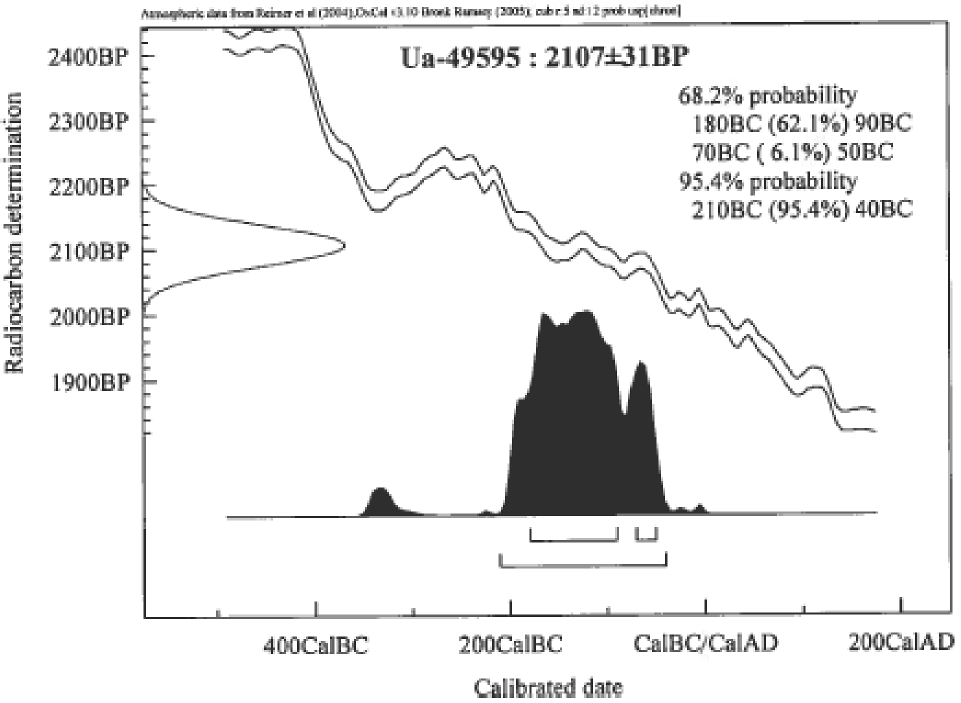
Explanation of the radiocarbon calibration output from the OxCal program

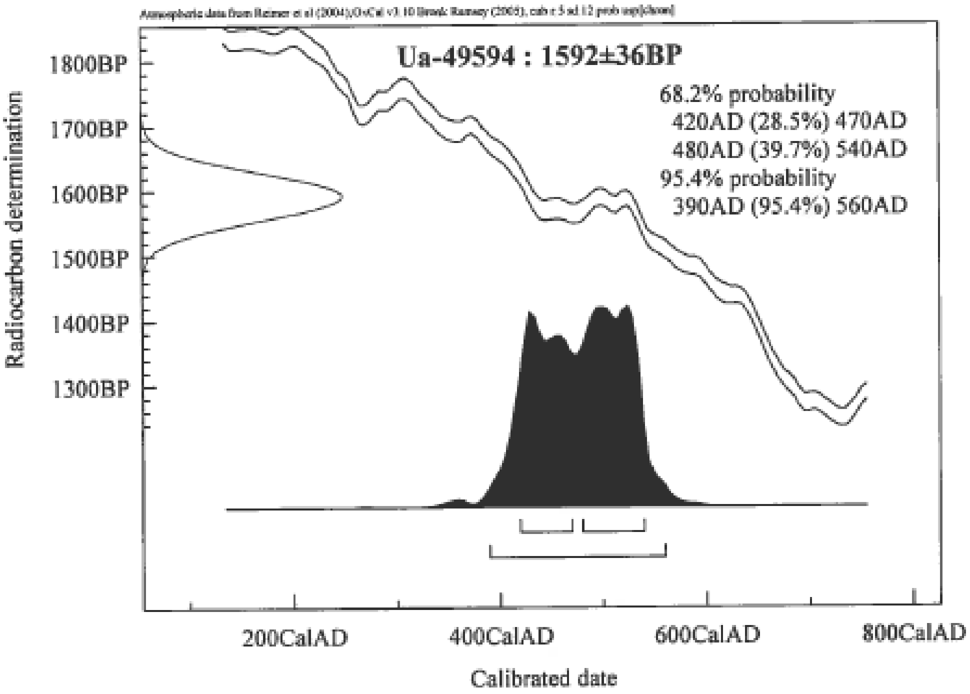


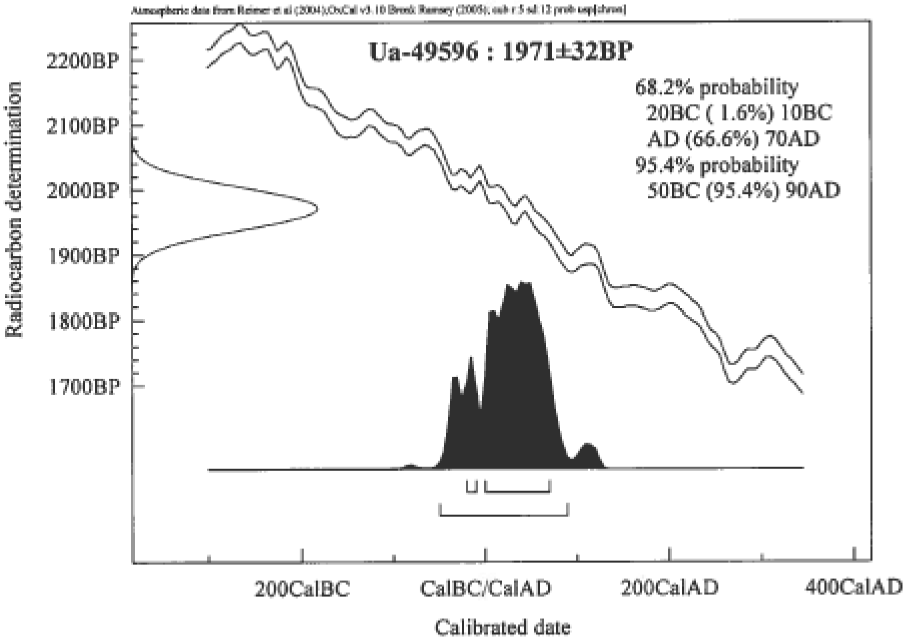
The horizontal axis represents the calibrated (calender) age


Atmospheric data from Reimer et al (2004);OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd:12 prob usp[chron]
Ua-49593 1427±30BP
Ua-49594 1592±36BP
Ua-49595 2107±31BP
Ua-49596 1971±32BP
1000CalBC
500CalBC
CalBC/CalAD
500CalAD
1000CalAD
Calibrated date


Atmospheric data from Reimer et al (2004);OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd:12 prob usp[chron]
Ua-49593 : 1427±30BP
68.2% probability
605AD (68.2%) 650AD
95.4% probability
570AD (95.4%) 660AD
Radiocarbon determination
1700BP
1600BP
1500BP
1400BP
1300BP
1200BP
300CalAD
400CalAD
500CalAD
600CalAD
700CalAD
800CalAD
900CalAD
Calibrated date


Atmospheric data from Reimer et al (2004);OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd:12 prob usp[chron]
Ua-49595 : 2107±31BP
68.2% probability
180BC (62.1%) 90BC
70BC (6.1%) 50BC
95.4% probability
210BC (95.4%) 40BC
2400BP
2300BP
2200BP
2100BP
2000BP
1900BP
Radiocarbon determination
400CalBC
200CalBC
CalBC/CalAD
200CalAD
Calibrated date


Atmospheric data from Reimer et al (2004);OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd:12 prob usp[chron]
Ua-49594 : 1592±36BP
68.2% probability
420AD (28.5%) 470AD
480AD (39.7%) 540AD
95.4% probability
390AD (95.4%) 560AD
1800BP
1700BP
1600BP
1500BP
1400BP
1300BP
Radiocarbon determination
200CalAD
400CalAD
600CalAD
800CalAD
Calibrated date


Atmospheric data from Reimer et al (2004);OxCal v3.10 Bronk Ramsey (2005); cub r:5 sd:12 prob usp[chron]
Ua-49596 : 1971±32BP
68.2% probability
20BC (1.6%) 10BC
AD (66.6%) 70AD
95.4% probability
50BC (95.4%) 90AD
Radiocarbon determination
2200BP
2100BP
2000BP
1900BP
1800BP
1700BP
200CalBC
CalBC/CalAD
200CalAD
400CalAD
Calibrated date