Development of the Ósmelur sedimentary sequence in Hvalfjörður, W-Iceland

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Development of the Ósmelur sedimentary sequence in Hvalfjörður, W-Iceland

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Abstract

Sedimentary structures of the Ósmelur sediment formation are studied in this thesis in order to determine its formation and development. Presented are eight stratigraphical sections which were investigated with state-of-the-art field techniques, along with interpretation of aerial images, bathymetric data, radiometric datings of shells and chemical analyses of tephra. Although the Ósmelur formation represents both vertical and lateral changes in sedimentary facies, five major sedimentary units are recognized along with two glacial deposits. Radiocarbon datings on shells from the lowest and oldest unit yielded a median probability age of 14.191 cal. ka BP. Unit 2 shows signs of a regressive phase, with sandy, fluvial deposits. Unit 3 suggests climate deterioration and transgression of relative sea level, established with Unit 4, which contains radiocarbon dated shells which yielded median probability age of 13.199 cal. ka BP. Unit 5 consists of cobbles and boulders, deposited in a regressive phase in a littoral, high energy environment when isostatic rebound was occurring due to a glacier retreat. A hiatus divides Ósmelur into two parts, a table-shaped one to the west, and a terrace-shaped one to the east. This study reveals that this hiatus was caused by an erosional event, when a glacial river and a glacier from the Miðdalur valley eroded the upper/younger part of the eastern part in late Allerød or early Younger Dryas, leaving glaciofluvial sediments and a meltout till on top of it. This glacier did not reach the western formation, but a glacier from Hvalfjörður fjord reached its shoulder, leaving evidences such as diamicton and striated clasts.
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Abbreviations

a.s.l.: above sea level
BP: Before present
Cal.: Calibrated
DEM: Digital elevation model
E: East
ESL: Eustatic sea level
IIS: Icelandic ice sheet
ka: kilo annum
km: kilometre
LGM: Last glacial maximum
LIA: Little ice age
m: metre
mm: millimetre
myo.: million years old
myr: million years
Mwp-1a: Meltwaterpulse 1A
ML: Marine limit
N: North
NE: Northeast
NW-Northwest
GIU: Glacio-isostatic uplift
RESL: Relative eustatic sea level
RSL: Relative sea level
S: South
SE: Southeast
SW: Southwest
W: West
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1 Introduction

1.1 Motivation

Sedimentary sequences can provide important information on environmental developments. Through their different appearances processes can be interpreted and thereby get an insight into environmental changes such as glacial-isostasy, ice-marginal changes and past ice dynamics. Fluctuations in relative sea level have been used to interpret variations in extent of glaciers since the LGM and different landforms were formed during each environmental phase. Geoscientists have studied both terrestrial and marine environments and attempted to interpret palaeo conditions that can later be used as a modern analogue for future environmental developments.

The Ósmelur sedimentary sequence is an erosional remnant on the southwestern coast of Hvalfjörður. It is divided into two parts, separated by an erosional hiatus. It has hitherto been interpreted as a submarine formation that was formed when an outlet glacier in Hvalfjörður was calving and thus releasing material from its basal parts into the sea which subsequently was deposited on the bottom of the fjord. As changes in relative sea level took place, Ósmelur evolved and built up. However, little attention has been paid to the different geomorphological appearance of the two parts and they have been described as a unity, formed by comparable processes. Further, no bathymetric data has yet been taken into account to establish whether the main factor was in fact the outlet-glacier in Hvalfjörður. A detailed, multicriteria study of Ósmelur was therefore necessary to conclude up on its formation.

1.2 Scope of the Thesis and Approach

The main focus of the present thesis will be stratigraphic logs in combination with geomorphological interpretation of areal images. Bathymetric data and clast fabric analysis are presented to further assist interpretation along with previously radiometric datings of mollusc shells. Two tephra samples were chemically analyzed. It is essential to consider all these datasets to be able to understand past processes during the build-up of the Ósmelur sedimentary sequence.

A total of eight sections were excavated and logged, six in the western part and two in the eastern part. The sections are individually described and in context to each other, also describing additional features observed in the field such as escarpments and lateral changes. Bathymetric data, provided by the Icelandic Coastguard, turned out to be very insightful and corroborated the suggestion that Ósmelur is made of two sedimentary formations resulting from interaction between a Hvalfjörður outlet-glacier and a valley-glacier flowing out of the Miðdalur valley, where the latter one contributed considerably more to the built-up of Ósmelur than previously thought. The geomorphological interpretation is largely based on aerial images taken with a DJI Phantom 4 drone. A clast fabric analysis was performed on conspicuous fluvial looking sediments.
An attempt to get a clear perspective on the history of Ósmelur is attempted by analyzing all datasets in context to each other. The aim of this thesis is to provide an insight into this history. It is suggested that Ósmelur is largely formed in a subaerial, deltaic environment when glaciers in the Hvalfjörður fjord and Miðdalur valley started to retreat in Late Weichselian time and that sediments of the eastern part were eroded by a glacier flowing out of the Miðdalur valley, leaving glaciofluvial sediments and meltout till as an evidence for that event in the upper sectors of the eastern part.
2 The Last Deglaciation of Iceland

The last glacial, the Weichselian was initiated ca 110 cal. ka BP. It is generally divided into three stages, Early, Middle-, and Late Weichsel. The Late Weichsel ice sheet became the largest and it starting to expand around 28.0 cal. ka BP (Siegert et al., 2001). The Last Glacial Maximum (LGM) thus occurred in Late-Weichselian time and it is thought to have reached its peak in Europe 25.0 cal. ka BP, but in Iceland it has been constrained between 24.4 and 18.6 cal. ka BP by dates from sediments in outer part of the Reykjanes peninsula and from sediment cores retrieved from the shelf north and west of Iceland (Norðdahl and Ingólfsson, 2015). It is generally believed that the Icelandic ice sheet (IIS) responded considerably later to climate forcing than ice sheets in North America, Scandinavia and the Barents Sea, which had by this time been retreating for thousands of years and thereby delivering great amount of freshwater to the oceans and causing global sea level rise (Norðdahl et al., 2008). The position of Iceland on a hot spot over plate boundaries and close to the polar front, make it very sensitive to changes in global temperature and changes in ocean circulation (Geirsdóttir, 2011; Ingólfsson and Norðdahl, 1994). On basis of geomorphological evidence such as glacial striae, glacially carved landscape and position of glacial deposits both on land as well as off shore, Iceland is considered to have been covered with a glacier that reached far out onto the Icelandic shelf (Einarsson and Albertsson, 1988). However, we still lack evidence to fully determine the LGM extent of the IIS (Geirsdóttir, 2011). The average thickness of the IIS has been estimated to 940 m with a maximum thickness of more than 2000 m above central parts of Iceland based on erratics and glacial striae on top of high coastal mountains and modelling of the maximum situation (Pétursson et al., 2015; Norðdahl et al., 2008, Hubbard et al. 2006). As considerable proportion of the Icelandic ice sheet was marine-based in LGM times, it was sensitive to changes in relative eustatic sea level as well as to changes in sea temperatures that eventually took place, mainly driven by increased solar insolation (Hubbard, 2006; Norðdahl and Ingólfsson, 2015; Norðdahl et al., 2008). Norðdahl and Ingólfsson (2015) suggest that the deglaciation occurred stepwise, starting at 18.6 cal. ka BP by a slow deglaciation of the outer shelf. This process was caused by warmer sea-water and sea-level rise causing grounding line retreat of the marine based part of IIS. Figure 2.1 demonstrates the LGM extent of the IIS.
The Bølling interstadial was characterized by an ongoing deglaciation and relative sea-level rise (Ingólfssson et al., 2010). At 15.0 cal. ka BP, the second phase of the deglaciation of Iceland took over with an extremely rapid glacial retreat from the shelf areas, a process that occurred in only 300 cal. years due to a fast sea-level rise and intensive calving. This suggestion of an extremely quick retreat is supported by a dated sediment core taken from the shelf off West Iceland, in which a series of radiocarbon dates with an extrapolated basal age of the core and thus also a minimum date for a retreat of the IIS and beginning of marine sedimentation in that part of the shelf off West Iceland was established. Further, high marine limit (ML) shorelines in Iceland have been radiocarbon dated in a few places. In West Iceland, only 20 km apart, the Stóri-Sandhól and Stóra-Fellsöxl ML shorelines are found at 150 and 105 m a.s.l., respectively. Radiocarbon dated shells at Stóri-Sandhóll and a whalebone at Stóra-Fellsöxl returned an average age of 14.7 cal. ka BP. It is thus highly likely that during the time from 15.0 to 14.7 cal. ka BP, glaciers retreated from the shelf and onto land, causing the formation of the elevated ML shorelines when a temporary equilibrium between the rate of glacio-isostatic uplift and relative eustatic sea level rise prevailed (Norðdahl and Ingólfsson, 2015). The third and last phase of the deglaciation was, according to Norðdahl and Ingólfsson (2015), a steady, but slower retreat of the IIS that by 14.7 cal. ka BP was already inside the coastline. Inland features in Northeast Iceland, such as the estimated ages of lava capped tuyas and subaerial lava flows both from the Þeistareykir volcano and the Krafla volcano affirm that large areas in Northeast Iceland were ice free and that by 13.8 cal. ka BP only 20% of the LGM IIS remained (Licciardi et al., 2007; Ingólfssson et al., 2010; Sæmundsson, 1991; Norðdahl and Ingólfsson, 2015; Pétursson et al., 2015; Norðdahl and Pétursson, 2005). Although the IIS had retreated substantially inside the

Figure 2.1 The Icelandic ice sheet at LGM. (From Pétursson et al., 2015).
present coast in Southwest and Northeast Iceland, Norðdahl et al., (2008) pointed out that the IIS persisted in the South and Southeast Iceland. Figure 2.2 shows a hypothetical outline of the IIS after the Bølling deglaciation.

![Hypothetical outline of the IIS](image)

**Figure 2.2 After the Bølling deglaciation, only 20% of the IIS remained. (From Pétursson et al., 2015).**

More climatic improvements occurred during the Allerød interstadial in Iceland. Initially, it was a cold marine-environment with the coastal areas being largely submerged in the sea but due to the rapid Bølling glacial retreat and thereby reduction of glacier load on the crust, the rate of glacio-isostatic uplift was far greater than the rate of eustatic sea level rise. The result was that relative sea level (RSL) fell fast, well below the marine limit shorelines in Northeast and Southwest Iceland (Ingólfsson et al., 2010). Arctic mollusc species in fossiliferous marine sediments have been described e.g. in Breiðafjörður, Borgarfjörður and Reykjavík. In Borgarfjörður, the accumulation of the sediments indicates that towards the latter part of Allerød RSL rose again (Norðdahl et al., 2012; Ingólfsson et al., 2010; Norðdahl et al., 2008). Cold favoring mollusc species such as *Portlandia arctica* and *Buccium groenlandicum* along with a rather quick sedimentation and brackish water caused by the inflow of glacier meltwater show that cold arctic ocean circumstances existed in late Allerød times, and transgression of RSL occurred again due to both glacier growth and therefore a subsidence of the crust, as well as by rise of eustatic sea level (Ingólfsson, 1988; Norðdahl et al., 2008).

The climate deteriorated further in Younger Dryas times, when glaciers continued to expand and overrun areas that had been inundated by the sea during the Allerød Chronozone. Areas that had been ice-free ever since the Bølling were again overrun by an expanding IIS and around in Iceland evidence such as truncated shorelines at the mouths of fjords and valleys indicate both the extent the marine environment as well as the extensive glaciation
of the Younger Dryas Stadial which prevented formation of shorelines (Norðdahl and Pétursson, 2005; Norðdahl et al., 2008; Ingólfssson et al., 2010). An evident collapse in the concentration of pollen along with a much less lake productivity has been identified through studies made on a sediment core from the bottom of Lake Torfadalsvatn on the Skagi peninsula in North Iceland (Rundgren, 1995, 1999). Cooling trends have also been noted in cores from the shelf areas. Off North Iceland, two cores were retrieved from east and west of the Kolbeinsey ridge (Eiríksson et al., 2000) where studies of foraminifera and sediments along with identification of the constraining Vedde and Saksunarvatn tephra layers indicate a deteriorating climate in Younger Dryas times. The same cooling trend was also seen in a core from the shelf area in the outer Faxaflói Bay, Southwest Iceland (Jennings et al., 2000). It is not exactly known when the IIS started to withdraw from its Younger Dryas position, but information gathered from the Greenland ice cores demonstrate a swift change towards a milder climate at the end of Younger Dryas (Dansgaard et al., 1989; Rasmussen et al., 2006). Figure 2.3 shows the extent of the IIS in Younger Dryas time.

![Figure 2.3 The extent of the IIS during the Younger Dryas. (From Pétursson et al., 2015).](image)

Just after about 12.1 cal. ka BP the IIS had started receding from its Younger Dryas position towards the end of the Chronozone. However, during the Preboreal Chronozone a new, but ephemeral expansion of the IIS took place and culminated about 11.2 cal. ka BP (Norðdahl and Pétursson, 2005; Ingólfssson et al., 2010; Geirsdóttir, 2011). The Búði moraine in South-central Iceland has proven useful to infer the different extent of the IIS between the Younger Dryas and the Preboreal Chronozone in the region (Norðdahl et al., 2008; Pétursson et al., 2015). The Búði moraine is complex and comprised of many, discontinuous moraine ridges more or less parallel to the border between the southern lowland and the interior highland (Geirsdóttir, 2011). Studies have revealed that the Búði moraine is in fact a set of moraines, the inner being of Preboreal age and the outer of Younger Dryas age (Norðdahl and
Pétursson, 2005; Ingólfsson et al., 2010). The extent of the Preboreal glaciation was similar to the Younger Dryas, but about 20% smaller (Figure 2.4) (Hubbard et al., 2006; Norðdahl et al., 2008; Ingólfsson et al., 2010). Glaciers reached the sea only in a few areas, mostly in the East, but probably also in the Tröllaskagi peninsula, and in the Gláma area in Northwest Iceland (Norðdahl and Pétursson, 2005; Ingólfssson 2010). Towards the end of Preboreal the IIS retreated (Norðdahl et al., 2008) and the great Þjórsárhraun from 8.6 cal. ka BP was erupted from a crater row located 140 km inside the present coastline of southern Iceland (Hjartarson, 1988). The nature of the lava flow affirms that by this time the IIS had disintegrated, and large ice caps were at that time almost none existing (Kaldal and Vikingsson, 1991; Norðdahl and Pétursson, 2005; Norðdahl et al., 2008).

![Figure 2.4 The IIS in Early Preboreal times. (From Pétursson et al., 2015).](image)

Little glaciological information exists on the Neoglaciation around 5 cal. ka BP nor other glacier advances in Iceland after the Holocene deglaciation, possibly because they were all eroded by later advances. The strongest evidence lies in pollen records, but it is debated whether the data can be interpreted to directly indicate an expansion of glaciers (Geirsdóttir, 2011; Ingólfsson, 1991). Glacial formations from the Little Ice Age (LIA) that took place between 1300 and 1900 AD are found around the country. The moraines from this last confirmed advance demonstrate that it was the greatest expansion of glaciers since the glaciers practically entirely melted away during the Holocene deglaciation (Geirsdóttir, 2011).
2.1 Relative Sea-Level Change and Glacial Isostasy

Earths asthenosphere and lithosphere respond to changes in overburden load, i.e. growth and reduction of glaciers (Benn and Evans, 2010). The rheologic response causes land to subside whenever the glacier load increases on it and thus to ascend when the load decreases (Lambeck et al., 2002, 2014). When the large Laurentide ice sheet started melting at the end of LGM, great amount of freshwater entered the oceans in a series of meltwater pulses. These alterations in the composition of the ocean are thought to have caused changes in both ocean and atmospheric circulations (Blanchon and Shaw, 1995). Amongst oceanic changes was the strengthening of the warm palaeo-Irminger ocean current, a warm, saline branch of the North Atlantic Current, that flows clockwise around Iceland (Eiríksson et al., 2000, 2008; Geirsdóttir; 2011). The combined effects of warmer ocean, overall climatic improvement and continued deglaciation caused a rapid glacio-eustatic sea-level rise. Ice sheets with a base grounded below sea level are exceptionally sensitive to sea level changes (Benn and Evans, 2010; Ingólfsson et al., 2010). During the LGM, the IIS was largely grounded below sea level (Norðdahl and Ingólfsson, 2015). The sudden rise of global sea level thus rendered it unstable, eventually causing the marine based part to float up and brake off and the grounding line thereby to move landwards (Ingólfsson et al., 2010; Norðdahl and Ingólfsson, 2015). This process is believed to be coeval with meltwater pulse 1A (Mwp-1A) event (Lambeck et al., 2002, 2014; Norðdahl and Ingólfsson, 2015). The global eustatic sea level (ESL) rose by ~130 m in a relatively short time (Norðdahl, et al., 2012) and coastal areas in Iceland became inundated by the sea, since the ESL rise surpassed the rate of isostatic uplift. As a result, the highly elevated marine limit (ML) shorelines in Iceland, such as Stóri-Sandhóll at 150 m a.s.l., formed during the Bølling (Norðdahl and Pétursson, 2005; Norðdahl and Ingólfsson, 2015). Relative transgressions of sea level in Iceland have been translated as both rise of eustatic sea level and subsidence of the Icelandic crust due to growth of the IIS (Norðdahl and Pétursson, 2005; Norðdahl et al., 2008). Figure 2.5 demonstrates conceptual RSL curve in calibrated $^{14}$C ages for Late Weichselian and Holocene times.

![Figure 2.5 Relative sea-level changes in Late Weichselian and Holocene times (a solid line). Global eustatic sea level changes are; according to Fairbanks (1989) (a stapled line) and according to Fairbridge (1961) (a dotted line). (From Ingólfsson et al., 2010).](image-url)
The unique position of Iceland, being located on a hot-spot on the Mid-Atlantic Ridge, renders it with a distinct rheological structure (Pollitz and Sacks, 1996). Because of the upwelling mantle plume in relation to the hot spot on a spreading ridge, the asthenosphere under Iceland has a much lower viscosity than for example the asthenosphere under Scandinavia and North-America, making it capable of flowing at high velocities (Sigmundsson, 1991, 2011; Kaban et al., 2002, Árnadóttir et al., 2009). The half-life of isostatic rebound of the Icelandic crust is only ~400 years, whereas the half-lives of Svalbard and Franz Josef Land are 2050 and 2200 years, respectively (Ingólfsson and Norðdahl, 2001). This fast rate of rebound needs to be considered with the mode of deglaciation and formation of elevated shorelines in mind. Norðdahl and Ingólfsson (2015) argue that the glacial retreat from during Bølling must have been extremely rapid and that the rate of glacio-isostatic uplift (GIU) needed to be equal to the rate RESL rise for ML shorelines to form.

2.2 West Iceland: RSL Change and Regional Characteristics

The last few decades have brought substantial advances in our understanding of ice sheet behavior (Marshall, 2005). It is now thought that some ice sheets respond relatively quickly to changes on a local and global scale and that ice sheets can to some extent demonstrate independent behavior. Research suggest that the retreat of the IIS from the shelves around Iceland was to a large extent driven by a collapse and intensive calving, rather than a long-term negative mass-balance (Norðdahl and Ingólfsson, 2015). The side effect was the response of the crust and a more or less instantaneous glacio-isostatic uplift due to the characteristics of the asthenosphere and lithosphere below Iceland, as discussed above. Bjarnason and Schmeling (2009) concluded that both the asthenosphere and lithosphere are thinner in West Iceland, which might explain a fast glacio-isostatic response there than in other places and therefore the formation of the highest ML shorelines found in Iceland (Norðdahl and Ingólfsson, 2015). The high ML shorelines in the West have been dated to 14.7 cal. ka BP. At 14.0 cal. ka BP, the RSL had regressed to 50 m a.s.l. and at 13.4 cal. ka BP, it was at or slightly below present sea level (Fig. 2.6). At the culmination of a transgression of RSL, caused by expansion of the Younger Dryas ice sheet, shorelines as high as 60 m a.s.l. were formed in Southwest Iceland (Norðdahl and Pétursson, 2005). The following glacial retreat and concurrent regression of RSL by as much as 40 m in West Iceland. An expansion of the Preboreal ice sheet lead to a rise of RSL by 25 m and formation of shorelines at 40 m a.s.l. (Ingólfsson et al., 1995; Norðdahl and Pétursson, 2005). A subsequent retreat led to a fall of RSL to a position below present sea level and a minimum position at -40 m at Hraunin on the floor of Faxaflói Bay in Southwest Iceland. Since then, an ongoing transgression, from -40 m to present sea level at about 6.0 cal. ka BP, was mainly controlled by eustatic changes (Fairbanks, 1989; Lambeck et al., 2002, 2014; Ingólfsson et al., 2010). Figure 2.6 shows the developments of the RSL according to data from West Iceland (Norðdahl and Ingólfsson, 2015).
Another important and contributing factor for the deglaciation of the west coast are the ocean currents around Iceland. At the end of LGM, warm water originating from lower latitudes, arrived at Iceland when a branch of the North Atlantic Current, the Irminger Current, reached the southern and western shelf of Iceland (Stefánsson, 1981; Geirsdóttir, 2011). Therefore, it must be considered highly likely that the Irminger Current first and foremost affected the areas of South- and West Iceland but Norðdahl and Pétursson described that its affects had also reached northeast Iceland at 15 ka BP. (Norðdahl and Pétursson, 2005).

Figure 2.7 shows the oceanography around Iceland.
3 Regional Setting and Study Area

The Ósmelur sedimentary sequence is located in West Iceland (64°18'47.66" N 21°47'35.21"W) on the southern coast of the Hvalfjörður fjord, between the sea and river Kiðafellsá. The river flows along the southeast side of Ósmelur and into the sea, passing the northeastern tip of the formation. The formation is an erosional remnant, approximately 2.2 km long and rises a little less than 60 m a.s.l. where it is highest. An erosional event has split the formation in two. The Ósmelur formation lies on top of a glacially striated bedrock and comprises a sequence of glacial and glaciomarine sediments of Late Weichselian age, overlain by coarser, gravelly sediments of early Holocene age (Norðdahl and Pétursson, 2005). Figure 3.1 and 3.2 show Hvalfjörður and its surroundings.

Figure 3.1 Overview of Hvalfjörður. (Landsat 8 image from www.earthexplorer.usgs.gov).

Figure 3.2 Overview of Ósmelur and its near surroundings. (Esri, DigitalGlobe, Geoeye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo and the GIS User Community).
### 3.1 Previous Volcanic Activity and Bedrock

Hvalfjörður is positioned on a SW-NE trending late Pliocene to early Pleistocene zone (0.7-3.1 myr) on the western edge of the present-day Reykjanes-Langjökull rift zone (Bergerat et al., 2013). The bedrock northwestern of the fjord is of late Neogene age, whilst bedrock south and northeast of the fjord are of early Quaternary age. Regional dip of the bedrock south of the fjord is 5-9° towards the SE, caused by the rifting at Thingvallavatn graben (Weisenberger and Selbekk, 2009). The research area was earlier within an active rift zone and the strata is thus consisting of lava flows, tillites, fluvial sediments and volcanic debris flows (Geirsdóttir and Eiríksson, 1994). The bedrock consists of lava flows from four central volcanoes which were active whilst they were still within the volcanic zone. Those are Hafnarfjall, Kjalarnes, Stardalur and Hvalfjörður central volcanoes. Figure 3.3 shows the position of the four central volcanoes in the area. The volcanic activity was not constant. The Hafnarfjall central volcano was active from 6-4 myr and the Hvalfjörður central volcano was active about 3 myr ago. As these volcanoes drifted out of the volcanic zone, due to the westward crustal drift caused by the spreading of the Mid-Atlantic ridge, they became extinct and other volcanoes were born (Franzson, 1978; Harðarson, et al., 2008). The Kjalarnes central volcano and eventually the Stardalur central volcano contributed to the formation of the bedrock of the Hvalfjörður area, the youngest one dying out about 2 myr ago (Friðleifsson, 1973).

![Figure 3.3 Bedrock and position of central volcanoes in the Hvalfjörður area. (Modified from Jóhannesson and Sæmundsson, 1998).](image)

The volcanic horizons are mainly made of tholeiitic flood basalts with intercalations of hyaloclastites and rhyolites (Geirsdóttir, 1990; Weisenberger and Selbekk, 2009). The basalt underwent progressive low-grade zeolite facies metamorphism due to burial of the lava succession and high rate of heat flow caused by the Hvalfjörður and Kjalarnes central volcanoes. These two volcanoes were also responsible for basaltic and rhyolitic dykes that are seen cross-cutting the bedrock along the coast of Hvalfjörður (Weisenberger and Selbekk, 2009).
3.2 Glacial Geomorphology

The landscape of the area has been carved out and eroded by glaciers mainly controlled by topography and regional structure of the area. The Hvalfjörður fjord is approximately 35 km long and overdeepened trough that was eroded by a large outlet glacier that at some time was interconnected with outlet glacier flowing along the Svínadalur valley and feeding into the Borgarfjörður fjord (Ingólfsson, 1988). The depth of Hvalfjörður ranges from -2 m where it is shallowest along the coastlines, down to -60 m in the center of the fjord. There is a noticeable depression NE of Ósmelur, where the waterdepth is as much as -80 m. The morphology on the SW side of Hvalfjörður is the result of intensive glacial activity of several small glaciers and a Miðdalur valley glacier, that eroded the land into a U-shaped valley and cirques. Figure 3.4 shows the topographic features of the area.

![Figure 3.4 A hillshade map of Ósmelur, showing the topography of the area. (Data from National Land Survey of Iceland).](image)

3.3 Previous Studies

Hitherto, only few studies on the sedimentological processes behind the formation of Ósmelur have been carried out and published, although a few undergraduate and bachelor projects have reported the sedimentology and the foraminiferal fauna of Ósmelur. Finnbogi Rögnvaldsson (1989) investigated stable oxygen isotope ratio $^{18}\text{O}/^{16}\text{O}$ and the age of foraminiferal faunas in a bachelor thesis with his study area close to Section 6 is in this study. The radiocarbon dated shells in Rögnvaldsson’s work were all *Mya Truncata* and yielded ages from 14.2 to 13.2 cal. ka BP (See Table 1 in Appendix E), landing the formation of Ósmelur in Bølling-Allerød Chronozones. The upper limit of the age range was based on the age of reworked shells fragments. Based on the $^{13}\text{O}/^{12}\text{O}$ ratio of the fauna, the water temperature was estimated between -1.5 and +0.23°C. Furthermore, Rögnvaldsson (1989) concluded that the lowermost unit of Ósmelur was formed in less than -60 m deep water,
based on the oxygen ratios of the shells and that accumulation of sediments seemed to have been more or less continuous from 14.2 to 13.2 cal. ka BP (Rögnvaldsson, 1989).

Njáll Fannar Reynisson (2008) investigated 10 sections in the area, 9 in Ósmelur itself and 1 in a gravel pit close by. He identified 7 sedimentary units. His interpretation is that Ósmelur started to build up when a glacier retreated from the underlying 3 myo bedrock and refers to the radiocarbon dated shells of Rögnvaldsson’s (1989) work previously mentioned. According to his interpretation, the first unit was deposited in Bølling times, when a glacier retreated from the area and sand, silt and clay were deposited in front of the retreating glacier. The second unit, containing mostly silt, he interpreted to be due to deposition from suspension and a calving glacier when RSL was up to 100 m higher than today. The third unit, consisting of diamict, indicates that glacier overrode unit two in Younger Dryas times, and since unit three is unconformably overlying a rouche mountonnée shaped sediment feature in unit 2. The fourth unit is sand and fines, interpreted as a deposition after a glacier retreat. Flow structures in the sediments suggest fluvial influences from a delta in the Miðdalur valley. The fifth unit is mostly fine-grained material settled from suspension in a transgressive environment. The sixth unit bears witness to a fast isostatic rebound surpassing the effects of oceanic transgression. The unit is sand and fine-grained material. The seventh and topmost unit is trough-cross bedded gravel which Reynisson interpreted to be deposited in a submarine, deltaic environment when RSL was 50 m higher than today.

Ógmundur Erlendsson (2009) investigated foraminifera from one of Reynisson’s (2008) sections, which was close to Section 3 in this study. This section contained units 2, 5, 6 and 7 of Reynisson’s interpretation. Erlendsson (2009) concluded that the two topmost units were not formed in marine environment. In contrast to Reynisson, he suggests that the fauna in the upper units do not suggest sedimentation close to a glacier but he did not have sufficient number of foraminifera from unit 5 to be able to conclude about the sedimentary environment.

Sandra Karen Ragnarsdóttir (2011) also studied the foraminiferal fauna. Her samples were collected close to Section 2 in this study. Some of the foraminifera were preserved in situ in the lower parts of a fine-grained silty/clayey unit, which lies on a bedrock and corresponds to unit 2 in Reynisson’s and Erlendsson’s work. Ragnarsdóttir concluded that the fine-grained groundmass points to sedimentation in deep marine environment and that the in situ position of foraminifera suggested a low energy environment and a high rate of sedimentation, burying the fauna before it could dislodge itself. The fauna is less well preserved further up in the section where only fragments, impossible to identify, were found and possibly indicating that the material has been reworked. The species found prefer waterdepths from -5 to -45 m. Based on that and of the fine-grained sediments, Ragnarsdóttir concluded that the deposition occurred in the deeper range of that depth interval. Ragnarsdóttir measured the size of Hiatella arctica shells that from the sediments, and compared it with a known scale in order to predict the palaeo ocean temperature between -2 and +1°C. This is close to Rögnvaldsson (1989) conclusion. At present, the sea temperature in Hvalfjörður is between +2°C and -3°C during the coldest months of the year (Marine and Freshwater Research in Iceland, 2015).

Auður Þorleifsdóttir (2008) investigated the stratigraphy and fauna at Gröf, facing Ósmelur on the opposite site of Hvalfjörður. There, only fragmented shells were found, leading her to conclude that the location is a tanatocoenosis, an assemblage of organism brought together after death, due to redeposition by flowing water in a high energy environment. She described the lowest units there to be made of sandstone, with diamictite in the upper units. Her interpretation suggests different circumstances than are thought to have existed at Ósmelur, a more energetic and turbulent environment.
Radiocarbon dated shells from the mouth of Hvalfjörður show that glaciers had withdrawn from the area in Bølling times (Hjartarson, 1992). Datings on shells and geomorphological studies have hitherto suggested that Ósmelur has not been overrun by glaciers since the LGM, but experienced the common side-effects of glacier growth and retreat in its nearest neighborhood. Notably, changes in RSL as a response to different load on the crust and increased fluvial processes due to flow of meltwater.
4 Methods

Different types of dataset were acquired and assessed both individually and in coherence with each other. The following chapter discusses each of the methods and datasets.

4.1 Fieldwork

Fieldwork was carried out during the summer and autumn of 2017. General observations and evaluation of the geomorphology were made and sections dug, measured and their characteristics noted in a geological fieldbook. Parts of the area are inaccessible due to the steepness of slopes and were therefore only visually inspected. The slopes are mostly covered with debris and weathering processes have affected the sediments. In order to see layers and contacts, substantial digging was necessary and to investigate finer features, sections were cleaned with a trowel. Each layer was described individually according to sediment facies. Texture, composition and structure were evaluated in the field.

When sections are descending towards the sea, they appear thicker, as can be seen in Figure 4.1. It was therefore necessary to measure the degree of the inclination of each layer (S), the apparent thickness of each layer (s) and the true thickness (T) of the bed was calculated. Since the contacts are either moved, tilted or eroded, the dip (d) was assumed to be 0. The equation is therefore:

\[ T = S \sin (s - d) \]

Simplified according to assumptions:

\[ T = S \sin (s) \]

Figure 4.1 Illustration that explains the different parameters used to evaluate true thickness of a layer. (From Eiríksson, 1978).

4.2 Sedimentological and Stratigraphical Logging

Landscape features and layers were described according to their physical characteristics such as clast sizes, color, texture, composition, structure and thickness. Where applicable, orientations of features and strike and dip were measured using Recta DS 50 compass and thickness measured with a tape measure. A total of 8 sections were dug, from the top of the hill towards the root of it. Additional features, such as overhangs or single outcrops were
described independently. The sections were logged in a geological fieldbook in the scale 1:10 and facies were explained using a lithofacies key code after Eyles et al., (1983) (See Appendix A), where 1st code explains the grain size and the 2nd code (written in minuscules) explains the structure of each layer. The logs were then drawn in a computer using the program Microsoft Power Point.

4.3 Clast Shape Analysis and Clast Fabric

A clast shape analysis was made in a fluvial-like deposit in the western end of Ósmelur in order to classify the material according to shape and try to see if a pattern existed or not. On the basis of Evans and Benn (2014) methodology, clast shape, texture, roundness and lithology were measured or observed and described in the field. A sample of 50 clasts with a minimum of 20 mm and maximum 70 mm long-axis were analyzed. The minimum of 15 mm was decided since smaller clasts were difficult to measure with accuracy and they were stuck in the groundmass. Clasts were measured using a ruler, determining the long- (A), intermediate- (B) and short-axis (C). Figure 4.2 A explains the dimensions. Due to the state of consolidation/segmentation of some of the sediments, a systematic study of clast shape was at places impossible. Their shape was therefore assessed visually in the field and evaluated using the Powers Roundness Index (1953) which is shown on Figure 4.2 B.

![Figure 4.2 A) A visual explanation of the 3 axis of a clast. A- long axis, B- intermediate axis and C- short axis. (From Benn, 2004a). B) Powers Roundness Index. (From Powers, 1953).](image)

The measured values of the clasts were then entered into an excel template which can be accessed through the Loughborough University’s website. The template illustrates the results of the clast shape in the Sneed and Folk-diagram, see Figure 4.3 (Sneed and Folk, 1958). The diagram demonstrates the distribution of clast shapes in a block, platy and elongated triplot.
Figure 4.3 The Sneed and Folk diagram. A) Clast shapes and the C_{40} line. B) Descriptions of shapes. C-compact, P-platy, B-bladed, E-elongated, V-very. (Modified from Benn and Ballantyne, 1993).

Using the Sneed and Folk diagram, one can calculate the C_{40}-index, which is the percentage of clasts with a c:a ratio of ≤0.4. This index has been used to distinguish between different modes of transportation, for example whether sediments have been subjected to supra-, en-, or subglacial transport, but have not been proven useful for fluvial sediments (Benn and Ballantyne, 1993).

Clast fabric analyses were made on some distinctively tilting deposits in the eastern part of Ösmelur. First measurements were made close to section 7, in the very eastern end of Ösmelur, and the second and third measurements were made 30 m apart in the western end of the eastern part. The objective was to see whether a preferred orientation could be detected. On basis of Benn’s (2004b) methodology, dip and dip direction (azimuth) were measured at three locations and 25 clasts in a limited area were measured at each location. The results were then plotted in the software Stereonet 10, provided and designed by Rick Allmendinger (Allmendinger et al., 2013; Cardozo and Allmendinger, 2013).

### 4.4 Swath Bathymetry Data

The Icelandic Coastguard has carried out an investigation of depth and morphology of the seafloor in Hvalfjörður using a multibeam echo sounder. Many individual beams are used to scan the seafloor (Figure 4.4) and create a high-resolution 3D dataset to reveal the modern appearance of the seabed. This data is presented as a digital elevation model (DEM), providing the observation of spatial elevation changes and major landforms. The data can be used to interpret possible glacial influence in the area.

Figure 4.4 How a multibeam echo sounder operates. (www.sipl.eelabs.technion.ac.il)
4.5 Remote Sensing

High resolution photographs were taken with the use of a DJI Phantom 4 drone that was flown across Ósmelur. Prior to that, Ground Control Points (GCP) (Figure 4.5) were placed in several locations and GPS marked using a Trimble R7/5700. The objective with the GCP’s was to connect them in a software, wherever they overlapped in photos. However, unfavorable weather conditions made the drone flight impossible and by the time it was possible to reinvestigate the area, the GCP’s points were gone with the wind. However, the GPS points could be used to get information on altitudes of Ósmelur’s parts. The coordinates and an image showing the locations of GPS points is shown in Appendix D.

Figure 4.5 A GPS coordinated Ground Control Point using Trimble R7/5700.

4.6 Chemical Analyses of Tephra

Two tephra samples were obtained from the Ósmelur sediments, one in Sections 5 and one in Section 8. In Section 5, a 1.3 m thick deposit of fine-grained, pitch black material at an altitude of 15.2 m in the section was deemed likely to be tephra. In Section 8 a 0.9 m thick deposit of very fine-grained, pitch black material was observed at an altitude of 3.8 m in the section. Its upper and lower boundaries were marked by thin layers of clay with a light blue tint. The materials had similar appearances in the field, but no conspicuous clay was seen demarcating the fine-grained material in section. Figure 4.6 shows the tephra layer in Section 8 on top of a sandy deposit with flow structures. The characteristics of the samples were analyzed and photographed using the microprobe at the

Figure 4.6 A pitch black tephra layer with blue clay horizons in Section 8.
Earth Science Institute of Iceland as well as a visual comparison in a microscope was made and photographed. Results of the chemical analyses are shown in Appendix C.

4.7 Radiocarbon datings

Three isotopes of carbon exist in our nature. These are $^{12}\text{C}$, $^{13}\text{C}$ and $^{14}\text{C}$, the rarest one and which is also the only unstable isotope and “decays” to a stable form of nitrogen, $^{14}\text{N}$. It is due to this instability that the name “radiocarbon” is derived. The $^{14}\text{C}$ isotope is formed in the upper atmosphere through interplay between cosmic ray neutrons and nitrogen. The unstable carbon isotopes formed is combined with oxygen to form carbon dioxide ($^{14}\text{CO}_2$) which mixes with the $^{12}\text{CO}_2$, and $^{14}\text{C}$ becomes part of the global carbon cycle through both the assimilation by plants via photosynthetic process and animals through the ingestion of plant tissue. The oceans take in over 95% of the $^{14}\text{C}$ as dissolved carbonate, and thereby organisms in sea water such molluscs will also take up $^{14}\text{C}$ while they live. When an organism dies, it ceases to take up $^{14}\text{C}$ and the unstable isotope starts to “decay” at a constant rate. Since $^{14}\text{C}$ in organic matter can be measured and compared to the modern $^{14}\text{C}$ in standard material, an age can be derived for the death of a particular organism. For such calculations, it is also necessary to know the rate at which $^{14}\text{C}$ decays, i.e. the half-life of $^{14}\text{C}$, which is 5730 years. Radiocarbon dating method can be used on organic material up to 45000 years old, after that time all $^{14}\text{C}$ will have decayed (Walker, 2005).

Since $^{14}\text{C}$ age is not a “true age” it is necessary to calibrate the $^{14}\text{C}$ age results. The calibration can e.g. be made with the INTCAL98 software, which uses the most recent radiocarbon calibration curve, mainly based on dendrochronological series. When calibrating, two things must be considered. Firstly, radiocarbon dates are calculated with a probability which is generally of $±2\sigma$ (95.4%) and secondly, perturbations in the calibration curve can lead to radiocarbon dates with more than one calibrated age (Walker, 2005). Note that all dates mentioned in this thesis are calibrated and presented as calibrated kilo-years before present (cal. ka BP = AD 1950). The radiocarbon dated shells from Ósmelur were from the western formation, close to Section 6 (see Appendix F), with the exception of one, which was sampled from the mouth of Hvalfjörður, by Arnarholt on Kjalarnes at about 2.5 m a.s.l.
5 Results

Results from each dataset is put forward in the following chapter.

5.1 Geomorphology

The overall appearance of Ósmelur is that it has been divided into two parts by an erosion over about 200 m long stretch. The western part is a table-shaped feature (as seen on Figure 5.1), approximately 1.4 km long with gravels and current formed sedimentary structures that sometimes are cross bedded and rippled in its upper sectors. The lower sectors are characterized by fine-grained sediments such as silt and clay in different proportions, often containing high amount of shells, and with sporadically dispersed boulders, some of which are glacially striated. The slopes facing the sea are covered with loose material, indicating an active erosion on the ocean side, whilst the slopes facing inland are more vegetated. The hillsides appear to have slumped in places and outcropping features are in many cases proboscis-shaped, stretching towards northeast.

Figure 5.1 Overview of the western part of Ósmelur reveals it's table shape.
The figure was taken towards west with a DJI Phantom 4 drone.

A conspicuous dyke on the westernmost edge of Ósmelur (Figure 5.2) with a NE-SW direction and parallel to numerous other dykes in Hvalfjörður (Bergerat et al., 2013). Figure 5.2 shows one such dyke which is at the western end of Ósmelur. Figure 5.3 shows the easternmost component of the western part of Ósmelur.
Figure 5.2 Frontal view of the westernmost part of Ósmelur. A SW-NE trending dyke is seen in the bottom right corner. Figure captured using a DJI Phantom 4 drone.

Figure 5.3 Frontal view of the easternmost component of the western part of Ósmelur. Figure captured using a DJI Phantom 4 drone.

There are extensive shallows in front of Ósmelur, as has been confirmed by swath bathymetry data discussed in chapter 4.4. Possibly, it is a continuation of the sedimentary sequence, but it has not been investigated. Figure 5.4 shows the eastern component of the western part and further away is the eastern part.

Figure 5.4 An aerial photo of Ósmelur reveals how shallow the sea is in front of Ósmelur. Figure is taken towards east. using a DJI Phantom 4 drone.

The eastern part is approximately 600 m long, terrace-shaped feature, with sorted sands, gravels, cobbles and boulders in its upper parts. The lower sectors are similar to the lower parts of the west part of Ósmelur. It is possible that the two parts once were a whole unity.
based on resemblance of their lower parts, and that an erosional event has molded the east part into a terrace, leaving glacio-fluvial deposits at the top. Figure 5.5 shows the frontal view of the eastern part and Figure 5.6 shows an aerial photo of it.

Figure 5.5 Frontal view of the eastern part. Figure captured using a DJI Phantom 4 drone.

Figure 5.6 An aerial photo of the eastern part reveals its terrace shape. Figure is captured using a DJI Phantom 4 drone.
5.2 Logged Sections

Sections 1-6 are in the western part of Ósmelur, whereas Sections 7 and 8 are located in the eastern part of it. The following text describes individual sections. Each section is described in a stratigraphic log where the layers are labelled L1, L2, etc. Note that when a layer is very thick and uniformly looking, the metre scale is shortened with a zig-zag line. The key explaining the lithofacies and characteristics for all the sections is shown in Figure 5.7. The location of the sections is shown in Appendix F.

![Key][1]

**Figure 5.7** A lithofacies key, explaining the color coding of the grain sizes and other characteristics of the sections. (Modified after Krüger and Kjær, 1999).
Section 1: A 13.5 m high, striated (239°) basaltic bedrock is underlying Section 1.

Layer 1: This layer is mostly a scree and it was not possible to access its lower. The material is very consolidated, consisting of massive, matrix supported, brown silty clay with clasts, shown in Figure 5.9 F. The clasts are of different sizes, mostly subangular and angular pebbles to cobbles (approx. from -1 ϕ up to -3 ϕ. The number of clasts and coarseness of the matrix increases upwards. Upper contact is unclear. Thickness of Layer 1 is around 3 m.

Layer 2: This layer contains coarser groundmass of fine sand and silt, where the finer of the two seems to be more abundant. The groundmass is grey and consolidated. It breaks up into irregular pieces and when closely looked at, reveals quite a lot of subrounded pebbles (see Figure 5.9 E). Roughly 1.5 m upwards, shell fragments appear in the consolidated groundmass and are seen in the next metre upwards and then they disappear. No clear layer boundary nor differences in groundmass are seen above the shell fragments and therefore the layer is considered as one layer above and below the shell fragments. Further up the layer contains pebbles of various sizes. Upper contact is sharp. Thickness of Layer 2 is 7.1 m.

Layer 3: Consolidated matrix consisting of silt and clay. It is grey-brown in color and the matrix coarsens upwards. The lower part of the layer is rich in angular clasts larger than 5 cm in diameter. The clasts get smaller upwards in the layer – normal sorting. Small clasts are in the consolidated matrix of the upper part of the layer. Upper contact is unclear. Thickness of Layer 3 is 0.85 m.

Layer 4: A gradual change in facies. This layer is highly convoluted and consists mainly of brown clay (Figure 5.9 C). Rippled lamination is in the lower part of the layer (Figure 5.9 D) which then fades out and multiple lenses of dark grey sand and silt in a clayey matrix characterizes the upper part. The upper contact is covered by grass. Measured thickness of Layer 4 is 4 m.

Layer 5: This is the topmost layer. It consists of a fine grained, yellow sand. It is rather consolidated, massive and matrix supported. See Figure 5.9 A. Its lower part is structureless, but at 1.8 m height, trough cross bedding is observed but it is rather vague due to weathering, see Figure 5.9 B. Above the through cross bedding comes a horizontal/planar parallel bedding of the same material. A small unconformity is in the bedding. Small pebbles are lying in direction of flow in parts of the horizontally bedded material. Thickness of layer 5 is 3.3 m.

A stratigraphic log of section 1 is shown in Figure 5.8, and Figure 5.9 shows images taken at the section.
Figure 5.8 A stratigraphic log of Section 1, the westernmost section. Note that the bedrock is \(~13.5~\text{m}\).
Figure 5.9. Photographs showing characteristics of the layers in section 1. A) The uppermost part of the Layer 5, yellowish structureless sand in the bottom part but planar parallel bedding above. B) A close-up of trough-cross bedding divided between a structureless part and a planar parallel bedding. C) A very convolute bedding of clay intwined with lenses of silt and fine sand. D) Horizons of silt and clay, which are sometimes ripple laminated. E) The consolidated groundmass of Layer 2. It breaks in to irregular pieces and reveals shell fragments. F) Consolidated silty clay with pebble-sized clasts.
Section 2: A 5 m thick, striated (239°) basaltic bedrock is underlying Section 2. The section is vegetated for the first 2.4 m. The slope is gentle, about 12°.

Layer 1: A consolidated matrix, consisting mainly of silt of brown color. The layer is massive, and matrix supported with brecciated appearance. One metre upwards in this layer, fragmented shells and subrounded pebbles appear within the groundmass. Erosional upper contact. Thickness of layer 1 is 6.3 m.

Layer 2: Very fine grained and consolidated matrix of silt clay, but the ratio between the fines has changed from what it was in layer 1, with more silt being present and seems to increase upwards. No shells are seen. The layer is brown colored, similar to layer 1. The groundmass is uniform and massive. Sharp upper contact. Thickness of layer 2 is 7.4 m.

Layer 3: Consolidated silty clay is at the lower part of this layer. It seems of similar ratios as layer 1, but no shells are seen nor has it a brecciated appearance. Many horizons of grey, medium grain-sized sand, sometimes with climbing ripples in the upper contact, appear and become more abundant than the silty clay up in the layer. Upper contact is defined by climbing ripples of silty material. Thickness of layer 3 is 7.8 m.

Layer 4: This is the topmost layer. Rounded cobbles and boulders of basaltic lithology in a sandy matrix which coarsens upwards to a coarse gravel. Thickness of layer 4 is 3.3 m.

A stratigraphic log of Section 2 is shown in Figure 5.10.
Figure 5.10 A stratigraphic log of Section 2.
Section 3: No bedrock is underlying this section. However, further out on the beach, in the foreshore, striated (220°) bedrock is seen.

Layer 1: A layer consisting silty clay of light brown color. The matrix is rather loose, and the layer appears as a scree, very rich in shells, many of which are whole. Identified species are mostly *Mya truncata* and *Chlamys islandica*. Upper contact is rather gradual. Thickness of layer 1 is 4.5 m.

Layer 2: The matrix is similar to the one in layer 1, but the facies is different in the way that it is much more consolidated and has a brecciated appearance. No shells are seen. Boulders are observed sticking out of the layer, but most of them are inaccessible due to steepness. Boulders that were seen, did not have glacial striations, see Figure 5.12 A. Upper contact is sharp. Thickness of layer 2 is 9.7 m.

Layer 3: This layer greatly resembles layer 1 (light brown silty clay and brecciated appearance), except no whole shells are found, only small fragments. This layer is richer of boulders, subangular to subrounded, which stick out of the matrix. Upper contact is gradual but obvious facies change, see Figure 5.12 B. Thickness of layer 3 is 10.9 m.

Layer 4: A very consolidated matrix of silty clay. It is light brown colored and has a brecciated appearance. It greatly resembles layer 2. No shells are seen. Observed 3.3 m upwards in the layer is a pitch black, 10 cm thick deposit of a very fine-grained sand. Could possibly be tephra, but unconfirmed. The silty clay layer continues after the sandy deposit for further 2.4 m. Upper contact is sharp. Thickness of layer 4 is 5.8 m.

Layer 5: This layer is of a darker matrix, still a mix of consolidated clay and silt, but the silt is now more dominant. The appearance is smooth, and the layer seems tilted to southwest, towards the mouth of the fjord. Many lenses of sand are within the deposit and at its top is a 0.7 m deep sand pocket, see Figure 5.12 C. The sand is black, and very fine. Upper contact is sharp. Thickness of layer 5 is 1.3 m.

Layer 6: A very consolidated matrix of silty clay. It is light brown and of brecciated appearance, similar to layer 4 and 2. No shells are seen. Sharp upper contact. Thickness of layer 6 is 4.5 m.

Layer 7: Medium grain-sized sand with interbedded, white colored silty horizons, some of which are ripple laminated. See Figure 5.12 D and E. Upper contact is sharp. Thickness of layer 7 is 2.1 m.

Layer 8: This is the topmost layer. A 5 cm thick line of clast supported, basaltic boulders and cobbles, lying mostly in the same direction (a-axis towards the fjord of the mouth). On top is a coarse gravel deposit with rounded and subrounded boulders. Thickness of layer 8 is 6.6 m.

A stratigraphic log of Section 3 is shown in Figure 5.11, and Figure 5.12 shows images taken at the section.
Figure 5.11 A stratigraphic log of Section 3.

5 cm thick, clastic supported, CoG
mS with interbedded, white Si horizons,
some of which are ripple laminated

Very consolidated. Brecciated appearance.

Sand pocket in a consolidated clayey silt layer. Sand lenses.

10 cm deposit of black sand.

Similar to L2.

Boulders, subangular to subrounded.
Fragmented shells within the matrix.

Facies change.

Could not see any shell fragments in this layer.
Brecciated appearance.

Scree, rich with shells, arctica histrio,
some are whole and in situ.
Section 4: No bedrock is seen below this section.

Layer 1: Lowest 4.5 m are of black, fine sand with shells, both whole and fractured. Cobbles and boulders are in the matrix. The section is heavily covered in debris and heavy rainfall for the past days has caused it to be rather muddy, which made it difficult to determine the upper contact. The majority of the lower part of the section is also grass covered. Thickness of layer 1 is around 4.5 m.

Layer 2: Consolidated silty clay, light grey-brown colored. Breaks up into irregular pieces when attempted to dig into it. Shell fractions are within the groundmass. Sharp upper contact. Thickness of layer 2 is 10.9 m.

Layer 3: A slightly coarser matrix than below, consisting of silt. No structure is seen, nor shells at the base of this layer. The matrix coarsens slightly upwards to a fine-grained sand and shell fragments appear. Sharp upper contact. Thickness of layer 3 is 0.7 m.

Layer 4: Fine sand that grades into coarser sand with shell fragments. Thickness of layer 4 is 3 m.

Layer 5: Consolidated matrix of silty clay, light grey-brown colored. This part of the section is very steep, making closer inspection difficult. No shells were seen. Thickness of layer 5 is 4.7 m.

Layer 6: Tilted, stratified pack consisting of silt with horizons of silty clay. Dip is around 5°, strike 85°. Upper contact is characterized by a fluvial deposit, see Figure 5.14. Thickness of layer 6 is 1.5 m.

Layer 7: Consolidated silty clay with brecciated appearance. Shell fragments are seen in the groundmass as well as large boulders (dropstones) sticking out of it. Sharp upper contact. Thickness of layer 7 is 3 m.

Layer 8: Consolidated silty clay, not brecciated as below. Interbedded with horizons of fine sand and silt. Elusive upper contact. Thickness of layer 8 is 3.2 m.

Layer 9: Slightly consolidated matrix of medium grain sized sand with flow structures. Dark grey colored. Sharp upper contact. Thickness of layer 9 is 0.5 m.

Layer 10: Very grass covered layer. Peak windows show that it is consolidated, dark grey-brown silty clay. The section here is very steep, making it hard to investigate thoroughly. No shells were seen where the layer was accessible. Sharp upper contact. Thickness of layer 10 is 2.5 m.

Layer 11: This is the topmost layer. It consists of rounded and subrounded, basaltic cobbles and gravel in a sandy matrix. Thickness of layer 10 is 2.4 m.

A stratigraphic log of Section 4 is shown in Figure 5.13.
Figure 5.13 A stratigraphic log of Section 4.

Very grass covered. Difficult to determine characteristics with precision.

Silty clay with interbedded fine sand and silt.

Brecciated, silty clay with striated boulders (dropstones) and shell fractions.

Tilted, stratified pack of silt with horizons of silty clay.

Large shell fractions and whole shells.

Cobbles in the lowest 4.5 m.
Figure 5.14 A pack of dark colored silt interbedded with horizons of consolidated silty clay in layer 6. Upper contact features a fluvial deposit. Consolidated silty clay lies on top, containing both shell fragments and clasts in its groundmass.
Section 5: No bedrock is seen below Section 5.

Layer 1: Fine, black sand, massive and no structure can be seen. The matrix is rich in shells, many of which are whole. Cobbles are also seen, but 5 m upwards the large clasts disappear as the groundmass also gets finer grained and is considered silty clay. Due to very much debris cover, upper contact is difficult to determine, but since a clear difference is found above, a consumption of a different layer was made. Thickness of layer 1 is 5 m.

Layer 2: A grey-brown, consolidated groundmass of silty clay containing shell fragments. Heavily covered with debris, which is extremely muddy and wet. Upper contact is sharp. Thickness of layer 2 is 10.2 m.

Layer 3: Pitch black, fine grained sand or silt. Analyzed as mafic tephra of Katla-like composition. Chemical composition is shown in Appendix C. The layer might be reworked, as small, angular pebbles are in it. No shells are seen. Upper contact is sharp. Thickness of layer 3 is 1.3 m.

Layer 4: A wet and muddy layer, consisting of clay. Coarsens gradually upwards to silt and fine sand. Matrix is dark grey, but it has rained for the last 2 days, and the wet might be distorting the color. No structure is observed nor shells. Sharp upper contact. Thickness of layer 4 is 4.3 m.

Layer 5: This layer appears as an overhang. See Figures 5.16 A and B. It consists of silt and fine sand that are ripple laminated and cross bedded, respectively. The sand is blue-grey, and the silt is light grey or white. The silt is more consolidated than the sand. The sandy horizons are thicker, and more eroded leaving the silty horizons sticking out. The strike measures 195° and dip 22° on the northwestern side of the overhang, and 118°, dip 22° on the southeastern side. Upper contact is gradual. Thickness of layer 4 is 1.9 m.

Layer 6: Dark grey, medium grain sized sand with interbedded silt and clay horizons. At 3.3 m up in the layer, the clayey horizons become more prominent and the layer is there defined as silty clay with horizons of sand, both fine and medium grain sized. Upper contact is sharp/erosional. Thickness of layer 6 is 8 m.

Layer 7: Consolidated silty clay, similar to layers 1 and 2, except more brecciated appearance. Few and small fractions of shell and small pebbles in the groundmass. Upper contact is sharp. Thickness of layer 7 is 3.3 m.

Layer 8: Dark grey, medium grain sized sand with flow structures. Lenses of clay and silt are seen. Upper contact is sharp. Thickness of layer 8 is 0.6 m.

Layer 9: Consolidated silty clay with brecciated appearance, similar looking as layer 7, but no shell fragments were seen. Sharp upper contact. Thickness of layer 9 is 0.6 m.

Layer 10: This is the topmost layer. Rounded and subrounded basaltic cobbles and boulders in a sandy matrix. Thickness of layer 10 is 2.4 m.

A stratigraphic log of Section 5 is shown in Figure 5.15.
Figure 5.15 A stratigraphic log of Section 5.

Sand w/flow structures, Si and C lenses

Consolidated.
Few and tiny shell fragments

Silty clay interbedded with horizons of $S$ and Si.

Sand interbedded with clayey horizons.

Fine, cross bedded sand with horizons of ripple bedded silt.

Structureless.
Silty clay, groundmass gradually coarsens upwards.

Fine sand or silt, analyzed as mafic tephra, pitch black. Small angular pebbles.

Shell fragments in a fine matrix.

Lowest ~5m are of coarser material.
Cobbles and boulders.
Figure 5.16 An overhang in Section 5. A) Figure taken towards northeast. Silt is ripple laminated and fine sand is often cross bedded. B) Frontal view of the overhang gives a clear view at the ripples.
Section 6: No bedrock is seen below Section 6.

Layer 1: This layer consists of consolidated silty clay of grey-brown color. It is rich in shells, both whole and fractured. Radiocarbon dated shells from this site yielded the median probability age of 14.2 cal. ka BP (See Appendix E). Boulders and cobbles are in the matrix. Sharp upper contact. Thickness of layer 1 is 14 m.

Layer 2: Black, unconsolidated medium grain-sized sand with vague flow structures. Reminds of a typical beach sand. The sand contains particles of various colors. Approximately 2 m up in the layer, a thin horizon of blueish clay deposit is seen, and just about 3 m upwards in the layer, a thin horizon of darker, finer sand is also observed. From there, the medium grain-sized sand layer continues. Upper contact is sharp. Thickness of layer 2 is 11.6 m. Note that the length is collapsed in the log.

Layer 3: A thin deposit of consolidated, grey-brown silty clay. Could simply be regarded as a lens in the sandy layers above and below it, but contacts – both lower and upper are sharp and this is therefore interpreted as a separate layer. Thickness of layer 3 is 0.5 m.

Layer 4: Black, half-consolidated medium grain-sized sand with flow structures and lenses of clay and silt. The lenses of fines disappear 1 m upwards in the layer, but the flow structures remain. Upper contact is sharp. Thickness of layer 4 is 1.8 m.

Layer 5: Consolidated, grey-brown silty clay. No shells were seen. Small pebbles are within the matrix. Could maybe be considered as diamict, if not for the lack of larger components. Upper contact is sharp. Thickness of layer 5 is 7.4 m.

Layer 6: A thin layer of half-consolidated, medium grain-sized sand. Flow structures are observed, but no shells nor clasts. Upper contact is sharp. Thickness of layer 6 is 0.6 m.

Layer 7: A grey-brown, consolidated matrix of silty clay with tiny shell fragments and small pebbles within the matrix. Radiocarbon dated shells from this layer yielded the median probability age of 13.2 cal. ka BP (See Appendix E). Sharp upper contact. Thickness of layer 7 is 6.8 m.

Layer 8: A thin layer of dark grey, medium grain-sized sand which is structureless and half-consolidated. Lenses of clay and silt are in the sand. Sharp upper contact. Thickness of layer 8 is 1.7 m.

Layer 9: This is the topmost layer. Sandy to gravelly matrix with rounded to subrounded basaltic cobbles and boulders. Thickness of layer 9 is 8.5 m.

A stratigraphic log of Section 6 is shown in Figure 5.17.
Figure 5.17 A stratigraphic log of Section 6.

- Black sand with silt and clay in lenses.
- Consolidated, tiny shell fragments.
- Sand with silt and clay forming flow structures.
- Consolidated silty clay. Pebbles inside matrix.
- Flow structures in a black, medium grain sized sand. Silt and clay lenses in lower half. Thin layer of consolidated silty clay.
- Reminds of beach sand. Vague flow structure.
- Thin line of darker finer sand. Blueish clay horizon.
- Consolidated silty clay rich of shells, cobbles and boulders.
Section 8: This section is on the middle of the eastern part.

Layer 1: A coarse grained, brown-black sand. This layer has the appearance of a typical beach sand, with multiple colored particles. It is unconsolidated and rich in shells, but only fragments were seen. Upper contact is sharp. Thickness of layer 1 is 3.5 m.

Layer 2: A thin deposit of light brown, medium grain sized sand with flow structures. Upper contact is sharp. Thickness of layer 2 is 0.3 m.

Layer 3: Blue-black silty matrix with no structure, interbedded with light blue horizons of clay (See Figure 5.19). This is confirmed as a mafic tephra of Katla-like composition. (See Appendix C for chemical analysis). Sharp upper contact. Thickness of layer 3 is 0.9 m.

Layer 4: This layer consists of fine gravel. No structure can be observed. At 3.1 m upwards in the layer, the matrix grades into black, coarse sand which is structureless. Upper contact is sharp. Thickness of layer 4 is 6.6 m.

Layer 5: Consolidated deposit of grey-brown silty clay. Layer is thickly covered with debris. No shells nor pebbles are seen in the matrix. Upper contact is elusive. Thickness of layer 5 is 6.8 m.

Layer 6: A thin deposit of medium grain-sized, black sand which is unconsolidated. No structure could be seen. Upper contact is elusive. Thickness of layer 6 is 0.3 m.

Layer 7: Consolidated, grey-brown silty clay. Very similar to layer 5. No shells were seen. Sharp upper contact. Thickness of layer 7 is 5.9 m.

Layer 8: This is the topmost layer. Red-brown soil. A mixture of sand and earth. Thickness of layer 8 is 1.1 m.

A stratigraphic log of Section 8 is shown in Figure 5.18.
Figure 5.18 A stratigraphic log of Section 8.
Figure 5.19 A thick, basaltic tephra layer of Katla-like composition. Interbedded with horizons of clay, which is light blue colored.
Section 7: This section is near the northeastern-most end of the eastern part. A 2.2 m high, striated (240°) basaltic bedrock is underlying Section 7.

Layer 1: Very wet and muddy layer of grey clay, rich in whole and fractured shells. Matrix coarsens upwards and whole shells become rarer. Pebbles are in the matrix at the upper part of the layer. Elusive upper contact. Thickness of layer 1 is 7 m.

Layer 2: A massive and matrix supported layer consisting of fine sand. It is brown colored and structureless. Rich in shells, both whole and fragmented. Sharp upper contact. Thickness of layer 2 is 1.2 m.

Layer 3: Consolidated silty clay of brown-grey color. Massive, matrix supported with pebbles in the groundmass. No shells are seen. Sharp upper contact. Thickness of layer 3 is 7.1 m.

Layer 4: Coarse grained sand of brownish color. It is half-consolidated. No structure is observed. No shells. Sharp upper contact. Thickness of layer 4 is 5.6 m.

Layer 5: Silt deposit of blue-black color. Possibly tephra, but unconfirmed. No structure is seen. Upper contact is sharp. Thickness of layer 5 is 0.5 m.

Layer 6: Consolidated layer of brown silty clay with shell fragments and pebbles in the groundmass. Elusive upper contact. Thickness of layer 6 is 8.2 m.

Layer 7: Medium grain-sized sand that has consolidated into sandstone. Horizons of clay and silt are in the sand deposit. No structure. Sharp upper contact. Thickness of layer 7 is 3.5 m.

Layer 8: Consolidated, light-brown silty clay. No shells are seen. Pebbles are within the hardened matrix. Sharp upper contact. Thickness of layer 8 is 1.8 m.

Layer 9: Coarse grained sand of dark grey color. Has consolidated into sandstone. Sharp upper contact. Thickness of layer 9 is 1.8 m.

Layer 10: Consolidated silty clay. Debris covered. No shells are seen. Pebbles are within the matrix. Sharp upper contact. Thickness of layer 10 is 1.8 m.

Layer 11: A clast supported deposit of boulders of various origin, both mafic and felsic. The matrix gets slightly finer, into gravel. Brown colored, fine material smears the clasts. Sharp upper contact. Thickness of layer 11 is 2.2 m.

Layer 12: A planar parallel laminated, stratified pack of fine gravel and sand Lenses of pebbles and cobbles sometimes disrupt the stratification. Inverse grading. Sharp upper contact. Thickness of layer 12 is 1.8

Layer 13: At the base of the layer, fines have sunk into a horizon of cobbles and boulders. Fine sand is on top and has sunk down into the cobbles, giving the notion of inverse grading. Sharp upper contact. Thickness of layer 13 is 1.4 m.
Layer 14: The layer is characterized by a stratified, planar parallel horizons of sand and coarse gravel. The pattern of coarsening upwards seems to repeat itself several times. Clasts of various origins and spanning a range from angular to rounded. Ripples are seen in a fine sand at the top of the layer. Upper contact is sharp. Thickness of layer 14 is 4.2 m.

Layer 15: A fissile, sandy diamict of dark brown color. Has an imbricricated appearance. Upper contact is elusive. Thickness of layer 14 is 2 m.

Layer 16: This is the topmost layer. A consolidated, red colored, medium grain-sized sand. Tilted 20° SSW. This is a lag, erosion remnant. Thickness of layer 14 is 0.3 m.

A stratigraphic log of Section 7 is shown in Figure 5.20 (lower part) and Figure 5.21 (upper part).

Figure 5.20 A stratigraphic log of the lower part of Section 7.
Figure 5.21 A stratigraphic log of the upper part of Section 7.
Figure 5.22 A) A fissile, sandy diamict with brecciated appearance. Layer 15. B) Reversely graded material. Fines smearing the bouldery deposit below. Layer 11. C) Laminated, stratified sand and gravel. Lenses of boulders. Layer 12.
Figure 5.23 All sections (1-6 from left to right) of the western part. Section 1 is furthest to right, Section 6 is furthest to left. Not to scale.
Figure 5.24 Sections of the eastern part. Section 7 is to left and Section 8 to right. Not to scale.
5.3 Other Features

Since Ósmelur contains a number of unconformities, it is necessary to mention other features observed outside the sections.

At about 35 m east of Section 1, three unconformities are seen. At least 3 units are identified which display flow structures, sometimes rippled, or horizontally bedded. (Figure 5.26 B). A thrust fault is at the lowest deposit shown in the magnified rectangle in Figure 5.25. The topmost layer of Section 1 was not found at this site. Clasts are common in the flow-looking deposits and clusters of large clasts (A-axis 8-10 cm) are seen in the lower two units as is shown on Figure 5.26 A.

Figure 5.25 An unconformity in fluvial-looking sediments, 35 m east of Section 1. At least 3 deposits are distinguishable (in the magnified rectangle). To the right of the rectangle, another unconformity is observed.

Figure 5.26 A) Large clasts are observed in the flow-looking deposit. B) Fine sand, both climbing ripples and horizontal bedding.

Between Sections 4 and 5, a large proboscis stands out at around 26 m height, considering Section 4. The feature is around 8 m long and between 2-3 m high. It has a brecciated appearance and consists of a silty clay matrix. Small shell fragments are within the matrix as well as large boulders, with A-axis over 20 cm long. A horizon of a darker material is at the lower part of the proboscis. The feature is shown on Figure 5.27 A. Figure 5.27 B shows that many cobbles and boulders of various lithology are within the matrix.
To the east of Section 5, a large outcrop of silty clay sits on top of a sandstone (Figure 5.28 A). The silty clay is more brecciated at the top and small pebbles are in its matrix. However, neither shell fragments nor boulders were observed. On the western side of the outcrop is a small cave/overhang (Figure 5.28 B) with a sandy floor and a through-cross bedding of medium grain sized sand is seen in the cave wall.

Although no conspicuous diamict has been described in any of the sections of the western part of Ósmelur (Sections 1-6), a diamict was observed at the eastern-shoulder of the western part, to the east of Section 6. There, a bullet shaped clast with glacial striae, along with coarse clasts and fine material (Figure 5.29).
A diapir shaped erosional remnant made of stratified pack of medium and coarse grain-sized sand with silty horizons was observed between the western and eastern parts of Ósmelur. The sand is often grey-blue colored (Figure 5.30 A). Climbing ripples, cross bedding and horizontal bedding seem to be repeated upwards, perhaps a sign of episodic influx of sediments. An unconformity is on its western side appears to be a thrust fault and is shown in a red rectangle on Figure 5.30 B. The height of the diapir is 4.4 m.

A few metres east of the diapir is an outcrop of brecciated and vertically standing silty clay sediments with clasts (Figure 5.31 B). Its northern and seawards facing side is rather smooth and its lower part is lying parallel to the hillside. The strike of the outcrop is to the NW. Fragments of unconsolidated clay rich sediments with convoluted bedding are found around this outcrop (Figure 5.31 A).
At the western edge of the eastern part of Ósmelur is a 2.8 m thick three layers succession of fluvial sediments made of cobbles and gravels (Figure 5.32). Single clast fabric analysis was made in the lower part of the succession, close to the handle of the shovel (Figure 5.32) and it is further discussed in Chapter 5.4.
A clastic dyke (water escape feature) was observed in a sandy deposit a few metres west of Section 7 (Figure 5.33).

Figure 5.33 A clastic dyke left of and above the shovel.
5.4 Clast Characteristics

Clast measurement was made at an overhang, 35 m east of Section 1 (Figure 5.34 A). The clasts are of variable shapes, ranging from rounded to angular and of various lithology although the majority are basaltic. The shape of most of the clasts turned out to be ranging from compact, blocky clasts to elongated clasts. The statistical results are displayed on a triangular diagram in Figure 5.34 B. No striated clasts were observed.

Figure 5.34 A) The measurements were made on a conspicuous overhang on a fluvial-looking deposit. B) Statistical results of the measurements indicated a range from compact, blocky clasts to elonged.

Clast fabric analysis was performed on sorted sediments at three locations on the eastern part of Ósmelur. Figure 5.35 shows locations of measurements and Figure 5.36 shows results plotted on Stereonet, along with statistical information. The eigenvalue (S1) is the percentage of clasts following the primary (V1) orientation and dip. Thus, at Location 1.79% of the clasts follow V1, but slightly fewer at Locations 2 and 3.

Figure 5.35 Locations of clast fabric analysis.

Figure 5.36 Plotted results from the clast fabric analysis and statistical results from three different locations (Figure 5.35).
5.5 Seafloor Morphology

The projection of the seafloor in Hvalfjörður shows that there are quite extensive shallow areas on the southern flank of the fjord with a main trench on the northern side (Figure 5.37). A noticeable point is, that in front of the Ósmelur formation a distortion in the red colored area are due to a systematic quarrying of gravel from the seafloor. The depth of the area closest to the shore (light blue) is less than 3 m and in the grey-green shaded areas the depth is between 10 and 12 m. The red shade are rather steep terrace sides, where the depth drops to 24 m. The yellow area represents depths of around 30 m. The greatest depth in Hvalfjörður is in Galtavíkurjúp (deep blue color), where the plunge is 85 m. According to Thors and Helgadóttir (1991), the shape of the channel suggests that it was eroded/formed and maintained by running water when RSL was situated between -30 and -35 m in Late Weichselian times. Seismic profiles revealed that sediments fill up the space between bedrock and sea bottom. An unconformity on the southwestern side of the fjord (a lense of sediments) is interpreted as a drowned beach at the depth of 30 to 35 m. A wide threshold to the west off the Galtavíkurjúp depression is thought to be of glacial origin, a moraine.

![Figure 5.37 Bathymetry of the Hvalfjörður fjord. Depth is shown with digits on the map with subscripted decimals (Icelandic Coast Guard, measurements from 2003 and 2010).](image)

5.6 Volcanic Material (tephra)

Chemical analyses of tephra samples, sampled in Sections 5 and 8, revealed them as mafic tephras and their chemical composition is shown in Appendix C. The ratios of major elements indicate that the tephra in both samples is likely to be originated from the Katla
volcano. The samples were also visually compared under a microscope (Figure 5.38 and 5.39) show that a great resemblance is between the two tephra samples.

Figure 5.38 Tephra samples, from Section 5 on the left side and from Section 8 on the right side. Figures captured in a microprobe.

Figure 5.39 Tephra samples from Sections 8 and 5, from left to right, under a 10x0.25 POL magnification.
6 Interpretation

In the following chapter, environmental processes involved in the developments of Ósmelur are accounted for.

6.1 Sedimentary Environments

Where terrestrial and marine forces meet, diverse and complex environment is formed (Davies, 1978). Coastal environments are extremely dynamic and sensitive to both global and regional changes, such as RSL and seasonal changes, and tidal cycles. Calving glaciers, glacial drainage systems and other fluvial processes further add to the complexity of the sedimentary environments. The following subchapters describe each type of sedimentary environments that controlled and influenced the formation of Ósmelur.

6.1.1 Marine Environment

A large part of the Ósmelur sediments is fine-grained material such as silt and clay. This type of sediments can be found in considerable amount below slowly moving glacier, abrading and plucking their substratum (Nichols, 2009) with the greatest input of debris at the interface between the glacier and the substratum (Benn and Evans, 2010). Although it is debatable whether one should classify sediments derived from the base of a calving glacier as marine or fluvial, but as fluvial process certainly participates in the process, it was reasoned that the location of the source (in this case a calving glacier) should determine the classification. Sediments from the glacier bed can be transported directly into lakes and the sea through channels in, under or on top of the ice. Ice shelves can be heavily laden with debris and are released fairly quickly when the basal part of the ice shelf melts when it reaches water (Benn and Evans, 2010). The term bed-parallel debris septum (septum meaning division or a partition) was introduced by Boulton and Eyles (1979) to specify types of concentrated zone of debris near the margins and bed of glaciers. The bed-parallel septum is divided into two categories or zones: the basal tractive zone, with grains in frequent contact with each other and with the unmoving substrate at depth, and the suspension zone, in which grains are not in contact with each other nor the substratum. Debris-rich basal ice is normally in the lower part of the suspension zone, and cycles of melting and freezing leads to debris passing between the suspension and tractive zones (Benn and Evans, 2010). Grains that are kept in transport above the glacier bed are referred to as suspended load (Nichols, 2009). As the suspended sediment load is advected down glacier and into stagnant water, grains start to settle according to Stokes Law which is determined by particle size, the difference in the density between the particle and the fluid, and the fluid viscosity. The largest size of grains that can remain as a suspended load will increase as water gets more turbulent as well as with increased flow velocity, but they are normally smaller than fine sand or coarse silt (Benn and Evans, 2010). Sediment supply is one of the controlling factors for concentrations of suspended sediment in glacial streams. Singular flood events reflect swift flush out of available fine-grained sediments from both glacier bed and channel floor, resulting in the depletion of the sediment supply. Concentrations of suspended sediments often peak prior to peak discharges. Melt streams can also be indicative of abrupt pulses or ‘slugs’ of suspended load from storage caused by the collapse of a channel wall or changes in channel patterns (Benn and Evans, 2010). Due to cohesion between clay grains and fine
silt, suspension load tends to flocculate. The flocculated groups can settle faster than singular fine-grained particles and will fall out of suspension and deposit more rapidly. Saline water conditions increase flocculation, and when grains pass from freshwater into saline, as is known in deltaic or estuary environments, fast deposition occurs, and the grains are unable to rise again into suspension due to cohesion effects. This process allows clay and silt particles to deposit in tidal environment. In cases where clay- and silt-sized grains are blended and indurated in unknown proportions, the general term is mudrock (Nichols, 2009). This sediment type dominates the lower part of Ósmelur, especially in the table-shaped part of Ósmelur. As previously mentioned, grains that are kept in transport in a running water are dependent on the fluvial stream velocity and turbulence. When a running water enters the ocean or a standing water body, the velocity drops abruptly, larger grains fall out of transport and a delta can form at a rivers mouth (Nichols, 2009). Therefore, larger grains are generally deposited at shallower depths in subaqueous, deltaic environments and may instantly be reworked by waves and tides. The finer grains of clay and silt are deposited further from the mouth. The stratigraphy of Ósmelur indicates that it has started building up as a submarine delta when RSL was considerably high, with pulses of debris rich freshwater from the base of a glacier entering the saline and stagnant sea-water. These pulses may have caused the proboscis made of mudstone, sometimes containing convoluted sand. The second layer of silt and clay (mudstone) deposits can be indicative of a renewed glaciation and a rising sea level as a causal factor of increased glacial load on the crust.

6.1.2 Glaciofluvial Environment

Sediments deposited by glacier melt-streams, either in the proglacial zone or in the ice contact setting, are generally termed glaciofluvial material (Benn, 2009; Carrivick, and Russel, 2013). Fluvial material was found at many sites in Ósmelur, and its variations reflect different conditions of their deposition. In Sections 4, 5 and 6, sandy deposits at around 15 to > 20 m a.s.l. in the sections represent shallower water, lower RSL and glacio-isostatic uplift due to glacier retreat onto land, causing regression and sand to be deposited unconformably on top of the lower silty clay (mudstone) deposit. Much of these sandy deposits are structureless with uniform appearance. Some structural exceptions are discussed below.

Cross bedded sand with horizons of ripple laminated silt in Section 5 (Figure 5.16) indicate fluctuating energy conditions. Ripples have formed in a calmy flowing water and regular pulses of faster streaming water have occurred, causing formation of antidunes – which have the appearance of a cross bedding.

Antidunes form in the upper flow regime on subaqueous bed in fast flowing water (around 2 m/s) (Nichols, 2009). They are the result of low-amplitude, sinusoidal waves which are in phase with water surface waves (Benn and Evans, 2010). The running water was flowing from an easterly direction and towards west (from left to right in Figure 5.16 B).
The fluvial deposits (Figure 5.25) at about 35 m east of Section 1 were deposited in a braided stream with a low gradient, probably on an outwash plain in front of a retreating glacier. Networks of braided streams are common on a glaciers’ forefield. Active channels tend to switch positions or are deserted, and the transported sediment reacts to the changes of the flowing water (Benn, 2009). As a stream/tributary oversaturated with debris loses velocity and cannot carry its load, the water flow finds a new pathway. As this happens repeatedly, a deposit of overlapping material forms (Nichols, 2009).

Climbing ripple- and horizontally bedded sand deposits (Figure 5.26 B) about 30 m east of Section 1) also suggests fluctuating energy regime and possible a pulse-like input of water and sediments accordingly. Fluctuations in flow velocity are associated with short term changes of discharge common for glacial streams (Sudgen and John, 1976; Allen, 1971). A horizontal bedding can be formed either in the lower flow regime of shallow streams (grain size >1 \( \phi \)) or in the upper flow regime in a higher energy (floods) (Sudgen and John, 1976). Climbing ripples form in shallow streams when the sediment transportation exceeds or matches the capacity of the flowing water, for example when a stream is slowing down, and their presence suggest high sedimentation rates (Nichols, 2009).

The trough-cross bedded sand observed just east of Section 5 (Figure 5.28 B) is a further testimony of a braided river system. The flow was from east to west.

The diapir (Figure 5.30), located in the erosional hiatus between the two parts of Ósmelur, is of fluvial origin. Its appearance suggests that it was a bar, i.e. a stream bar deposited on the inside of the curve of a stream or where the flow velocity is low, generally in wide, shallow streams where shear stress is low (Carlson, Plummer and Hammersley, 2011; Benn and Evans, 2010, Brodzikowski and Loon, 1991).

The thick deposit of cobbles and gravels on Ósmelur’s western part (Figure 5.32) is the result of an energetic event. Rounded cobbles and boulders are generally associated with rivers who have both enough water and flow velocity to transport larger clasts (Bridge and Dominic, 1984). Aerial images of the area show how distinct the eastern part of Ósmelur is from the western. Whilst both consist of cobbles and boulders in their upper sectors, no structure can be found in the case of the western part, as well as the coarse material generally contains matrix of coarse sand or gravel. However, hardly any matrix is in coarse deposit of the eastern part, and the clast-fabric analysis revealed strong fabric from a southerly direction, probably out of the Miðdalur valley.

### 6.1.3 Glaciomarine Environment

As climate transitions between colder and warmer conditions, calving glaciers and destabilize ice shelves due to a rise or drop in RSL (Nichols, 2009). The changes in RSL causes the ice shelves to break up into often debris rich icebergs. The icebergs are subjected to transport by wind and ocean currents as well as faster melting rates (Benn and Evans, 2010). As the icebergs melt, the sediment within them, termed *ice-rafted debris (IRD)*, drops onto the ocean floor and or subjected to reworking. Boulders derived from such processes are termed dropstones (Nichols, 2009). Such stones can be found in significant amounts in the silty clay sediments of Ósmelur and often stick out of slopes and sections.

### 6.1.4 Littoral Environment

A topmost layer of cobbles and gravels in Sections 2-6 is deposited in a high energy shore environment suggesting a fast, regressive phase following a glacier retreat. Beach sediments, made of coarse grain sizes, are generally associated with steep slopes (Komar, 1976).
6.1.5 Glacial Environment

Evidence for presence of a glacier at Ósmelur are few in its westernmost part. However, a conspicuous diamict was observed at the eastern shoulder of the western part of Ósmelur, *i.e.* east of Section 6 (Figure 5.29) with a bullet shaped, striated boulder. Striated clasts were also observed in the diamict. The striations of the bullet-shaped boulder had the direction ~220° (SW-NE), towards the mouth of the fjord, suggesting a glacier moving along the Hvalfjörður fjord.

Another occurrence of a diamict was observed at the top of Section 7. That diamict was distinctly different from the previous one, with fissiles in a finer groundmass. Its appearance suggests that it is a meltout till from the base of a glacier flowing out of the Miðdalur valley. Meltout till is defined as sediments deposited when a debris rich basal ice melts in situ at a glacier front (Benn and Evans, 2010; Cook, 2010; Nichols, 2009). A clastic dyke was observed close to Section 7. Le Heron and Etienne (2005) concluded that clastic dykes form as a result of hydraulic fracturing, *i.e.* water escape, caused by a heavy load on top of the sediments, most likely a glacier.

6.2 Correlations

The following chapter discusses the main sedimentary units and correlation between sections and the two parts of Ósmelur.

6.2.1 Sedimentary Units

The sediments of Ósmelur as a whole display both vertical and lateral changes in facies. In general, 5 sedimentary units have been recognized, but their distribution varies greatly.

Sedimentary Unit 1 is the stratigraphically lowest unit of Ósmelur, resting on a glacially striated bedrock. It is a mudstone containing mollusc fauna and is the most widespread one. The proportions between silt and clay vary a little throughout all of Ósmelur especially at Section 1, where the matrix is generally coarser. The mudstone is interpreted as having been deposited in an ice-distal to ice-proximal marine environment, and its variations were probably caused by local and temporal differences in glacier proximity as well as variations in meltwater input from the base of the glacier. The mollusc fauna belongs to the *Macoma calcarea* community, which suggests a deposition in shallow/near-shore environment with low salinity and a large input of freshwater or glacial meltwater, a boreal to mid-arctic fjord environment (Ingólfsson, 1987; Sigfúsdóttir, *et al.*, 2018). The unit is massive and structureless, indicating deposition of fine-grained material settling from suspension when flow of debris laden water enters a marine setting. Clasts found within the matrix derived from floating icebergs in the area and are considered as ice-rafted debris. The characteristics of the sediments described above are shown in Figure 6.2 A B).

No radiometric datings were made specifically for this thesis, but previous studies on the fauna of Ósmelur was used as indicative for the approximate age Ósmelur. A total of 8 radiometric datings have been made from shells in the area. The results are shown in Appendix E. The samples turned out to show significant difference at 95% level. Two age groups were identified. Samples #1, #2 and #6 have the median probability age of 14.2 cal. ka BP, whilst samples #3, #4 and #7 have the median probability age of 13.2 cal. ka BP. Samples #5 and #8 can both be added to the younger group while only one of them can be
added at a time to the older group. The samples were taken close to Section 6 in this thesis, with the older group sampled at lower levels, from 7-15 m height in the section, i.e. from Unit 1 in this thesis, and the younger group at higher elevations, from 34-37 m height in the section, or Unit 4. One exception is sample #8, which was collected at the mouth of the fjord, by Arnarholt in Kjalarnes at ~2.5 m a.s.l. The results render the age of Unit 1 to be 14.2 cal. ka BP and of Bølling age.

Figure 6.2 A) Bedrock with striations directing 240°. B) Shell rich sediments at the bottom of section 3. C) Dropstone in a fine-grained material.

Sedimentary unit 2 lies unconformably on top of the mudstone and is made of sand of different grain-sizes. No shells were found in the sandy deposits and its appearance suggested a deposition by running water. It is interpreted as having been deposited in a shallower environment than the mudstone unit below it (Unit 1), probably when the RSL was lowering and isostatic rebound was taking place as a result of retreating glaciers. This unit is most conspicuous in the center of Ósmelur in Sections 4, 5 and 6 and in the eastern part, in Sections 8 and 7. Unit 2 was not found in the westernmost Sections of 3, 2 and 1. In Section number 5, a confirmed tephra layer was observed in the sand deposit at ~16 m height within the section. A very fine-grained layer was also found at similar height at Section 6 but was not sampled. Another confirmed tephra layer was observed in Section 8, but at 5 m height within the section, i.e. 11 m lower than in Section 5. The two confirmed tephra layers were of very similar chemical composition, both believed to be originated from the Katla volcano and thus may connect the two parts of Ósmelur.

Sedimentary Unit 3 lies unconformably on top of the sandy Unit 2. It is a shell-less mudstone intercalated with sands which showed evidences of having been deposited by streaming water of changing velocity (ripples, antidunes, etc.). This 3rd Unit varied greatly in distribution and thickness and had gone through more glaciotectonic deformation than the lower mudstone (see examples on Figure 5.31 A and B), suggesting that the climate deteriorated after Unit 3 was deposited.

Sedimentary Unit 4 comprises of mudstone with shell fragments and clasts within the matrix, lying unconformably on top of Unit 3 and is found at continually lower elevations towards west. Dropstones are common in Sections 3 and 4 and their surroundings. This Unit is interpreted as having been deposited in similar circumstances as Unit 1, in an ice-proximal to ice-distal marine environment when RSL had risen again. It was not found in Section 8.
but was seen at ~30 m height within Section 7. Radiocarbon dated shells from Unit 4 (the older age group) yielded median probability age of 13.2 cal. ka BP.

Sedimentary Unit 5 is a deposit of cobbles and gravels, deposited in a regressive phase in a littoral, high energy environment. It is interpreted as having been deposited when isostatic rebound was occurring due to a glacier retreat. This unit was not seen in Section 1 nor anywhere on the eastern part of Ósmelur. The sedimentary unit 5 for the eastern part of Ósmelur is glaciofluvial sediments and a meltout till.

In Sections 7 and 8 in the eastern part of Ósmelur, the upper halves of the sections are quite different than the sections from the western part. As before mentioned, Unit 4 (mudstone with shell fragments) was not either found in Section 8. That section is the shortest one and seems to have suffered significant erosion which has erased Units 4 and 5 from the top of it. Although the upper half of Section 7 seems to have little in common with the other sections, Unit 4 was observed there. The upper half of Section 7 is characterized by energetic river flow deposits, topped with a meltout till. The presence of the till is a clear evidence that a glacier did reach the seashore after Unit 4 was formed. This assertion is further fortified by the presence of a clastic dyke close to Section 7 as well as a thrust fault observed in the diapir formation. Figure 6.5 shows a conceptual model of the area from Section 7 to Section 6, with additional features.

The glaciofluvial sediments of the western end of the eastern part were deposited by an energetic river, probably deriving from a melting glacier located in Miðdalur valley, which had previously eroded the topmost deposits of the eastern part. Figure 6.3 shows Sections 1-6 with probable correlations and Figure 6.4 shows the corresponding for Sections 7 and 8.

Figure 6.3 Correlations between Sections 1-6. Section 1 is furthest to the right and Section 6 furthest to the left. Sections not to scale.
Figure 6.4 Correlations between Sections 7 (on the left) and 8. Sections not to scale.
Figure 6.5 A conceptual model that shows the features between Section 7 and Section 6. The three stereonets show that the fabric of clasts has a SW-SE trend, and the stress on the deformed clay comes from a SE direction.
7 Conclusions

Based on results from the different datasets it is concluded that the sedimentary formations of Ósmelur were formed as a submarine delta in an environment with alternating RSL due to glacier advance and retreat. The oldest sedimentary unit is a mudstone, resting on a bedrock with glacial striations towards 240°, suggesting that an outlet glacier from Hvalfjörður reached the Ósmelur area before the oldest mudstone unit was deposited. Radiocarbon dated shells from the mudstone yielded median probability age of 14.2 cal. ka BP, placing its formation within the Bølling Chronozone. As climate improved, glaciers retreated and the land was uplifted, a braided river system developed and glaciofluvial sediments were deposited on top of the mudstone. Intercalated with the sandy deposits of Unit 2 are two tephra layers in Sections 5 and 8. Unit 3, a mudstone with no shells, intercalated with sands, shows that climate had begun to deteriorate anew. Unit 4, another mudstone unit but this time containing shell fragments yielding the median probability age of 13.2 cal. ka BP suggesting that it was formed during the Allerød Chronozone. This places the tephra sample of Section 5 somewhere between the Bølling and the Allerød Chronozones, i.e. younger than 14.2 cal. ka BP and older than 13.2. cal. ka BP. In Sections 7 and 8, Unit 5 was not observed but it has been replaced by glaciofluvial sediments and a meltout till. Fabric analyses were made on glaciofluvial sediments at three locations in the eastern part of Ósmelur. Two were about 30 m apart from each other on the western end of the eastern part which revealed a strong SE trend and one close to Section 7- on the easternmost end of the eastern part which showed a strong SW trend. It is therefore concluded that an energetic, glacial river eroded the uppermost sediments of the eastern part and a glacier, flowing out of the Miðdalur valley, overrode it in late Allerød or early Younger Dryas times, deforming the unit below (Figure 5.31) and causing the formation of a clastic dyke close to Section 7.

![Figure 7.1 Aerial image from the eastern shoulder of the western part of Ósmelur looking towards the eastern part. Dashed lines on the seaward facing side show an erosional unconformity direction of the erosional event is indicated with red arrows.](image-url)
The glacier flowing out from Miðdalur valley reached the location of where the hiatus is today but did not reach the western part of Ósmelur. This assumption is based on the deformed sediments by the eastern part of Ósmelur (Figure 5.31 A B), the clastic dyke close to Section 7 and a meltout till on the top of the eastern part.

It is not certain whether a glacier from Hvalfjörður fjord was present at Ósmelur at the same time as when the Miðdalur valley glacier reached Ósmelur. However, the diamict found close to Section 6, as well as a striated (220°), bullet-shaped clast that was seen in the groundmass there show that at some point a glacier flowing along Hvalfjörður reached the present eastern shoulder of the western part of Ósmelur. The wide threshold west of Galtavíkurðjúp in Hvalfjörður (Figure 5.37) is thought to be of glacigenic origin, indicating an undated extent of the Hvalfjörður outlet glacier.
8 Summary

Where land meets oceans, extremely dynamic environment is created, which is in constant development. It is perhaps the most sensitive environment to both global and regional changes, such as RSL- and seasonal changes, and tidal cycles. As climate deteriorates or improves, coastal regions develop alongside. This study reveals that Ósmelur has gone through phases of changing climate and represents changes accordingly, whereas fine grained sediments generally represent cold phases and coarser sediments a braided river system on a delta plain in the forefield of a retreating glacier. However, differences both in lateral and vertical distribution of the Ósmelur sediments allow room for further researches at the site.
9 Discussion

Researches on geological records of climate changes in Iceland have been an interest of a wide range of scientists. Evidences of colder climate, such as raised ML, moraines and dated organic material has confirmed that at least four spells have occurred in Iceland since LGM (Geirsdóttir, 2011). The sedimentary sequence of Ósmelur is in accordance with hitherto accepted glacial history of Iceland, with dated cold-favoring shells from Bølling in its lowest unit as a proof of cold, deep marine environment, overlain by sand which deposited when land rose due to continuing glacial retreat through Bølling and into Allerød. The appearance of another fine-grained unit suggests that land had started to subside anew, and dated shells with median probability age of Allerød age indicate deteriorating climate, along with other direct evidences of glacier present in Ósmelur such as basal till and diamict. It has been suggested that the Younger Dryas stadial saw significantly more glacier growth than the other three post LGM cold events (Pétursson et al., 2015). However, the direct presence of a glacier flowing from Miðfjörður valley after LGM has been a matter of debate.
References


Einarsson, Th. and Albertsson, K. J. (1988). The glacial history of Iceland during the past three million years. Philosophical Transactions of the Royal Society of London 318, 637-644.


# Appendix A

## Lithofacies codes

### Sorted Sediment facies:

**1st code (grain size)**

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<thead>
<tr>
<th>Code</th>
<th>Description</th>
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<td>Boulders</td>
</tr>
<tr>
<td>CoG</td>
<td>Cobbles and gravel</td>
</tr>
<tr>
<td>G</td>
<td>Gravel</td>
</tr>
<tr>
<td>SG</td>
<td>Sandy gravel</td>
</tr>
<tr>
<td>GS</td>
<td>Gravelly sand</td>
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<tr>
<td>S</td>
<td>Sand</td>
</tr>
<tr>
<td>SiS</td>
<td>Silty sand</td>
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<tr>
<td>SSi</td>
<td>Sandy silt</td>
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<td>Silt</td>
</tr>
<tr>
<td>CSi</td>
<td>Clayey silt</td>
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<tr>
<td>SiC</td>
<td>Silty clay</td>
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<td>Clay</td>
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**2nd code (structure)**

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<tr>
<td>dp</td>
<td>delta planar, laminated</td>
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<td>tc</td>
<td>trough cross-laminated</td>
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<td>pc</td>
<td>planar cross-laminated</td>
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<tr>
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### Diamict facies:

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<td>Sandy diamiction</td>
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<td>D(Si)</td>
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<td>matrix supported, stratified</td>
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**3rd code (structure)**

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<td>(ig)</td>
<td>inversely graded</td>
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<td>(ong)(mng)</td>
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<td>(clg)(mig)</td>
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## Appendix B

### Clast shape values

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Appendix C

Results from the tephra analysis.

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From Section 8:
Appendix D

GPS points taken at Ósmelur and an aerial image of the GPS locations.
Appendix E

Table 1 All $^{14}$C dates in the text have been calibrated using the Calib.html ver 7.1 software and the MARINE13 calibration curve (Reimer et al., 2013). Ages of marine samples are corrected with respect to the $^{14}$C/$^{12}$C ratio and the apparent sea-water reservoir age.

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Appendix F

Locations of sections.