Late Holocene Glacial History of Sólheimajökull, Southern Iceland

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Faculty of Earth Sciences
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2011

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60 ECTS thesis submitted in partial fulfillment of a
Magister Scientiarum degree in Geology

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Abstract

Sólheimajökull is an outlet glacier draining the Mýrdalsjökull ice cap in southern Iceland. Mýrdalsjökull covers the Katla central volcano, one of the most active volcanoes in Iceland. Sólheimajökull is ~ 15 km long, 1-2 km wide and covers 44 km^2. It descends from the Katla caldera at 1505 m a.s.l. (Hábunga), and terminates ~ 100 m a.s.l. The base of the glacier is at 11 m above present sea-level, 0.8 km inside the present margin.

Subglacial eruptions of Katla have caused jökulhlaups at Sólheimajökull, with great impact on the proglacial landscape. The marginal fluctuations of Sólheimajökull correspond well to changes in the climate. In 2010, the glacier had retreated 1255 meter since annual ice front measurements were initiated in 1931, however, punctuated by a period of advance from 1969-1995.

The objectives of this study are firstly to: (i) map and interpret landforms and sediments exposed in the forefield since 1995: (ii) map and interpret changes in the size and extent of the glacier during the Little Ice Age (14^{th} – 19^{th} century AD): (iii) confine the extent of the glacier during the Late Holocene.

This has been done by analyzing a series of aerial photographs from 1945 to present using a topographical map from 1904 for reference. Fieldwork conducted during the summer of 2009 offered the possibility to check the quality of the remote sensing as well as to do stratigraphical and sedimentological work in the glacier forefield. Radiocarbon dates confine the end moraines in front of Sólheimajökull to the period after AD 1445 +/- 45, which is important for reconstructing the extent of the Little Ice Age glacial advances. Furthermore, geomorphological mapping shows a number of recently exposed landforms that allow reconstruction of the processes operating during these advances and subsequent retreats.

Dates derived from cosmogenic exposure dating show that the eastern flank of Sólheimajökull reached the outer-most moraine at AD 56, whereafter it retreated to the penultimate moraine at AD 91. Mt. Jökulhaus has probably been ice-free since AD 284 which seems reasonable with the retreat rate from the AD 56 and AD 91 moraines, although this is not in accordance with written sources.

From 1904-2009 Sólheimajökull lost 2.2 km^2 (70%) of the frontal part of the snout by melting. Newly found photographs places the 1910 margin of Sólheimajökull ~ 200 m further south than the 1904 margin.

Keywords: Glacial history, glacial morphology, GIS mapping, Sólheimajökull, Iceland history

Ágrip

Sólheimajökull er skriðjökull í Mýrdalsjökli. Mýrdalsjökull hylur megineldstöðina Kötlu, sem er ein virkasta eldstöð Íslands. Sólheimajökull er um það bil 15 km langur, 1-2 km breiður og þekur um 44 km^2. Hann á upptök sín í 1505 m hæð yfir sjávarmáli í svokallaðri Hábungu í öskju Kötlu. Þaðan rennur hann niður á láglendi og endar í 100 m hæð yfir sjávarmáli. Botn jökulsins liggur 11 m yfir núverandi sjávarmáli, 0,8 km innan núverandi jökuljaðars.

Kötlugos undir jökli hafa valdið jökulhlaupum úr Sólheimajökli sem mótað hafa landið framan við jökuljaðarinn að miklu leyti. Breytingar á loftslagi endurspeglast vel í sveiflum á jökuljaðri Sólheimajökuls. Árið 2010 hafði jökullinn hopað um 1255 metra síðan árlegar mælingar hófust árið 1931. Tímabilið frá 1969-1995 var þó frábrugðið en þá gekk jökullinn fram.

Meginmarkmið þessarar rannsóknar eru: (i) að kortleggja og túlka jökulmyndanir og jökulset sem komið hefur undan jökli frá 1995; (ii) að kortleggja og túlka breytingar á stærð og umfangi jökulsins á Litlu ísöld; (iii) að afmarka umfang jökulsins um miðbik Nútíma.

Þetta hefur verið gert með greiningum á loftmyndum frá 1945 til dagsins í dag og með hliðsjón af landakorti frá 1904. Útivinna sem framkvæmd var sumarið 2009 gaf tækifæri til þess að sannreyna niðurstöður fjarkönnunar auk þess sem mögulegt var að skoða nánar landmótum og setmyndanir framan við jökulinn.

Samkvæmt aldursgreiningum með kolefnisaðferð (^{14}C) eru jaðarurðirnar framan við Sólheimajökul frá þvi 1445+/-45. Þær upplýsingar eru mikilvægar til þess að meta umfang framrásar jökulsins á Litlu ísöld. Ennfremur sýnir kortlagning nokkurn fjölda myndana sem nýlega eru komnar undan jökli og gefur vísbendingar um þau ferli sem áttu sér stað á meðan framrás jöklanna varði og hörfun i kjölfarið.

Aldursgreiningar med geimgeislunar aðferð sýna að austari hluti Sólheimajökuls náði ystu jökulurðinni árið 56, þaðan sem jökullinn hefur hopað og byggt upp næstu urð fyrir innan árið 91. Jökulhaus hefur líklega verið íslaus síðan árið 284 og er það raunhæft ef miðað er við hopunarhraða jökulsins á tímabilinu 56-91. Það er þó ekki í samræmi við ritaðar heimildir.

Frá 1904-2009 minkaði fremri hlutinn af Sólheimajökli um 2.2 km^2 (70%), við bráðnun.

Ljósmyndir frá 1910 sem nýlega hafa fundist benda til þess að Sólheimajökull náði ~ 200 m lengra til suðurs 1910 en 1904.

Table of Contents

List of Figures

List of Tables

Acknowledgements

I wish to thank Ólafur, Anders and Ívar for helpful comments on my thesis and guidance during the master. I am grateful to Alessa and Jíri for assisting me during field work, Theo for translation of abstract into Icelandic, James Balog and the EIS (Extreme Ice Survey) project for allowing me to use the time-lapse photographs from Sólheimajökull, Oddur Sigurðsson for letting me use his photographs and providing data for fluctuations at Sólheimajökull.

Thank you very much to Eygló Ólafsdóttir and Halldór Ási Stefánsson for bringing me on their plane over the eruption of Eyjafjallajökull and Sólheimajökull in March 2010.

I wish to thank my girlfriend Anna for joining me on field trips, teaching me Word and listening to me complaints during difficult days of writing.

Support for the field work was received from the University of Iceland Research Fund, grant to Ólafur Ingólfsson.

The Royal Danish Army gave me the opportunity to take a masters degree.

Declaration

I hereby declare that this thesis was written by me and that it has not been, neither in part or as a whole, been turned in for a higher education degree.

Bjarki Friis
Reykjavik, Iceland, January 2011

1. Introduction

1.1 Background

Glaciers cover about 11% of Iceland. The glaciers are warm-based or temperate and respond actively to climate fluctuations. Around 60% of the glacial area in Iceland is underlain by active volcanoes (Björnsson, 2009).

The highest precipitation is on Mýrdalsjökull and Vatnajökull with more than 10.000 mm annually (Crochet et al., 2007). The glaciation limit in southern Iceland is 1100 m a.s.l (Björnsson & Pálsson, 2008).

Glaciers in Iceland are large compared to glaciers in mainland Europe. The topographic setting with glaciers spreading out in the lowlands provides a good analogue to the Pleistocene glaciers that existed in mainland Europe. Most of the Icelandic glaciers are not confined and controlled in the same way as in Scandinavia and the Alps; by fjords, mountains and valleys, but resemble past ice caps and ice sheets.

The marginal fluctuations of Sólheimajökull (Figure 1) correspond well to changes in the climate. In 2010, it had retreated 1.255 meters (Figure 2) since annual ice front measurements were initiated in 1931, despite a period of significant advance from 1969-1995 (Figure 4). The response time due to changes in climate at Sólheimajökull is within a few years to around 10 years and it is therefore an important field site for monitoring the effect of warming or cooling in southern Iceland. Advance or retreat of the glacier margin will lag behind the climatic forcing because the signal must be transferred from the accumulation area to the snout by the glacier flow. This time lag is called response time and is greatest for long or slow moving glaciers and least for small or rapid moving glaciers (Benn & Evans, 1998).

The connection between advance and retreat of Sólheimajökull, landforms in the proglacial area, their connection to formation and influence by climate is important. This is because landforms are well preserved, there is a good link between climate and the glacial forefield and the glacier has a well known history.

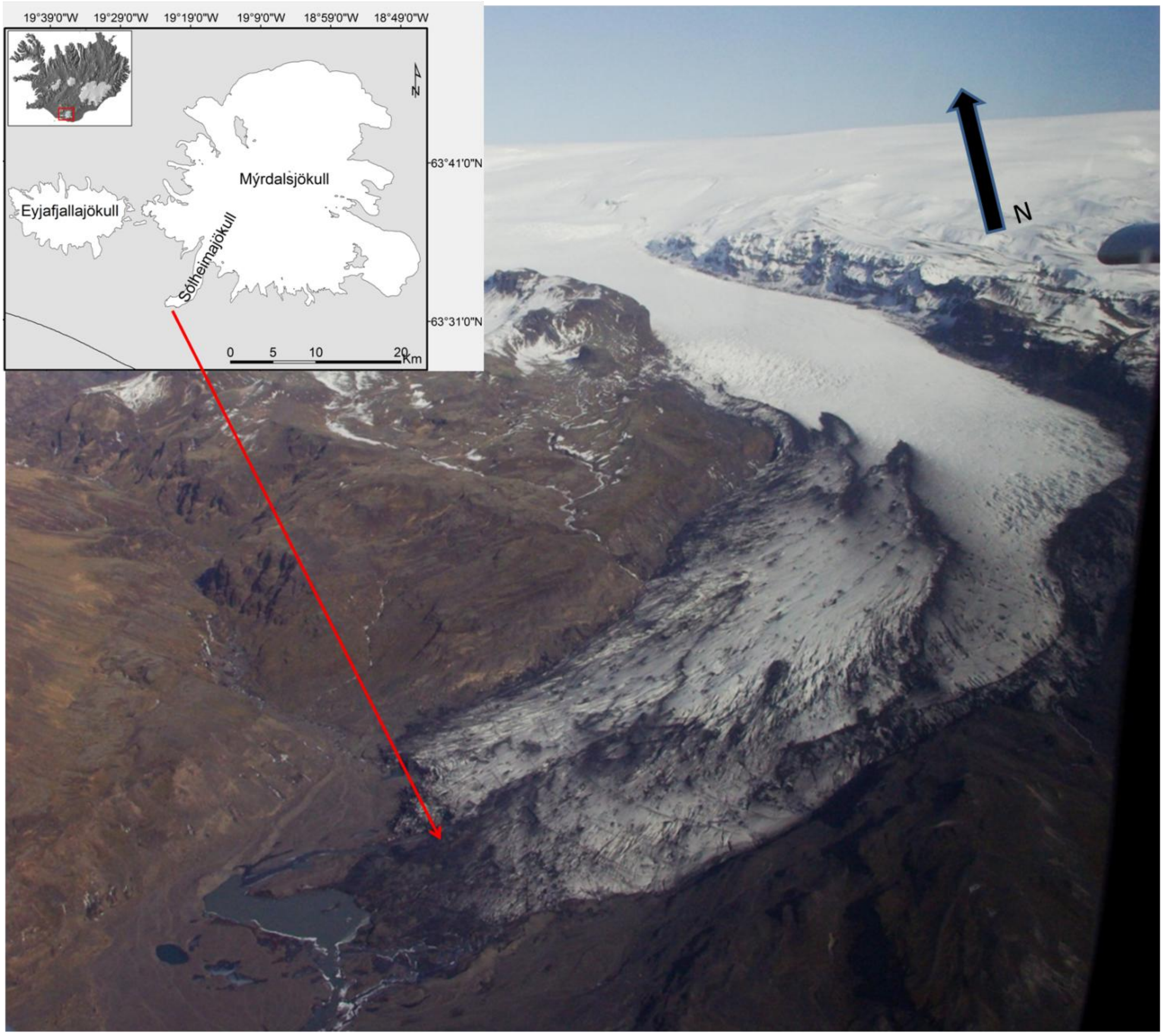


Figure 1. Location of the outlet glacier Sólheimajökull and Mýrdalsjökull in southern Iceland. Photograph by Eygló Ólafsdóttir, 2010.

1.2 Objective

The objective of the thesis is divided into three parts:

1. To map and interpret the area deglaciated since 1996. Sólheimajökull has retreated since 1996, thereby exposing a suite of glacial landforms. By mapping these landforms accurately and comparing them with newer aerial photos and digital elevation models (DEMs), landforms older than 1996 can be more confidently interpreted.

2. To map and interpret the size and area of the glacier during the Little Ice Age (1300-1900). The goal is to more accurately map the extent of the glacier as done by (Dugmore, 1987; 1989) on the size and fluctuations during the Little Ice Age. The size and distribution of landforms will be looked at with help from DEMs, which will provide a better image than has possibly been done before. Older aerial photographs, maps and radiocarbon dating will also be implemented.

3. To reconstruct the extent of the glacier in the late Holocene, dating and finding out reasons for the advances. The timing of Dugmore (1987, 1989) is poor and gives minimum ages of different advances. The use of newer methods such as cosmogenic exposure dating (CE), mapping in geographic information system (GIS) and digital elevation models (DEMs), can provide a better understanding of the sediments and landforms in the forefield of Sólheimajökull.

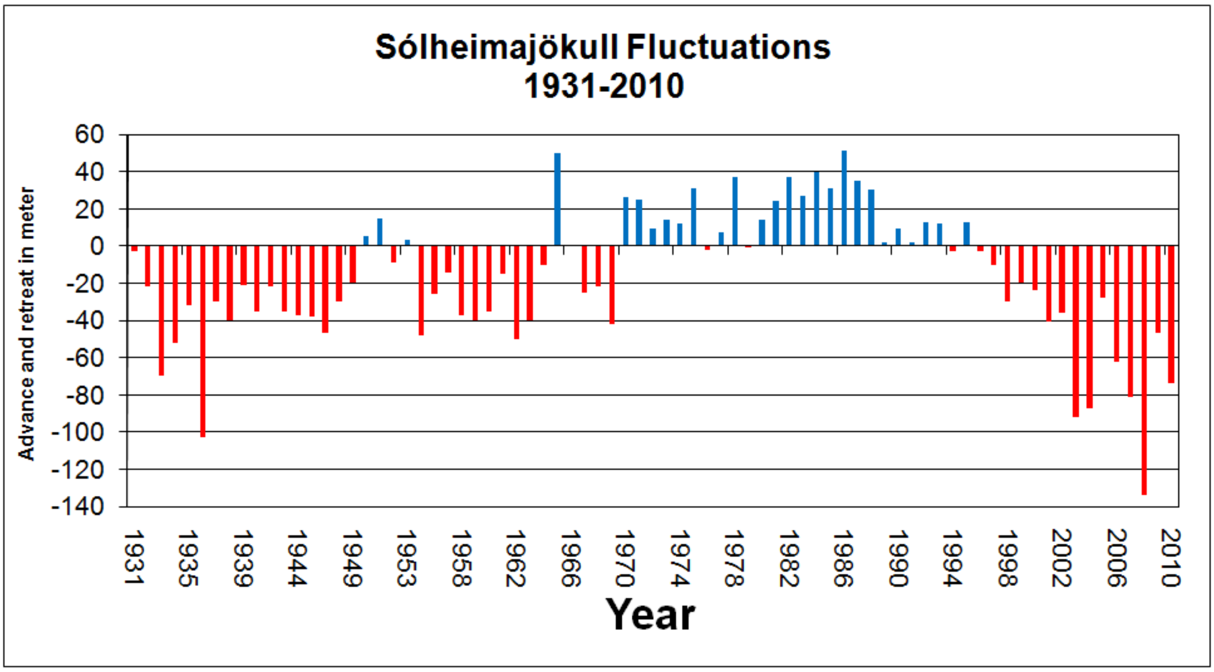


Figure 2. Measurements of the glacier front of Sólheimajökull from 1930 to 2010. Red colours show retreat and blue colours show advance. Compiled from the database of the Icelandic Glaciological Society.

1.3 Study Area

Sólheimajökull flows south of Mýrdalsjökull in a U-shaped valley. Mýrdalsjökull is the fourth largest ice cap in Iceland covering 596 km^2. The ice cap covers the 100 km^2 large caldera of the Katla central volcano, one of the most active and dangerous volcanoes in the country.

In the end of the 19th century Mýrdalsjökull and Eyjafjallajökull formed a single ice cap which separated into a larger eastern and smaller western portion in the middle of the twentieth century (Björnsson, 2009). Mýrdalsjökull retreated slowly after the Little Ice Age maximum. After 1925 the rate of melting was quite high due to a period of abrupt climatic warming. This rate slowed down during the 1950s and 1960s.

The reconstruction of the oscillations of Mýrdalsjökull caused by climate changes is difficult due to huge mass loss during volcanic eruptions (up to 10%), which has occurred two times per century on average (Sigurðsson, 2010). Figure 3 show the different outlet glaciers of Mýrdalsjökull and their drainage areas (Björnsson et al., 2000).

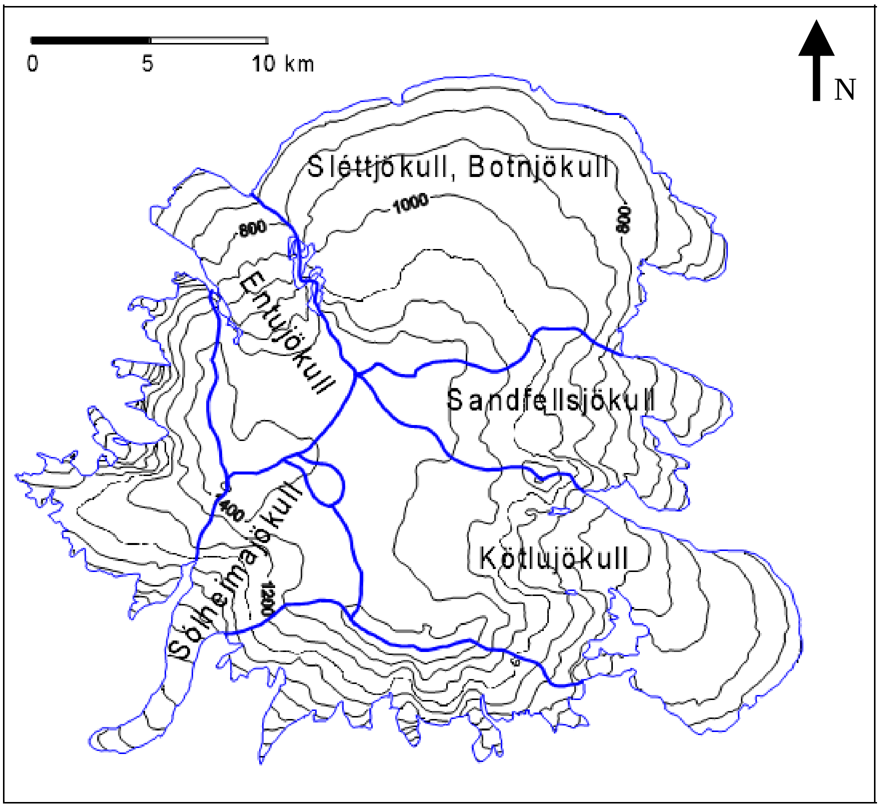


Figure 3. Ice divides of the main ice drainage basins of Mýrdalsjökull (Björnsson et al., 2000)

Sólheimajökull is 15 km long, 1-2 km wide and ~ 44 km^2 with an average slope of 5° (Mackintosh et al., 2002), consisting of 12.5 km^3 of ice (Björnsson et al., 2000). The glacier descends from 1505 m a.s.l to around 100 m a.s.l. The glacier is 433 m at the thickest part (Mackintosh et al., 1999). Since 1996 the glacier has retreated almost 800 m. The deepest part of the glacier is only 11 m a.s.l (Mackintosh et al., 1999). The river Jökulsá á Sólheimasandi also called Fúlilækur (stinky river) flows south of the glacier, dividing Skógasandur to the West and Sólheimasandur to the East. These sandar have been deposited by jökulhlaups through time (Pálsson, 2004). A jökulhlaup is a flood caused by sudden release of meltwater from a glacier or an ice sheet (Björnsson, 1992).

Subglacial eruptions of Katla have led to jökulhlaups at Sólheimajökull, which have had a huge impact on the proglacial landscape, destroying farms, roads, power lines and taking lives (Ingólfsson, 2008). Therefore it is important to understand Sólheimajökull and its connection to the Katla volcano. Sólheimajökull responds to climate change very fast and changes can be seen from year to year and even from spring to autumn.

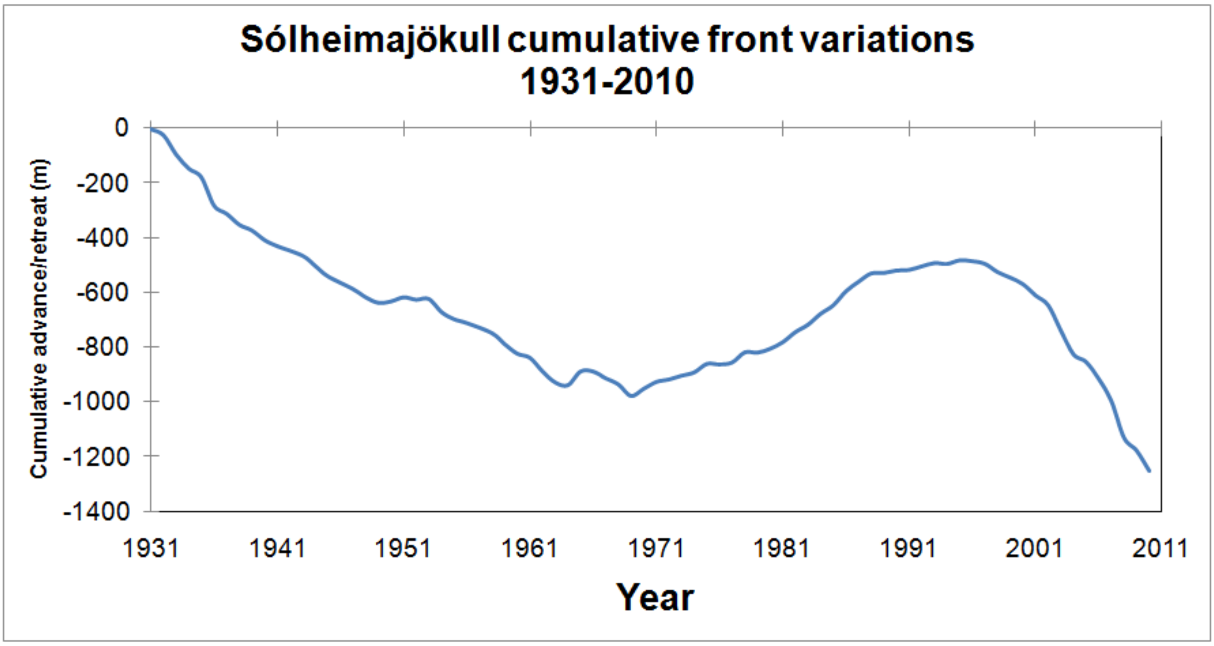


Figure 4. Cumulative front variations of Sólheimajökull from 1931-2010. Compiled from the database of the Icelandic Glaciological Society.

During the last 4000 years, tens of jökulhlaups have flowed down from Sólheimajökull to Sólheimasandur and Skógarsandur. Of the 20 eruptions in Katla after Landnám (AD 874) only two jökulhlaups occurred at Sólheimajökull (Figure 5) (Björnsson, 2009; Björnsson et al., 2000). These were in the 8th and 10th century and a small one in 1999 (Table 1) (Larsen, 2008). The last jökulhlaup associated with a glacial lake in Jökulsárgil, Sólheimajökull is ~ 1936 (Tweed, 2000).

Table 1. Volcanic eruptions in Katla connected to Sólheimajökull and the frequency of jökulhlaup. Modified from Guðmundsson, et al. (2004).

Volcanic eruptions in Mýrdalsjökull from the 8th. century						
Eruption site	Eruption year	Start	Jökullhlaup (days)	Route	Size eruption	Size jökullhlaup
Katla - S	1999	17.July	< 1	Sólheimasandur	Very small	1
Katla -K (S)	1860	8. May	20	Sólheimasandur/Mýrdalssandur	Small	1/4?
Katla - K,S	934	–	–	Sólheimasandur/Mýrdalssandur	Large	?
Katla - S	9th. Century	–	–	Sólheimasandur	Small	?
Katla - S	8th. Century	–	–	Sólheimasandur	Medium	?
Size of eruption is based on size and distribution of tephra layer (small: <0.1 km3, medium: 0.1-0.5 km3, large: >0.5km3)						
Size of jökullhlaup (small: 1, large: 5)						
Katla - K: Eruption in watershed of Kötlujökull						
Katla - S: Eruption in watershed of Sólheimajökull						

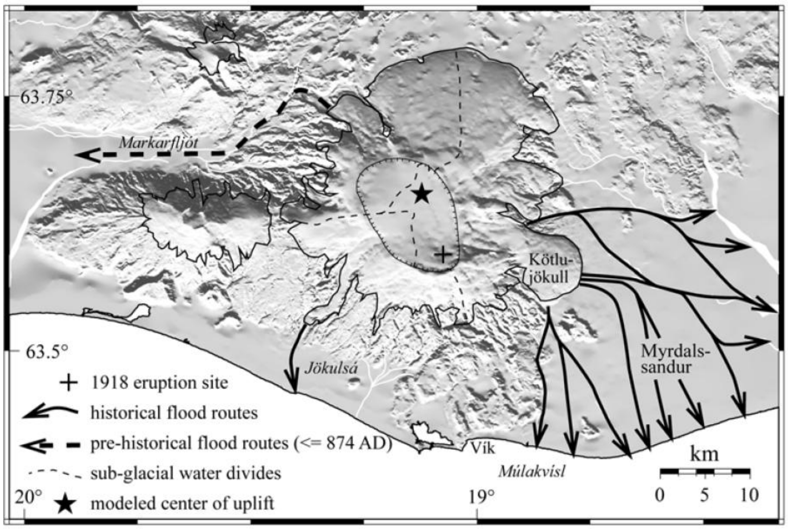


Figure 5. Sketch of jökulhlaup routes from the Mýrdalsjökull ice cap. Floodwater will drain to either side of the ice cap, depending on the exact location of the eruption site within the caldera. Through history it has mostly drained through Kötlujökull and onto Mýrdalssandur (Sturkell et al., 2008).

Sólheimajökull transports 500 to 600 m thick ice from a saddle between Háabunga (1505 m a.s.l.) and Goðabunga (1497 m a.s.l.). This saddle reaches 1-2 km inside the caldera rim (Björnsson, 2009). The average thickness of Sólheimajökull is 280 meters (Björnsson et al., 2000). The water drainage basin on Mýrdalsjökull draining to Sólheimasandur is 108 km^2, has a volume of 20.3 km^3 and a mean ice thickness of 189 m. The drainage basin within the caldera rim for Sólheimasandur is 19 km^2, with a volume of 7.7 km^3 and a mean ice thickness of 401 m (Table 2) (Björnsson et al., 2000).

Sulphuric smell from Jökulsá is indicating that geothermal water is flowing steadily from the vents between Goðabunga and Háabunga. These vents are just within the caldera rim, where geothermal water flow from vertical cracks in the bedrock warmed up by magma. The meltwater gathers in small lakes at the bottom of the ice cap, and thick ice seals off the flow while the lake is increasing and lets the water drain out now and then in small portions (Björnsson, 2009).

Average winter temperatures are around 0°C near sea level at the southern coast, with average summer temperature in July of 11°C and mean annual temperature of 5°C (Einarsson, 1984).

Table 2. Size of the different water drainage basins on Mýrdalsjökull. Modified from Björnsson et al., (2000).

Water drainage basins on Mýrdalsjökull			
Outwash plain	Area km^2	Volume km^3	Mean ice thickness (m)
Sólheimasandur	108	20,3	189
Markarfljótsaurar	167	38,5	230
Mýrdalssandur	323	79	244
Total	598	138	230
Water drainage basins within the caldera rims			
Sólheimasandur	19	7,7	401
Markarfljótsaurar	23	12,2	525
Mýrdalssandur	60	28	467
Total	102	48	470

The precipitation rate is ~ 2700 mm/yr. The snout of Sólheimajökull is subject to widespread longitudinal crevassing with a number of moulins and dirt cones present as supraglacial features. The surface of Sólheimajökull is covered with large quantities of black tephra, believed to have originated from the 1918 eruption of Katla, providing much of the supra glacial sediments (Tweed & Harris, 2003).

The forefield of Sólheimajökull is built up of fluted and drumlinized ground moraine with marginal moraine ridges, some produced annually, and others in periods with a stationary or re-advancing ice margin. The glacial river Jökulsá á Sólheimasandi is cutting through the forefield in the centre of the valley, exposing several sections of glacial deposits (Krüger et al., 2010). Usually the glacier has deep crevasses and openings which are filled up and mixed with sand and smaller or larger masses of snow, consisting of alternating layers of ice (Pálsson, 2004).

1.3.1 Sólheimajökull

The maximum extent of Sólheimajökull in the first half of the 18th century was the largest in historical times, probably the same extent as in the middle of the 19th century (Thorarinsson, 1939). The timing of the oscillations of Sólheimajökull is climatologically significant (Grove, 2004).

Small valley glaciers and minor outlet glaciers in Iceland reached their LIA maximum around AD 1750 and the larger outlet glaciers around AD 1890 (Grove, 2004). Sólheimajökull had three maxima during the LIA, AD 1705, AD 1794 and AD 1820 (Thorarinsson, 1943), but these were not the largest Holocene advances (Figure 16) (Dugmore & Sugden, 1991). Table 3 shows a summary of the oscillations of Sólheimajökull during the last 300 years.

Table 3. Summary of oscillations of Sólheimajökull last 300 years. Data was compiled from written sources (Grove, 2004) and the Icelandic glaciological society.

Year	Position
Preceding 1705	Advance
1705	Glacier same position as 1904, snout presumably a bit thicker
1783	Glacier significantly smaller than in 1705
1794	Glacier about as large as in 1705
1820	Glacier at least as large as in 1705
1820-1860	Stagnation
1860-1883	Retreat, possibly due to the 1860 Katla eruption and jökulhlaup
1883-1893	Stagnation, 1890 thought to be LIA maximum
1893-1969	Retreat
1969-1995	Advance
1996-2010	Retreat, 1999 jökulhlaup

The grazing area of Hvítmaga to the northern side of Sólheimajökull is described in written sources (Grove, 2004). Access to Hvítmaga is quite easy when the glacier is small but in years with a large glacier the sheep had to be herded over the glacier. In 1783 the glacier did not reach Jökulsárgil making the access to Hvítmaga (Figure 6) easy (same situation as presently). The small size of Sólheimajökull could be due to the 1721 and 1755 Katla eruptions (Sigurðsson, 2010). Although a jökulhlaup did not come down Sólheimajökull, melting of ice at Mýrdalsjökull could affect the catchment area of Sólheimajökull by lowering the amount of ice draining towards Sólheimajökull or changing the sub topography of Mýrdalsjökull.

In 1893 the glacier had advanced and blocked Jökulsárgil, though some sources imply that it had advanced even further in 1860, covering Jökulhaus entirely. A part of Jökulhaus must have been visible through the glacier, due to the 1860 Katla eruption (Eyþórsson, 1959). Glaciers on the northern side of Mýrdalsjökull were advancing at the same time (1855-1885).

The first eruption of Katla since Landnám, was recorded in AD 934. The second time was in AD 1000, noted in an annal written by Þorleifur Árnarson from Vestur-Skaftafellssýsla. According to Flateyjarannáll, Katla erupted for the third time in AD 1245 leaving a 14 cm layer of ash on the ground. In the year 1262 or 1263 it erupted for the fourth time, according to Flateyarannáll. Fallout of ash and downpour of pumice is thought to have added 36 meters to the elevation of Sólheimasandur, but it has not been proved that is was deposited by a jökulhlaup coming down Sólheimajökull (Grove, 2004).

V-shaped valleys cut by glacial rivers flank the U-shaped valley of Sólheimajökull. The central part of the glacier slopes gently and is deeply crevassed along the rock contact margins. Sólheimajökull at present has two snouts, the second and minor one being at higher altitude on the east side of Jökulhaus, but it will soon disappear because of the present rate of retreat. A third snout was present in Hólsárgil (Figure 6), on a map from 1905. Since that time the glacier has retreated and lowered.

The small canyon west of Hestaþingsháls (Figure 6) used to drain Sólheimajökull until some- time between 1921 and 1930. According to Tómas Ísleifsson, a local farmer said that water from Sólheimajökull didn´t flow in Jökulsá in the time around 1918, when water was routing in the canyon west of Hestaþingsháls (Pers. comm. Tómas Ísleifsson, June 2009). Tómas Ísleifssons’ mother remembered ice blocks falling from Jökulhaus in her youth, but Jökulhaus wasn´t covered completely by ice at that time. In 1921 the glacier was blocking the canyon Votagjá. After the glacier retreated behind Votagjá no water has been running into the canyon west of Hestaþingsháls (Figure 7).

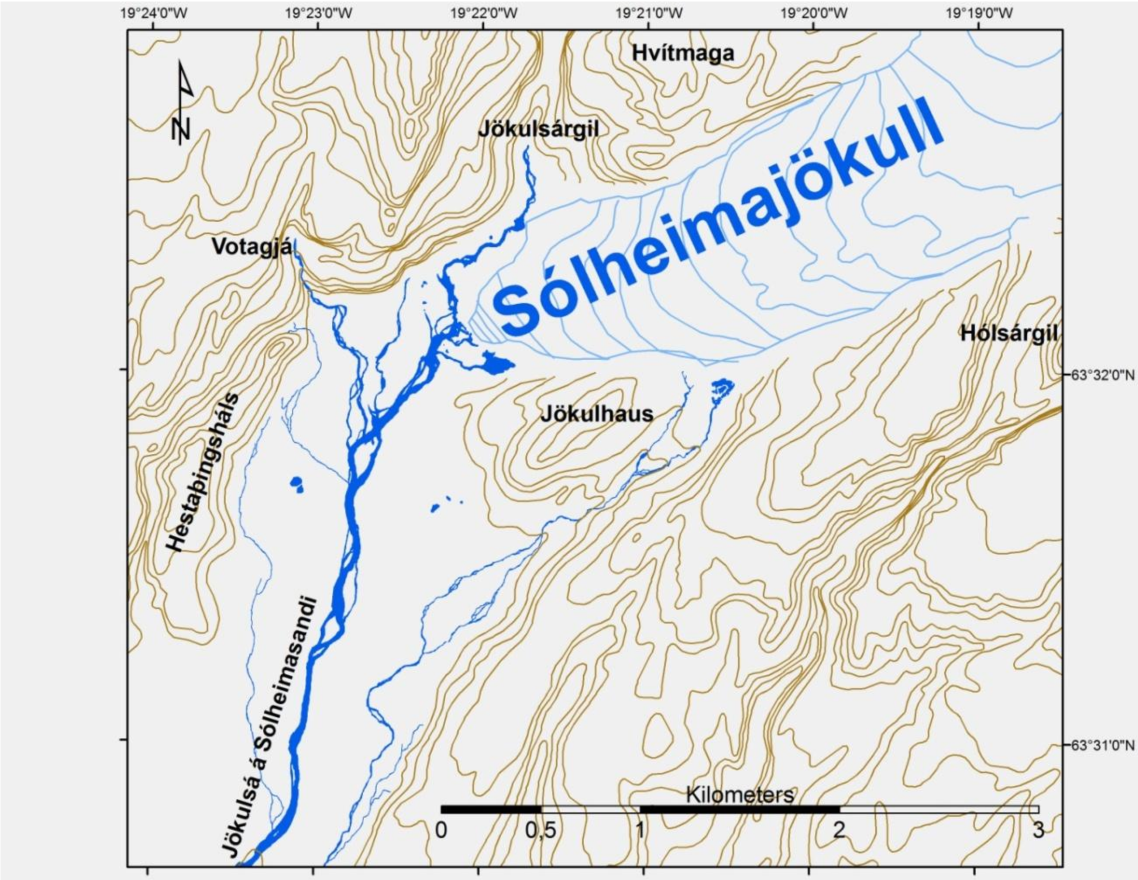


Figure 6. Topographic map of Sólheimajökull. Light blue colour show extent of the glacier in 2009. Made by extracting data from IS.50.V2.into ArcMap.

Figure 7. The canyon west of Hestaþingsháls.

Tephra horizons on the glaciers are used to calculate the turnover time of ice mass. The turnover time for the southern part of Mýrdalsjökull is 80-150 (Sólheimajökull 150) years and 200 years for the northern side (Sigurðsson, 2010). The difference is probably due to higher precipitation on the south side, which corresponds well with Figure 9 (Crochet et al., 2007).

Tephra bands from 1823 to 1860 can be identified on aerial photographs from 1945 from Sólheimajökull. These have later been flushed out of the system. The 1918 tephra band is very close to the location of the 1860 tephra band seen on a photograph from 1945. All the tephra bands on Sólheimajökull run obliquely across the glacier indicating a higher velocity at the eastern margin of the outlet glacier (Sigurðsson, 2010).

Mean annual precipitation and temperature for weather stations around Sólheimajökull (Figure 8) are shown in Table 4.

Table 4. Climate at different weather stations in the vicinity of Sólheimajökull. Data compiled from Veðurstofa Íslands.

Climate around the Sólheimajökull terminus (120 m a.s.l.), 1979 to 2008				
Mean annual temperature	°C	Mean annual precipitation mm	Elevation m a.s.l.	Distance to the coast km
Vík	7.95	1806	15	0.6
Vatnsskarðshólar	7.75	1810	20	1.3
Skógar	NA	2144	40	5

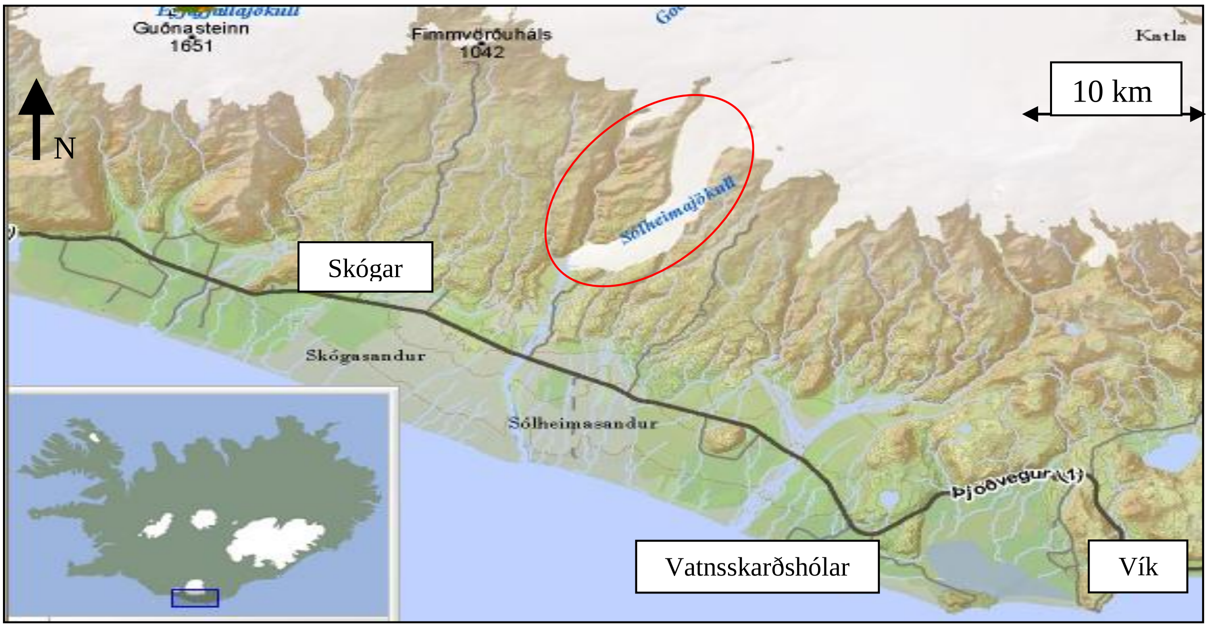


Figure 8. Map of Mýrdalsjökull showing positions of weather stations. Red ellipse show Sólheimajökull (Ja.is, 2010).

Based on the lapse rate (0,649°C pr. 100 m elevation), the mean annual temperature at the front of Sólheimajökull would be 7.1°C and -1.34°C at the top of Mýrdalsjökull, if the annual temperature from Vatnsskarðshólar (Table 4) is used.

Mýrdalsjökull received more than 10 000 mm/yr of precipitation for the period 1971-2000. The modeled precipitation in Figure 9 fits well with data from glacier mass balance measurements and from observations at meteorological stations in Iceland (Crochet et al., 2007).

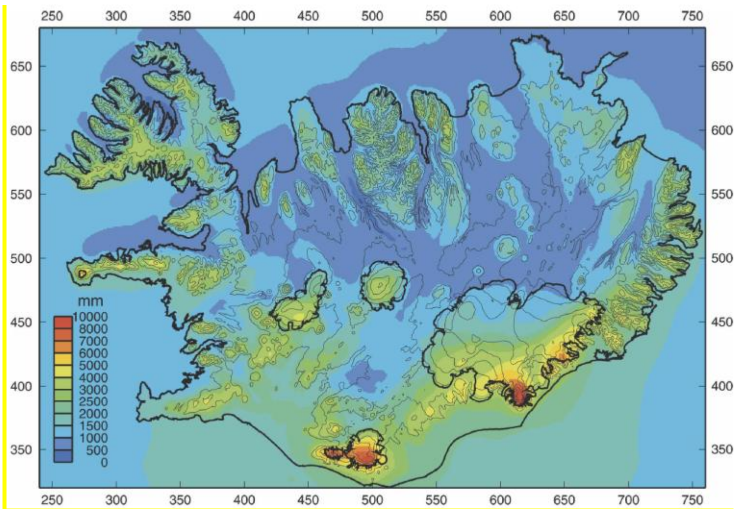


Figure 9. The 30 –yr averaged annual precipitation derived from LT model (linear theory model of orographic precpitation) simulations for the period 1971-2000. Figure adapted from Crochet et al.,(2007).

1.4 Previous research at Sólheimajökull

One of the earliest investigations at Sólheimajökull was conducted in 1704 when Arni Magnússon described Sólheimajökull as a "*flat, low outrun of Mýrdalsjökull, extending in a bend southwards from the glacier and then to the west*", and the shift in the course of the river Jökulsá on Sólheimasandur in 1690, "*This change must have been brought about by the retreat of Sólheimajökull, which has not since reached such an advanced position", indicating that Sólheimajökull was at least for some time during the Little Ice Age in anti-phase with other glaciers in Iceland"* (Grove, 2004). The description was accompanied by a sketch, one of the earliest known maps of an Icelandic outlet glacier (Figure 10). Sólheimajökull retreated considerably between 1703 and 1783 but advanced after that (Thoroddsen, 1905).

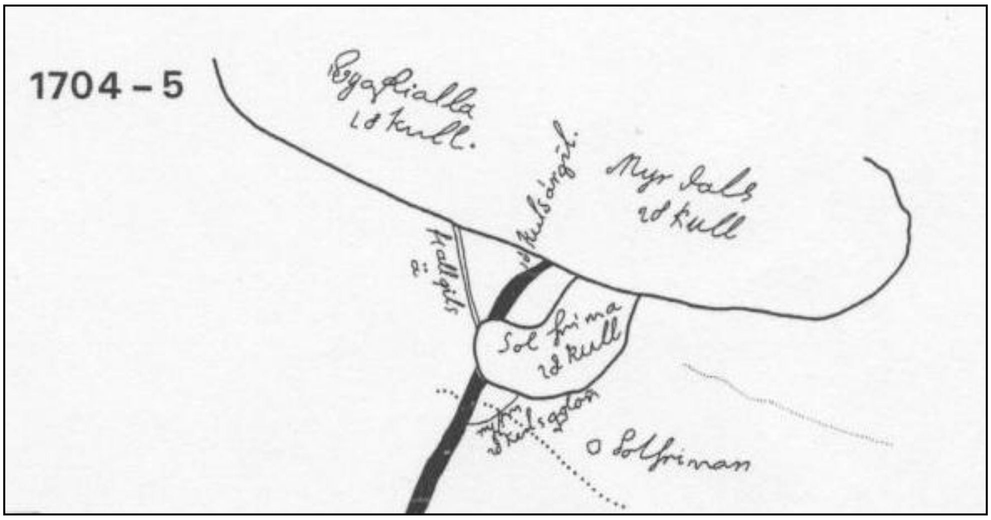


Figure 10. Sketch of the earliest known map of an Icelandic outlet glacier. Made by Arni Magnússon in 1704.

The second map of Sólheimajökull was produced by Keilhack in 1886 (Figure 11), accompanied by a description stating that the margin of Sólheimajökull was 40-50 m a.s.l. The end moraine was formed of unregular rows of 1-4 m high gravel hills. Jökulhaus was not covered completely by ice at that stage. The moraine ~ 100 meter in front of the glacier in 1886 was thought to be from 1860 (Grove, 2004). The glacier was divided into a broad western part and a narrow eastern part with Jökulhaus in the middle (Grove, 2004).

An old local man said that Jökulhaus was covered by ice in 1820 (Eythórsson, 1931). Jökulhaus was still covered by ice in 1860 (Thoroddsen, 1905). The bedrock at Jökulhaus must have been revealed sometime between 1860 and 1886 when Keilhack visited the area (Grove, 2004). Between 1860 and 1893 it retreated again, which was probably the result of mass loss due to the 1860 Katla eruption and the following jökulhlaup (Thoroddsen, 1905).

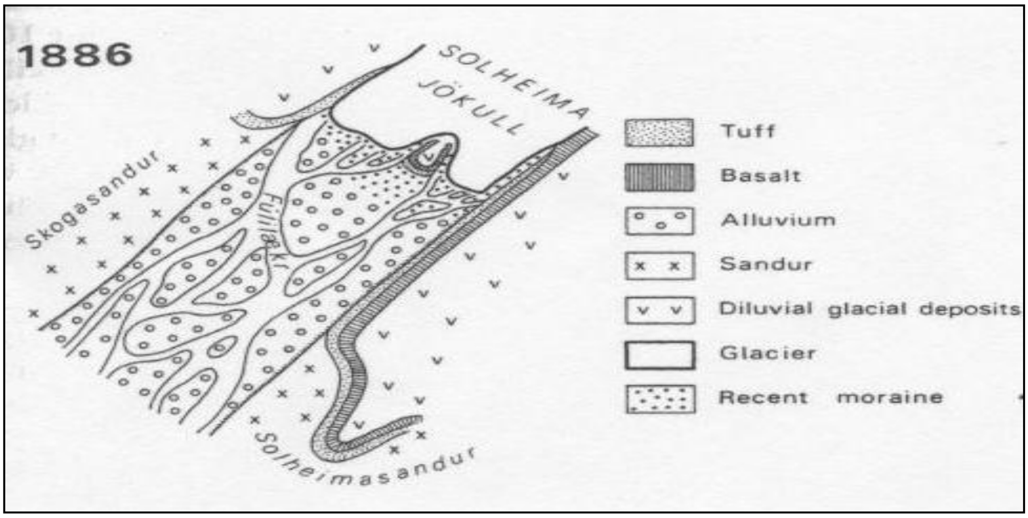


Figure 11. Map of Sólheimajökull made in 1886 by Keilhack (Grove, 2004).

A map showing the extent of Sólheimajökull during the last 1400 years (Figure 12) is based on tephrochronology and radiocarbon dating, of vegetated layers above and below tephra layers. Part of the 19th century limit is based on lichenometry. A climatic deterioration culminated at Sólheimajökull in the 6th-7th century (Dugmore et al., 2000).

Figure 12. Map and extent of Sólheimajökull from AD 1400. Black arrows indicate former jökulhlaup paths. From Dugmore et al. (2000).

The most accurate map of Sólheimajökull, predating the time of aerial photography is a map from 1905, surveyed by the topographical department of the Danish General Staff in 1904 (Figure 13).

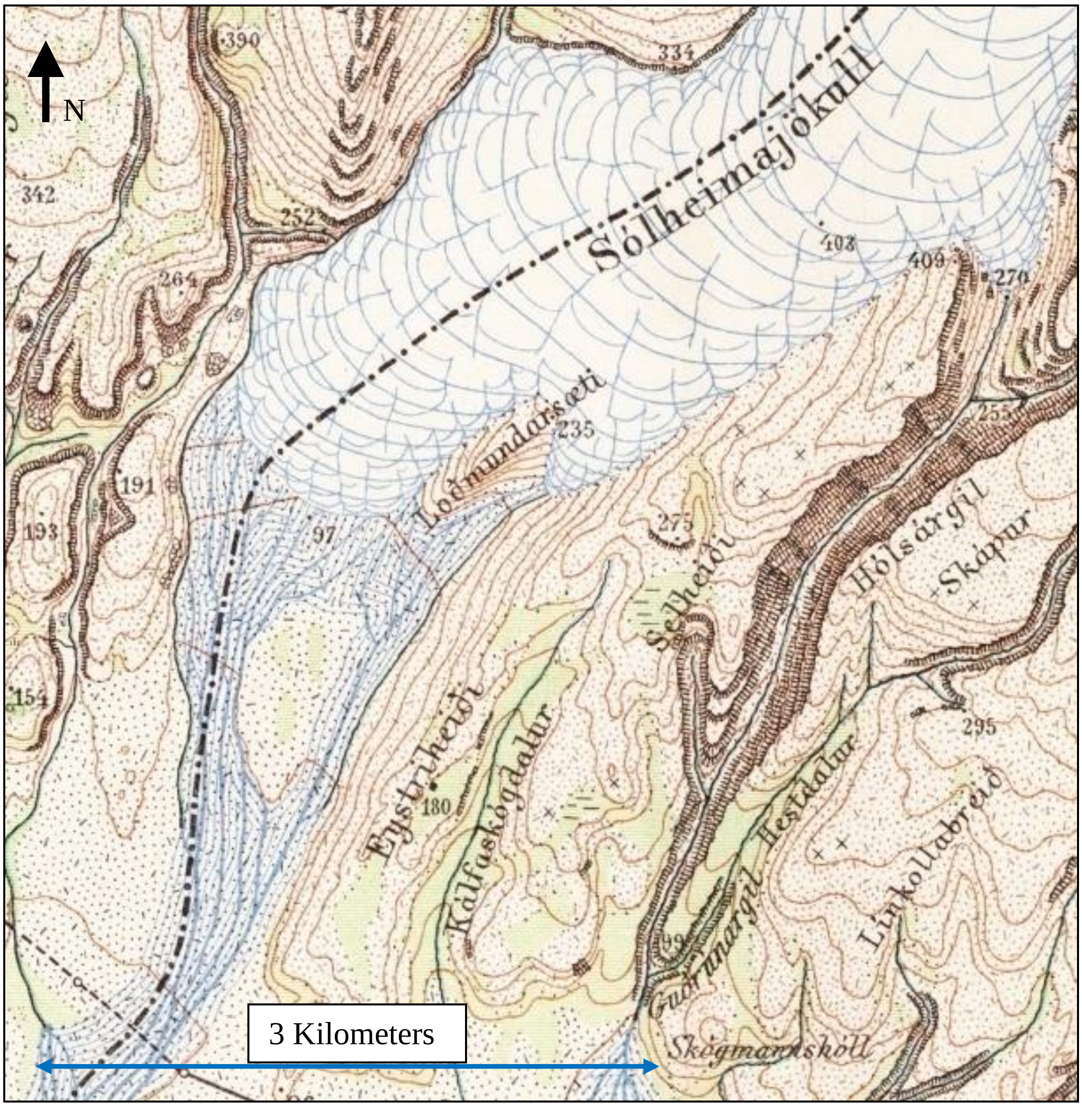


Figure 13. Sólheimajökull. Map No.69 NV, Danish General Staff, 1905. Scale 1:50 000, surveyed in 1904.

Sólheimajökull has not always been in phase with other outlet glaciers of Mýrdalsjökull, but advanced when other glaciers retreated (Dugmore & Sugden, 1991; Casely & Dugmore, 2004). Sólheimajökull was much bigger during earlier mid-Holocene advances than during the Little Ice Age. Sólheimajökull reached its maximum extent during the Little Ice Age at two advances in 1740 and in 1890 (Dugmore, 1987; 1989). One explanation is that the catchment area (ice-divide migration) at high elevations of Sólheimajökull was many times larger during the mid-Holocene than during the Little Ice Age (Dugmore & Sugden, 1991).

Evidence of a large advance at Kötlujökull 1610 years ago (Schomacker et al., 2003) could have been on the same time as one at Sólheimajökull 1200-1400 years BP (Dugmore & Sugden, 1991). Large advances like these needs cooling of several degrees and/or a huge increase in precipitation. In Iceland there is no evidence of this (Sigurðsson, 2010).

The different behaviour of fluctuations at Sólheimajökull is compatible with other outlet glaciers of Eyjafjallajökull and Mýrdalsjökull, e.g. Seljavallajökull, Steinsholtsjökull and Klifurárjökull (Figure 14), if the ice-divide of Mýrdalsjökull migrated southwards during its Holocene build up and northward during the warming in the first half of this century. Other possibilities could be that Sólheimajökull surged or was influenced by volcanic activity. These are less likely as Sólheimajökull has no history of surging and that Katla had to be higher than Eyjafjallajökull during the mid-Holocene. This would create a massive topographical change, moving the ice divide of Mýrdalsjökull. Thus more or less ice would drain into Sólheimajökull, depending on if the ice-divide moved north or south (Dugmore & Sugden, 1991). According to Sigurðsson (2010) volcanic or tectonic changes seems to be the best explanation in addition to the fact that most postglacial terminal moraines in Iceland extending further out than the Little Ice Age are at active volcanoes like Sólheimajökull (Sigurðsson, 2010).

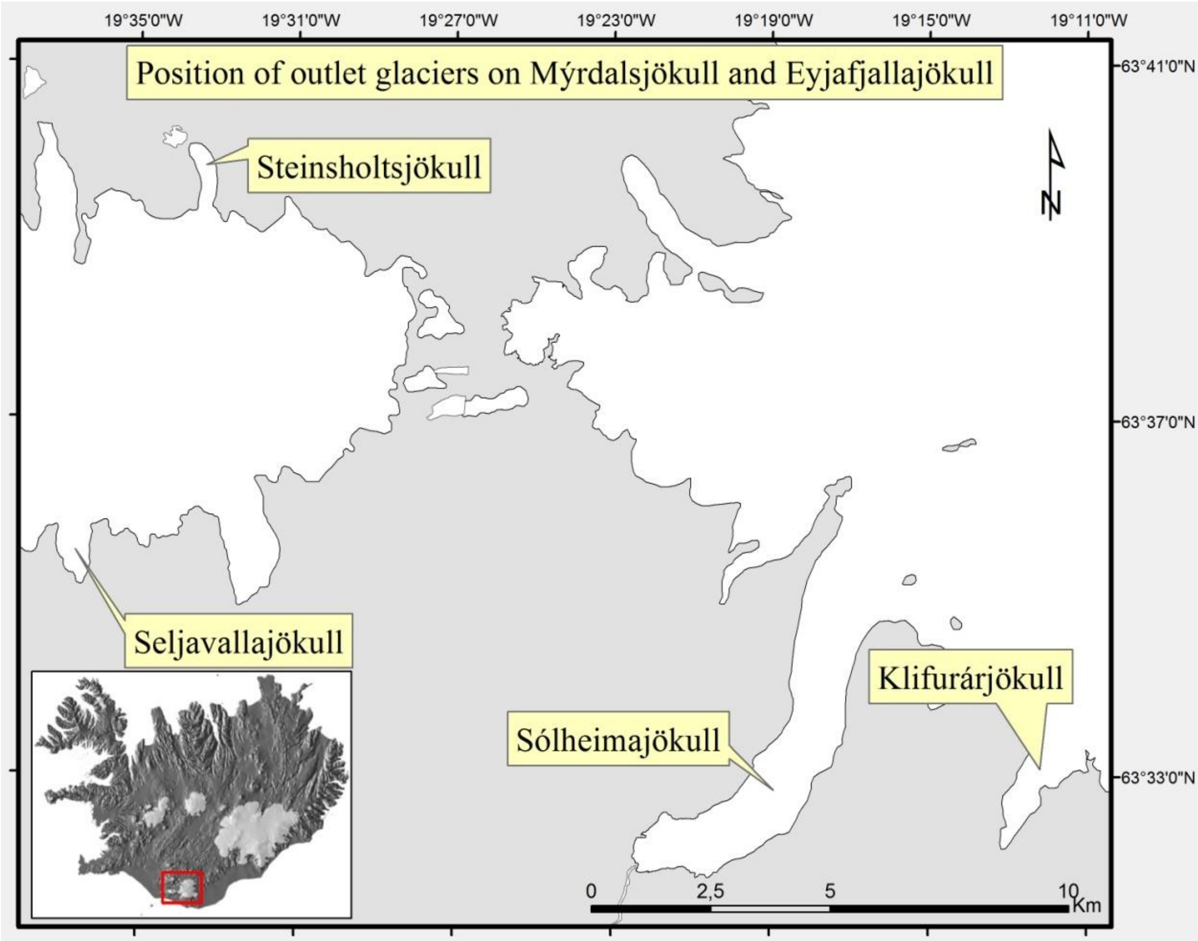


Figure 14. Position of outlet glaciers on Mýrdalsjökull and Eyjafjallajökull, made by exstracting data from IS.50.V2.2.

Lichenometry studies on Sólheimajökull confirmed that the glacier had its greatest LIA extent around 1890, where after it retreated (Jaksch, 1970; 1975). It is possible to date 140 year old sediments with lichens, but dating older than this is unreliable due to the climate variability of southern Iceland. For ages older than 140 years, radiocarbon dating was used (Maizels & Dugmore, 1985). In 1974, Crittenden (1975) studied macrolichens in the forefield of Sólheimajökull. Samples were collected from one young terminal moraine (1), a moraine of 100 plus years (the 1890 extent) (2), a gravel outwash of 100 years plus (3) and an old moraine on the eastern ridge (4) of the valley. A map based on an aerial photo from 1960 includes glacial limits from 1860 to 1960 as well as the four sample sites (Figure 15) (Crittenden, 1975).

Investigations by Dugmore and Maizels (1989) shows that Sólheimasandur was built up by 8 large jökulhlaups during the last 4000 years (Maizels, 1989). The discharge during the jökulhlaups have been estimated to be between 10 000 m^3/s and 100 000 m^3/s (Maizels & Dugmore, 1985).

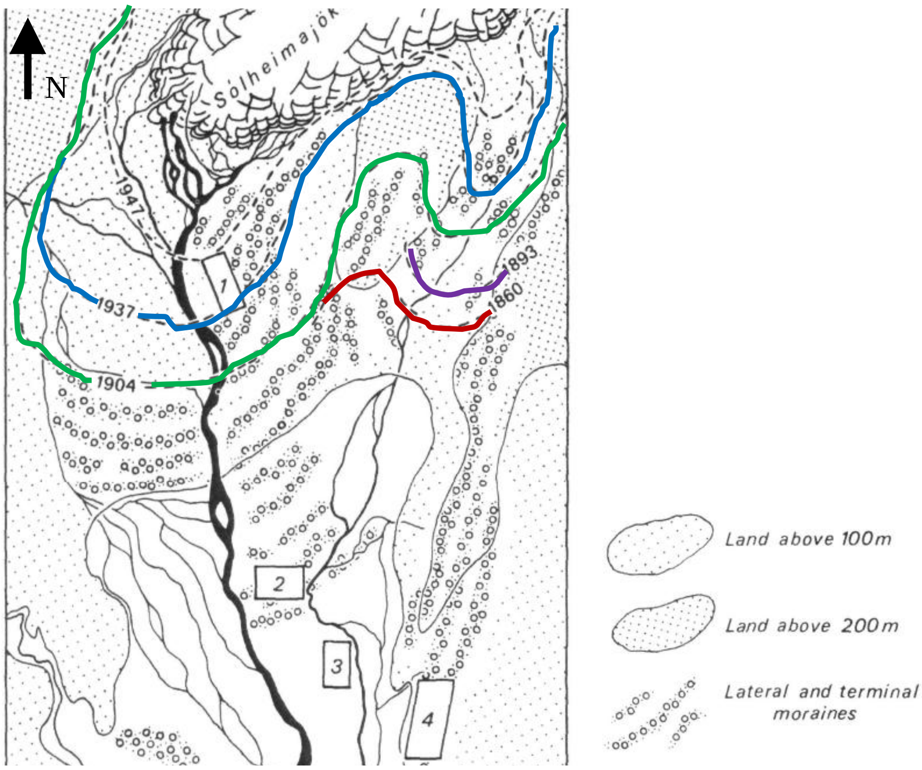


Figure 15. Map of Sólheimajökull with field sites and former moraine ridges with dates. Green colour is 1904, red 1860, purple 1893 and blue 1937 limits. The map is based on an aerial photo from 1960. Modified from Crittenden (1975).

Dugmore (1987; 1989) made radiocarbon dating on moraines on the lowlands of Sólheimasandur and Skógasandur to establish the extent of the glacier during the Holocene. Ash layers below and above glacial landscapes were investigated. The results show that Sólheimajökull had advanced in 4500 BP, 3100 BP, 1400 BP and in the 10th century (Figure 16) (Dugmore, 1987; 1989).

A coupled energy-balance/glacier flow model was used to reconstruct Holocene climate at Sólheimajökull. Cooling of 1-2 degrees was the cause of advances of Sólheimajökull 5000, 3100 and 1400 BP and in the 10th and 14th century. Warming occurred between AD 1700-1750 and the coldest period in historic times was AD 1750-1800. The climate in the 17th, 18th and 19th centuries was dominated by decadal-scale climatic variability connected to the sea-ice extent around Iceland (Mackintosh et al., 2002).

In the forefield of Sólheimajökull features believed to be clastic dykes were investigated by Le Heron & Etienne (2005). These dykes dissect the Holocene glaciogenic sediments. The orientation of the dykes supports development due to loading of the sediments during a previous advance of Sólheimajökull. The dykes were injected sub glacially over a long time in response to melt water-related hydraulic fracture processes (Le Heron & Etienne, 2005).

Ice movement on Sólheimajökull was measured between July and August 1948 for 40 days, giving an average movement of the ice between 0.6 to 1.2 m per day (Lister et al., 1953). The difference in area of Sólheimajökull from 1905 to 1948 was 3.1 km^2, a reduction from 11.67 km^2 to 8.76 km^2 (Lister et al., 1953).

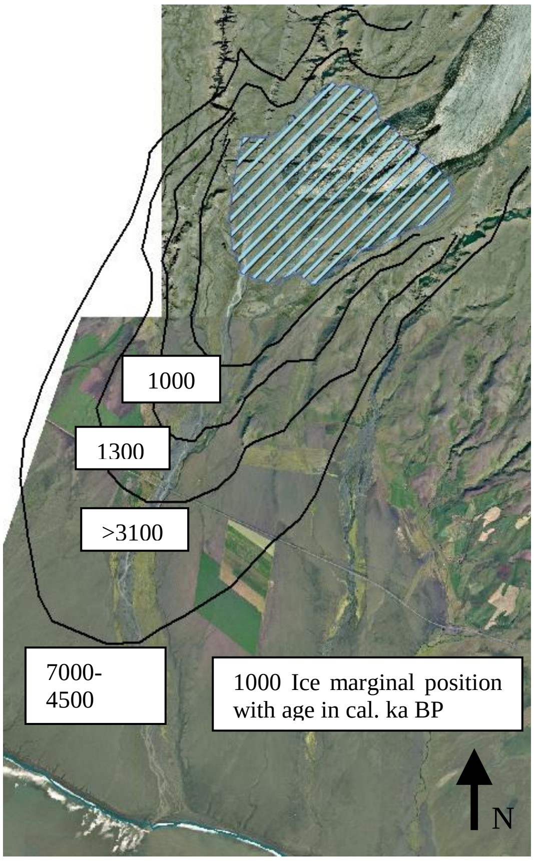


Figure 16. The extent of Holocene advances of Sólheimajökull as reconstructed from lateral moraines. Ages are based on tephrochronology and ^{14}C dating of sedimentary sections in the area. Modified after Dugmore & Sugden (1991).

In 1996/1997 a radio echo-sounding survey was conducted on Sólheimajökull, resulting in a map of the bedrock topography and a length profile of the glacier surface and two cross profiles. The radio echo-sounding was surveyed with a distance of 250 m between each sounding, giving a fairly low resolution of the bedrock topography. The deepest point is 11 meter a.s.l. (Mackintosh et al., 1999). When the measurements were performed in 1996 the thickness of the ice at this place was ~ 343 m. During fieldwork in 2009 a GPS survey line of ~ 1.5 km was taken to see the difference in ice elevation. The results show a thinning of 100-140 metres and a retreat of the glacier by ~ 700 metres (Figure 17).

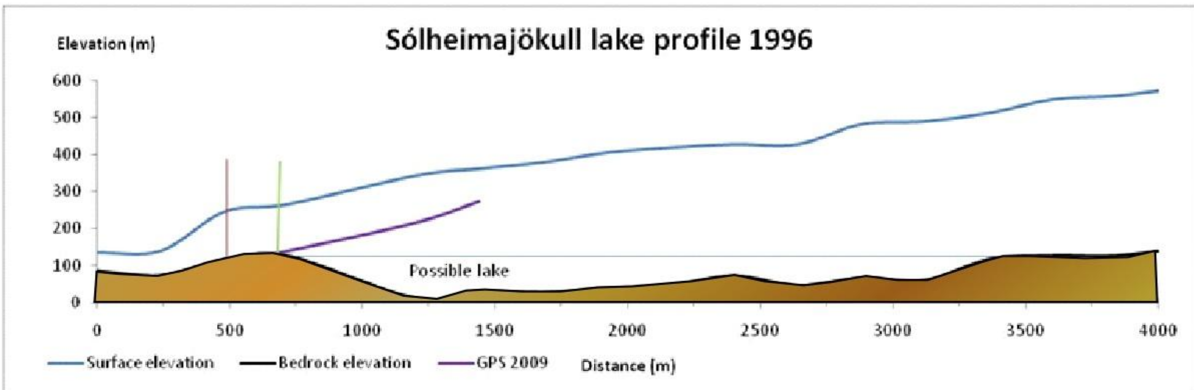


Figure 17. Detailed profile of the bedrock beneath Sólheimajökull. Green line is position of glacier front North end, red line position of glacier front Aug. 2009 and purple line is GPS elevation of ice surface in November 2009. Modified from Mackintosh et al., (1999).

On July 18th 1999 (Soosalu et al., 2006) a small unexpected subglacial eruption occurred in the catchment of Sólheimajökull, creating a 50 m deep and 1,5 km wide depression on the surface of the ice-cap (Russel et al., 2000). The jökulhlaup only lasted a few hours releasing 20 million m^3 of water (Björnsson, 2009), depositing blocks of ice, rocks, (Figure 18) and other debris 10-15 km away from the glacier margin (Sigurðsson, 2010). A huge amount of ice blocks (Figure 19) in the forefield of Sólheimajökull caused post-jökulhlaup formation of pitted sandur surface, still visible today (Figure 19). Proximal paleo-channels on the western side of Jökulsá were reactivated during the jökulhlaup, but most of the water stayed in the main river (Russel et al., 2010).

Figure 18. Kettle hole in the forefield of Sólheimajökull created as a result of dead-ice melting after the 1999 jökulhlaup. Huge boulders thrown around in the same event. Jiri Lehejcek (2009).

Figure 19. Ice blocks from the 1999 jökulhlaup at Sólheimajökull, as seen by the bridge at the main road (4 km south), Photograph by Árni Sæberg.

Moutney (2006) investigated a coastal dune field (Figure 20) of 50 km^2 on Sólheimasandur. It consists of aeolian sand and is up to 8 meter thick. The dune field rest on top of 8 major series of jökulhlaup sediments. The dune field was initiated around 1940. Prior to 1940 these dunes were not preserved due to episodic floods from Jökulsá (Mountney, 2006). The preservation potential is small, as even a modest jökulhlaup would rework the dune field (Mountney, 2006).

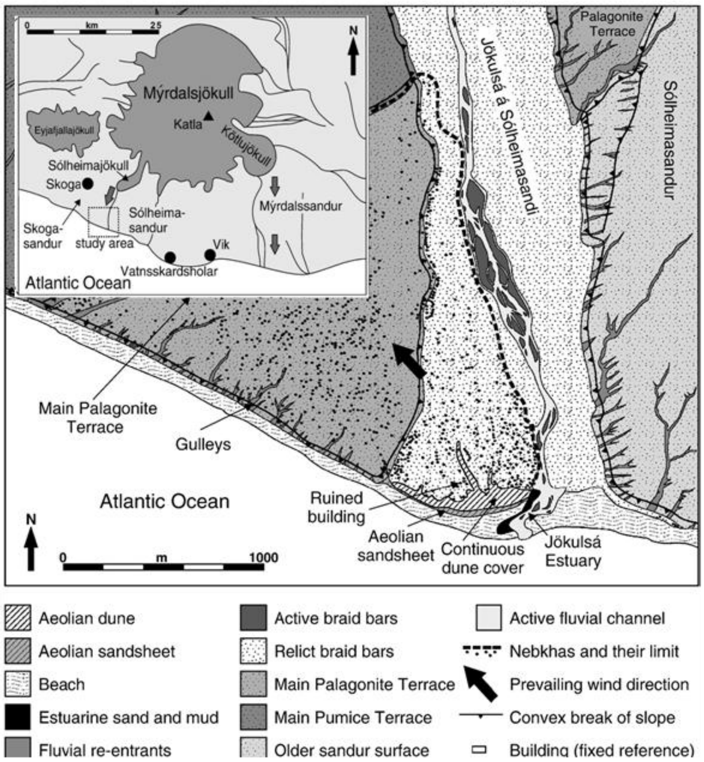


Figure 20. Dune field of Sólheimasandur with legend. Modified from Mountney (2006).

Jón Eyþórsson started monitoring the ice front of Sólheimajökull in 1930 (Eythórsson, 1931) (Figure 21). At that time the position of the glacier was ~ 100 m shorter than in 1904 and ~ 550 m shorter than in 1890 (Jaksch, 1975). The glacier has reacted more or less annually to the mean summer temperature since 1930 (Sigurðsson et al., 2007).

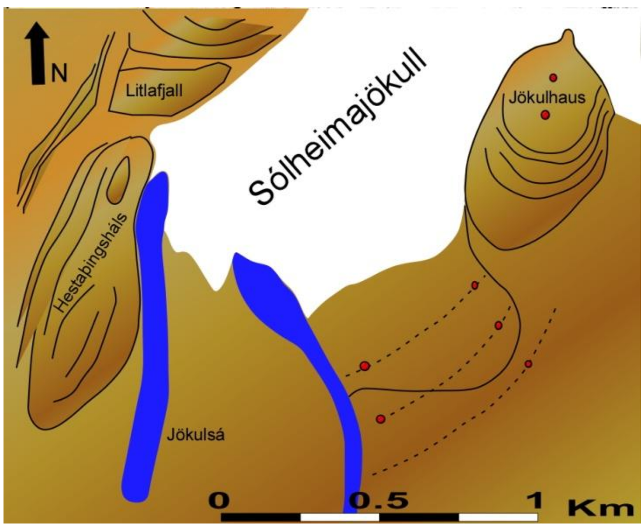


Figure 21. Map of the western outlet of Sólheimajökull in 1930. Red dots indicate initial measure points Modified from Jon Eyþórssons' sketch made in 1930/31.

1.5 Climate since Landnám (AD 874)

The Irminger current is a branch of the North Atlantic current (Figure 22) supplying Iceland with a relatively mild oceanic climate. There are large climate gradients from the central highlands and the northern part of Iceland, with relatively cold and dry conditions and the southern part with more humid oceanic conditions. This causes a different response and dynamics of glaciers in different regions of Iceland (Massé et al., 2008).

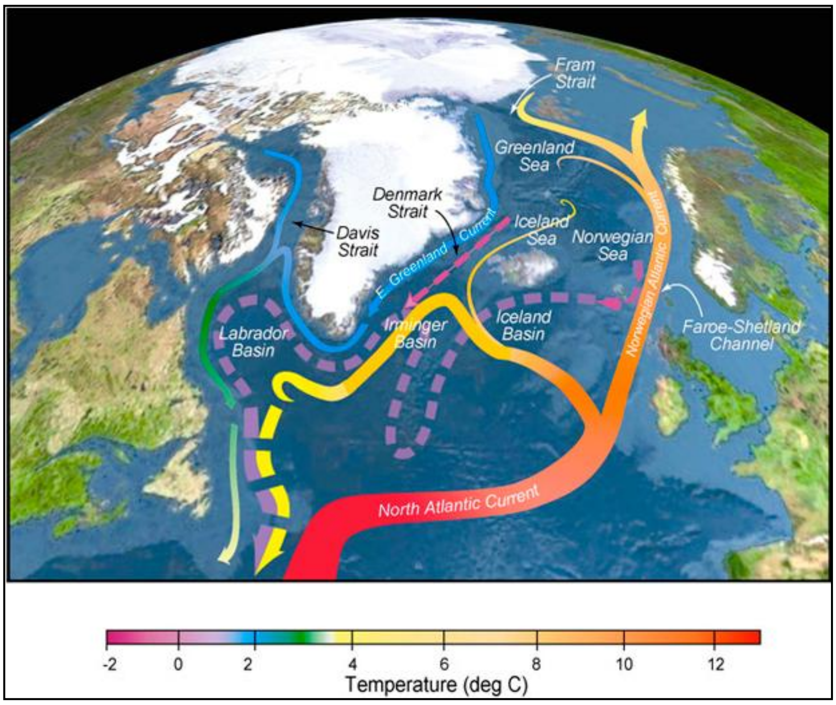


Figure 22. Icelands' position in the North Atlantic between cold and warm water. The North Atlantic Current carries warm, salty tropical surface waters northward. Iceland is sensitive to climate change due to its position between warm and cold waters close to the polar region. Ocean temperature show blue colour as coldest and red as warmest. (Curry & Mauritzen, 2010).

The coldest 30 years on instrumental record (since 1830) were the 1860-1890s. There is little indication of decline to be found in the history of glacier variations between 1600 and 1890.

Climatic evidence from Landnám (AD 874) until the 12th century is sparse since there are no written records available from Iceland before the 12th century (Sigmundsson, 2006). Evidence based on e.g. that two farms settled in the 12th century were overrun by glaciers in the early 18th century (Thorarinsson, 1974), thus assuming climate to be relatively mild in the 12th century.

The climate in the 14th century had a lot of variations, with cooling in the 1320s, 1350s and the 1370s (Grove, 2004). By the year 1364 the sea ice on the sailing route to Greenland is said to have increased. There are few records on the 15th century climate (Grove, 2004). By the mid 16th century the climate was cold with a lot of sea ice (Ogilvie, 1991).

The last decades of the 16th and 17th centuries were very cold and also the 1740s, 1750s and 1780s (Grove, 2004). The early part of the 18th century was milder until the 1730s when there was a shift to a colder climate. The three next decades were quite severe, especially the 1750s. The 1760s and 1770s, were not as cold but were followed by the coldest decade in the history of Iceland, the 1780s (Ogilvie, 1995).

The eruption of the volcano Laki in 1783 caused cold climate and sea ice, which resulted in a 25% decrease in the population of Iceland (Hálfdanarson, 1984). Most glaciers of small to moderate size were largest in the mid to late 18th century, during the period of great cold when conditions in Iceland were most favourable for glacier expansion, but the advances were not as extensive as earlier (Grove, 2004). After a long time with retreating glaciers in the beginning of the 19th century, continuing into the early 20th century, there were two decades of advance after 1970 (Grove, 2004). The advance after 1970 was the result of increased precipitation and cooling due to a cold period from the 1960s to 1995 (Sigurðsson et al., 2007).

The time frame of the Little Ice Age (LIA) in Iceland has been defined differently by scientists. It has been suggested that it started around 1750 and finished around 1900 (Ogilvie, 1995). Most authors suggest that it began in the late 16th century AD and lasted until AD 1900 (Grove, 2004). Lately some authors suggest that it began in AD 1300 (Figure 23). This is based on increased abundance in marine sediment cores of a biomarker produced by sea-ice algae (Massé et al., 2008). The time frame from AD 1300 to AD 1900 will be used as reference in this thesis, as this is the most recent definition of the timing of the LIA in Iceland.

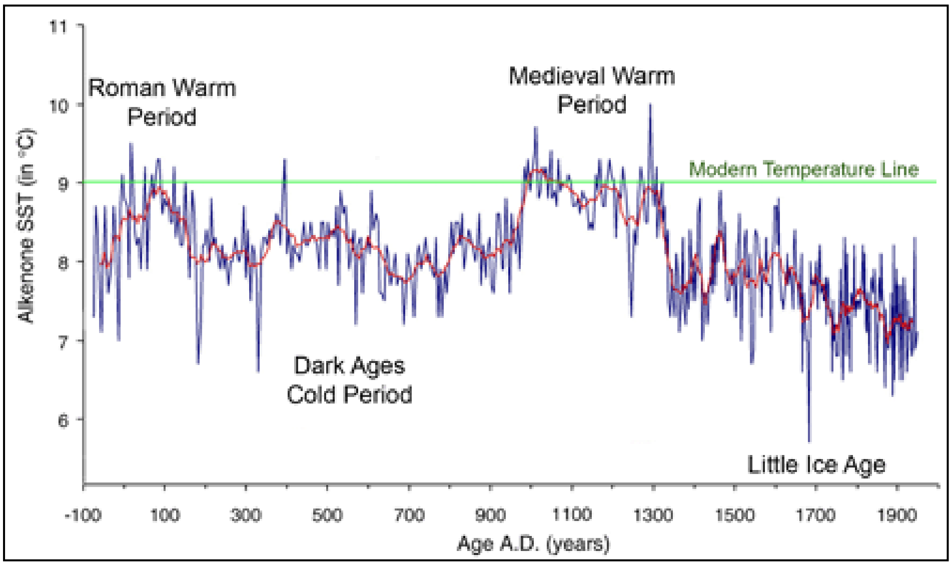


Figure 23. Sea surface temperature versus time. A 2000 year summer sea surface temperature record derived from an ocean sediment core off the coast of North Iceland. Adapted from Sicre et al, (2008).

2. Methods

2.1 Aerial photograph analysis and identification of landforms

Prior to field work in the summer of 2009, aerial photographs and satellite images from 1938 to 2008, were used to identify large end-moraines and other glacial landforms in the Sólheimajökull study area. A more accurate investigation, classification and position of the landforms was then carried out during field work in 2009. Aerial photographs covering the lower part of the glacier, the valley and the forefield of Sólheimajökull to the bridge over main road no.1, were used for mapping glacial landforms from an area of ~ 8.4 km^2.

The geomorphological map was constructed on the basis of the 2007 aerial photographs from Samsýn ehf. The landforms of the Sólheimajökull forefield were mapped in ArcMap. The maps are based on interpretation of aerial photographs and verification during the field work. Landforms drawn on the map were investigated in the field to establish how the feature would look like on the ground and later how it would look like on aerial photographs. Different scales were tried out in GIS to establish which features and what parts of the field area would look best on the map.

Aerial photographs and maps were bought from Loftmyndir, Samsýn ehf and Landmælingar Íslands. Some of the photographs were taken by the Royal Danish Defence (on behalf of Geodætisk Institut) and the USAF (United States Air Force).

Satellite images (250 m and 10 m resolution) were used when larger areas were investigated, to obtain pictures where aerial photographs were not available or to compare the aerial photographs with.

2.2 GIS (Geographical Information System)

ArcGis version 9.3.1 from ESRI was used in the mapping work and interpretation of aerial and satellite photos and maps.

The area from the present day glacier front of Sólheimajökull to the 1996 moraine was mapped in 1:2500, to be able to show the small scale details. The rest of the area with large scale morphology which was easier to draw was mapped out in 1:5000. Overview map was made in 1:20 000.

Elevation models in 3D were produced by converting contour lines into TIN (triangulated irregular networks) in ArcScene. The contour lines used in the TINs are of 20 meter, some of the models have included lines of 5 and 10 meter. These lines were extracted from IS50 V2.0, 2.2 and 2.3 from Landmælingar Íslands.

One DEM (Digital Elevation Model) fitting the Sólheimajökull glacier in 2004 was provided by Anders Schomacker. This is a high grid resolution, of 5 meter. The 2004 DEM was converted to a hillshade model which was used as shadow underlay on the final GIS maps. Because the DEM is from 2004 a lot of changes have since occurred and the underlay will then be imprecise using aerial photographs both older and younger than 2004. A DEM with a pixel resolution of 500 m, of Iceland was used as overview map of Iceland. This was extracted from IS50 V2.0 and V2.2 from Landmælingar Íslands.

Most of the photographs and the maps had to be georeferenced prior to mapping. This was done in ArcGis. Georeferencing is difficult as many points and parameters have to be aligned so that all photographs and maps used and overlaid on each other fits as good as possible. This is important when trying to establish e.g. how many m^2 have melted away on the glacier from one year to another. For the last 13 years it has been ~ 80 m^2 per year.

On the map, the large moraine systems were drawn as polygons to get an easier view of the features while annual moraines, flutes and drumlins were drawn as lines. Features like rivers and lakes, dead-ice, till plain, jökulhlaups-path and sediments, outwash fans, braided river plains and eskers were drawn as polygons. The size of the former extent of Sólheimajökull was drawn as lines to make it easy to plot on an overview map of the glacier.

The mapping was performed on the 2007 aerial photograph as it was the newest and had the best colours and sharpness of the available aerial photographs. Thereafter the aerial photo was replaced by a hillshade model from 2004. The different layers e.g. till, river, outwash sediments etc. have been placed ontop with the possibilities of interchanging the different layers and their order. Changes from 2007 to the 2009 and 2010 aerials are shown on some of the maps. The glacier has retreated around 200 meters between 2007 and 2009.
Classification of landforms was carried out in ArcMap using both DEMs and aerial photographs.

Digital elevation models are 3D figures and a digital representation of ground surface topography and terrain. These have been used with ArcMap and ArcScene, wich are GIS based programs.

The spatial analyst in ArcMap was used to convert a DEM into a hillshade model (Figure 24). This is a better model to use than a DEM. The reason is that the hillshade used as underlay will show depth of field, creating a 3D effect when making maps and drawings in ArcMap or ArcScene.

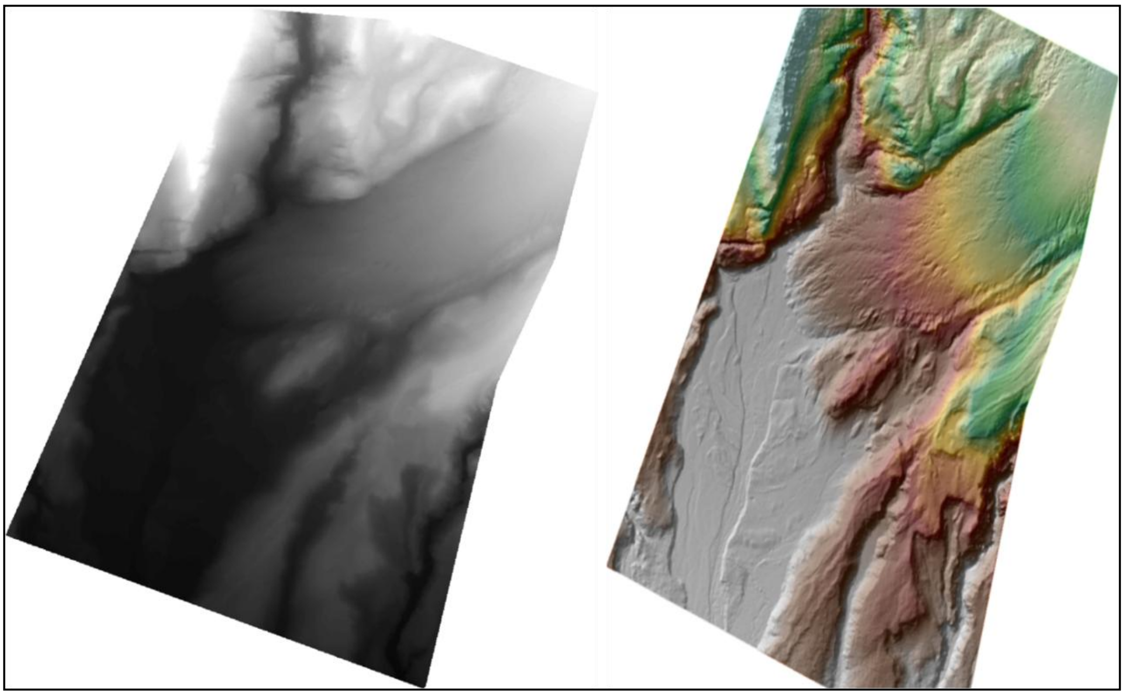


Figure 24. DEM (left) and Hillshade (right) models of Sólheimajökull 2004.

The different elevation models where used to clarify and enhance details to give a better view and understanding of the glacier and the landforms in the forefield of Sólheimajökull.

During the production of TINs from Sólheimajökull and Mýrdalsjökull I found out that there is no accurate elevation data on the glacier surface. All elevation data on glaciers from Landmælingar Íslands are marked as 29 999 m. This is because most of the glaciers in Iceland have not been properly measured by the use of DGPS, LIDAR or other methods. Where information was not available the same elevation data was used from the bedrock around, or the knowledge that there is 20 meter between each contour line. These data was altered for every contour line (more than 1000 lines) in ArcMap, before a complete TIN could be produced.

3D models of Sólheimajökull were made to simplify the surroundings of the glacier and the valley. This was done by draping aerial photographs from different years over a DEM or a TIN. The mapped landforms could then be moved over to ArcScene and draped on top of the aerial photograph. ArcScene is a program in ArcGis to produce and view 3D models. Vertical exaggeration could then be added to the model to enhance the features of the landscape. The exaggeration that looks best and most natural is normally 1.5 or 2 times. Using different colour codes and turning the model in different angels allowed me to get a better understanding of the glacier and the forefield.

2.3 Field work

Field work was conducted at Sólheimajökull during the summer of 2009, from the 20th of May to 16th of June. Sections were cleared so that they could be sketched and described, landforms were recognized and marked with GPS so they later on could be included in the GIS work.

The morphology of the forefield of Sólheimajökull, from the 1996 end moraine to the present day glacier front was mapped during the field season. Terrain profiles were measured with a TopCon levelling instrument, to get an impression of the forefield geometry. The instrument uses a laser beam to measure distances from a fixed point to a hand-held reflector at the point to be measured. By doing so, the location of the measured point, e.g. its height and distance, was accurately registered relative to the fixed point (instrument). Repeating this process for a number of selected points across e.g. moraine ridges or drumlins, an exact profile can be obtained.

Three sedimentological logs were made at the western side of Jökulsá and two logs and three profiles on the eastern side of the river. The logging site sites were selected where exposures of the sediments were good and easy to clear. During the mapping of the sections, the different sediments exposed were also studied. This included the size, shape, striations and roundness of grains.

One fabric analyses was taken at section 1 on the eastern side of Jökulsá. 25 samples were collected, dip and strike was measured and the results were plotted into the program *Stereo32*. The plot from *Stereo32* shows the preferred orientation of flow of the glacier during deposition of the sediments.

A Garmin 60CS GPS was used to get the correct positions of the profiles, sections and some features like moraines and drumlins were plotted and later on imported into GIS by using MxGPS or making tables in Excel.

2.4 Dating methods

2.4.1 Radiocarbon dating (^{14}C)

It was developed, by Willard Libby in the 1940s. ^{14}C atoms rapidly oxidise to carbon dioxide and along with $^{12}CO_2$ mixes throughout the atmosphere to be absorbed by the oceans and living organisms. ^{14}C is being produced in the upper atmosphere and then becomes stored in different global reservoirs e.g. the atmosphere, the biosphere and the hydrosphere.

All living matter absorbs carbon dioxide during tissue-building in a ratio that is almost in equilibrium with atmospheric carbon dioxide. When dying the organic tissue will decay and there will be no replacement of ^{14}C. Therefore if the rate of decay of ^{14}C is known the date of death can be calculated from the measured remaining ^{14}C activity. The half-life of ^{14}C has been internationally agreed on to be 5570+/-30 (Lowe & Walker, 1997).

Anything older than 40 000 years is not possible to date with this method (Manz, 2002). This method was used on organic material which was discovered around two meters below the surface (Figure 25). A moraine on the surface had been deposited on old surface consisting of compressed grass and old soil. From this organic layer two samples were extracted and sent to the Ångström laboratory, Uppsala University, Sweden.

Figure 25. Radiocarbon sample taken from the LIA moraine.

2.4.2 Cosmogenic exposure dating (CE)

The method was used on rocks situated on moraines both in the valley and on the ridges of the smaller mountains confining Sólheimajökull.

The technique of using ^{36}Cl in Iceland is a good method on surficial features because of difficulties using other methods e.g. radiocarbon dating. Ca spallation is 17% higher in Iceland than the western USA, due to persistent low atmospheric pressure in connection with the Icelandic low (Licciardi et al., 2008). ^{36}Cl which has a half-life of 300 ka was used as the amount of quartz in basaltic rocks is very small. The reaction of cosmic rays with certain elements in minerals leads to the formation and progressive accumulation of ^{36}Cl on exposed rock surfaces. Buried rock experience low subsurface neutron flux, therefore the amount of cosmogenic ^{36}Cl is proportional to the length of time that has elapsed since the rock was exposed on the surface.

What is needed for a good sample is a large surface that has been fully exposed and undisturbed since emplacement and contain no cosmogenic nuclides (cause errors) inherited from earlier exposures (Manz, 2002) Leaching of ^{36}Cl and erosion of the rock surface will lead to disturbance of the cosmic-ray clock (Lowe & Walker, 1997).

The dating range for this method is around one million years (Manz, 2002; Gosse & Phillips, 2001).

Three samples (Figure 26) were collected on rocks as big as possible, sitting on old moraines. Sample size was between 0.5 and 1 kg and shielding was measured on all places along with elevation and co-ordinates. Two samples were collected from each place, as one of them had to be used in geochemical measurements. The uncertainties could be between +/- 500 year, therefore samples were only taken from moraines we thought to be of old age and furthest possible away from the present-day glacier front.

Figure 26. Sampling rock for Cosmogenic Exposure Dating on a boulder situated on a moraine.

3. Results

3.1 Geomorphology

Subglacial lineations like flutes and drumlins on till plains, pitted outwash, eskers, annual moraines, dead-ice areas, outwash fans and lake sediment flats were mapped (Figure 27). In addition, erosional drainage channels (from jökulhlaups) and end moraines were mapped. The mapped glacial landforms originate from AD 56 and possibly older. The distribution and preservation of landforms in the Sólheimajökull forefield has been disturbed by jökulhlaups coming down Sólheimajökull and by the frequent release of ice-dammed lakes in Jökulsárgil, ripping up the forefield of Sólheimajökull. The present terrain surface at Sólheimajökull is the cumulated result of landform generations from several advances and retreats of Sólheimajökull through time, as well as alterations of the surface by several jökulhlaups and ice-dammed lakes.

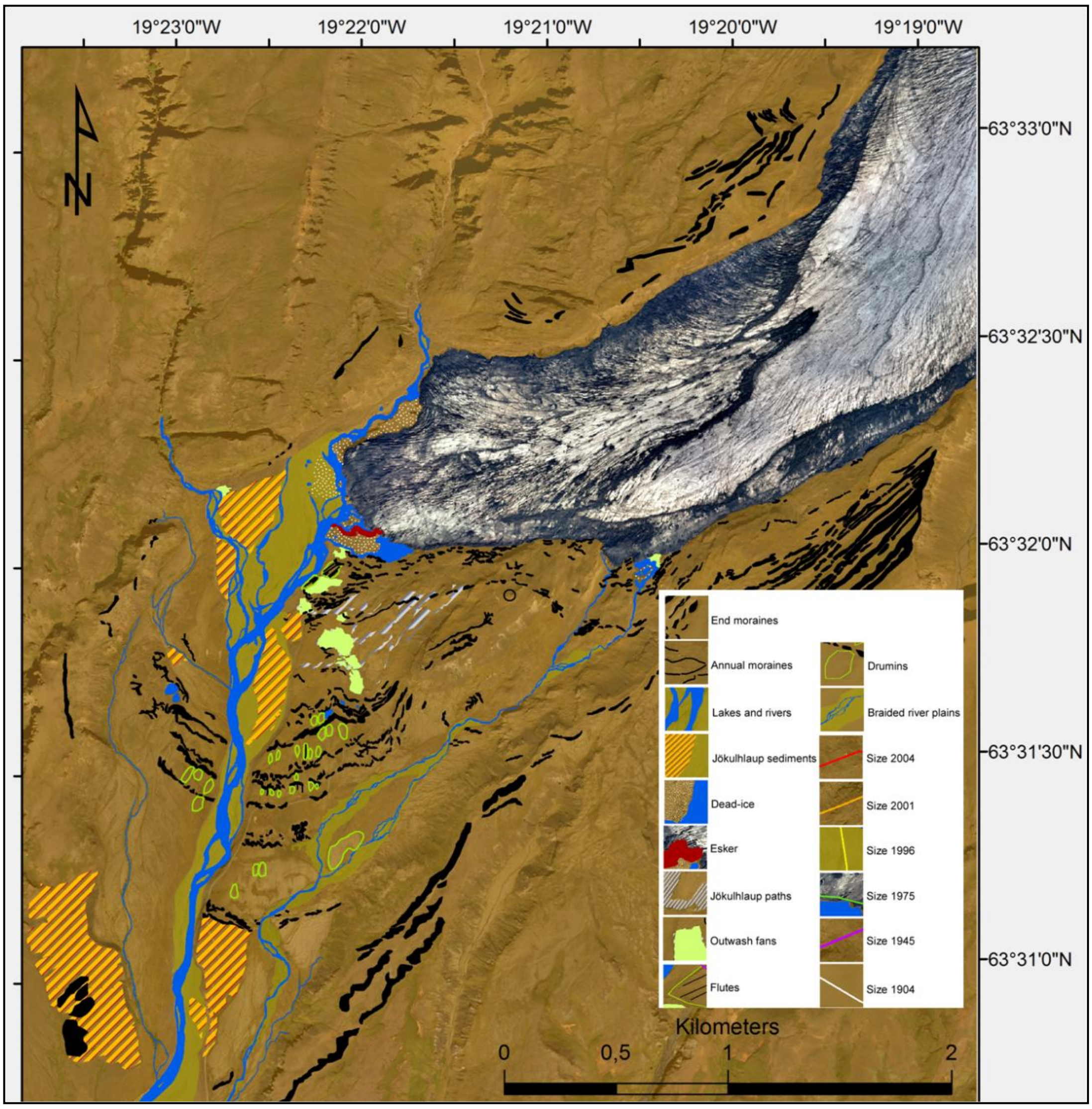


Figure 27. Geomorphological map of Sólheimajökull, with overview of the glacier and the forefield with the surrounding mountains. The scale is 1:20 000 and the photograph is from 2007.

Subglacial lineations

Landforms like drumlins and flutes are covering the exposed till plains in the forefield of Sólheimajökull. Using the Topcon levelling system (Figure 28) it was possible to recognize e.g. drumlins in the field (Figure 29) by its shape and form, by measuring the length and height over these landforms.

Figure 28. Topcon levelling instrument in use in front of the glacier.

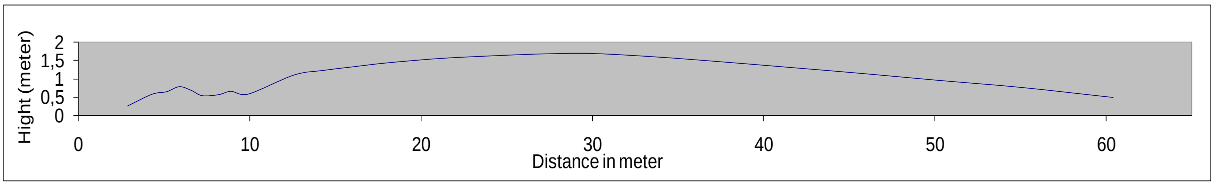


Figure 29. Profile of a drumlin in front of Sólheimajökull, ice movement was from the left to the right (N-S). The drumlin is 1.5 m high and 50 m long. The profile was made with a TopCon levelling instrument.

Recognizing drumlins will indicate the direction the glacier was moving during deposition. A drumlin (Figure 30) is defined as an oval-shaped hill, largely composed of glacial drift, formed beneath an glacier and aligned in the direction of ice flow. Most of the drumlins have their highest elevation (stoss end) pointing in an upstream direction and the gently sloping end (lee slope) facing down-ice. Drumlins exists as fields or swarms of landforms rather than isolated individuals. Within a swarm they have a similar long-axis and morphology as neighbouring drumlins and are close to each other. Drumlins can be between 250 and 1000 metres in length, 120 and 300 metres in width and upto 50 metres high (Clark et al., 2008). The drumlins at Sólheimajökull are small, up to 85 m long, 35 m wide and only a few meters high.

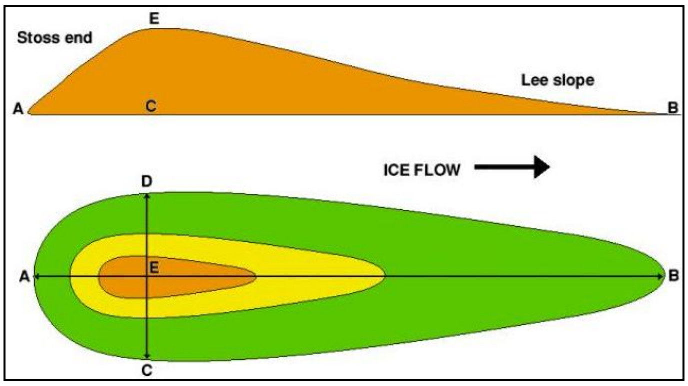


Figure 30. Ideal form of a drumlin (The Geography site, 2006).

Flutes are common and are found as continuous ridges on-top of the drumlins, some of which might be traced for the same distance as the drumlins with initiating boulders. Smaller flutes are sometimes difficult to distinguish from sediment prows distal to lodged boulders. Flutes are never more than 10-15 cm above the surrounding terrain.

Supraglacial landforms

Pitted outwash fans appears mainly closer than 0.8 km to the glacier front of Sólheimajökull, as fans with a length of less than 200 m. They consists of glaciofluvial sediments, which collapse when the underlying dead-ice melts. Grain size of the outwash sediments range from fine sand to boulders with a size of 10-15 cm. Remnants of dead-ice still continue to exist in parts of the pitted outwash surface, which can be seen on aerial photographs from different years, by growing proglacial lakes.

A large esker up to 400 m in length, consisting of a single ridge is developed in the main feeding channel to the proglacial outwash fans. It consists of mainly diamict and fluvial sediments. The esker is ice-cored, with slumping and backwasting occuring during the summer months. Eskers are formed by infillings of ice-walled river channels and could be evidence of subglacial, englacial or supraglacial drainage networks.

Proglacial landforms

The action of water in the proglacial environment is seen both as depositional landforms e.g. outwash fans, eskers and lake sediment flats as well as erosive forms e.g. drainage channels.
Most of the outwash fans are mapped within 1 km of the glacier margin. They comprise of horizontally bedded medium to coarse sand interbedded with massive and bouldery gravel beds.

Areas previously submerged by water, due to excess meltwater or dammed by ice, contain fine grained lake sediments. Sediment thickness vary from a few cm to ~ 10 cm in the largest lake sediment flat in front of the glacier margin.

Several channels are eroded into the different substrates of the landform surface. These channels range from canyons formed by jökulhlaups (Figure 31), to smaller channels eroded into fine grained sediments by the action of water. The jökulhlaup channels are abandoned and host only minor streams during heavy rainfall.

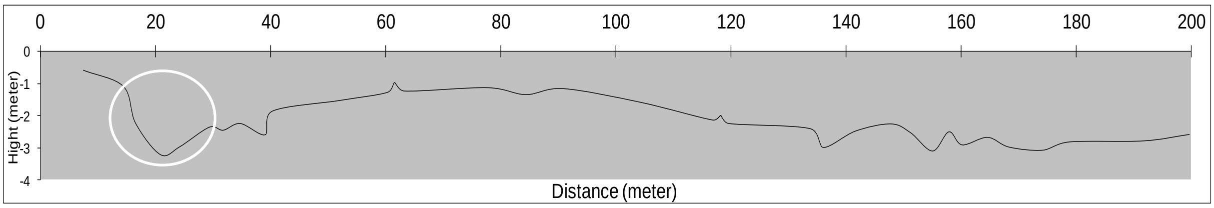


Figure 31. Jökulhlaup path (white circle) and channels in the proglacial area of Sólheimajökull.

Ice-marginal landforms

End moraines are ridges parallel to the former glacier margins (Figure 32). Some of the longest can be followed for ~ 4 km, thus indicating the configuration of the glacier margin at the time of formation. The long and large end moraines are situated on the eastern rims of the valley, where some are up to 30 m wide and 5 m high. The smaller end moraines are situated in front of the present day glacier front and spread around in the valley at distances up to 2.5 km from the present day glacier front. Some of the investigated end moraines might still contain ice, while all the smaller annual moraines are ice-cored.

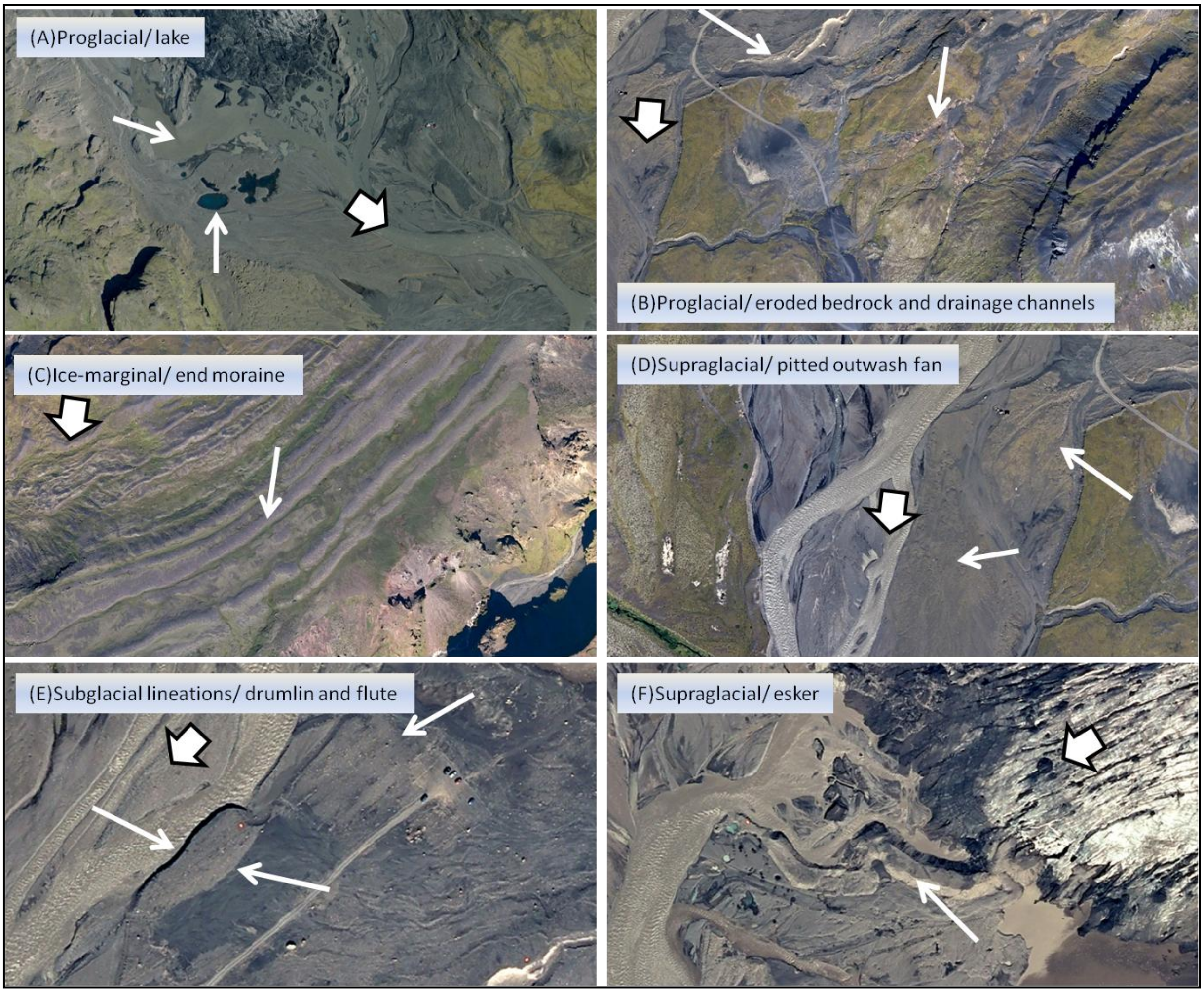


Figure 32. Examples of mapped landforms in the forefield of Sólheimajökull. Landforms are vizualized as aerial photographs. Large white arrow indicate ice-flow direction and small white arrows show landform. A)proglacial – lake.B)proglacial – eroded bedrock and drainage channels. C)ice-marginal – end moraines. D)supraglacial – pitted outwash fan. E)subglacial lineations – drumlin and flute. F)supraglacial – esker.

Maps

The scale of 1:5000 was used to get more details of the forefield without completely loosing the overview of the valley (Figure 33). The legend gives an overview of the landforms mapped in ArcGis, as well as a line showing the glacier margin in 1904.

Details that can be drawn from the map is e.g. that sediments from the 1999 jökulhlaup reached as far down-valley as 1 km, most of it following the river depression. The jökulhlaup sediments on the west side of the river are not from the 1999 event but probably from the early 1900s and older. The area of jökulhlaup sediments show many signs of dead-ice melting with the subsequent kettle holes and large rocks up to 10 meter high. Large amounts of sediments were deposited during the jökulhlaups, the thickest (6 m) amounts proximal to the glacier and 500 m away 1 m.

The drumlins on the map marked with green circles appear to be clustered mostly towards the centre of the valley and around the LIA moraines. Examples from Sléttjökull shows that drumlins can form by draping remnants of lower till, obstacles like sandy outwash and overridden end moraines (Schomacker et al., 2010). The flutes in the area are few and most of them are situated on top of the drumlins. Moving further north on the map fluvial processes has most likely wiped out many of the drumlins in that area.

Small lakes and ponds are marked with blue. They are neither deep nor large, from 10-40 cm deep and 5-30 long. In the area there are several old lakes which have dried in. only active lakes from 2007 were mapped on this map from 2007. Most of these lakes and ponds were probably created by dead-ice left behind, when the glacier retreated through the area.

Large end moraines are marked out with thick black lines show the distribution of the moraines on the map. It is quite easy to correlate moraines from one side of Jökulsá to the other after mapping them from aerial photographs. Most of the moraines on this map have been deposited during retreat or still stand of Sólheimajökull since 1890.

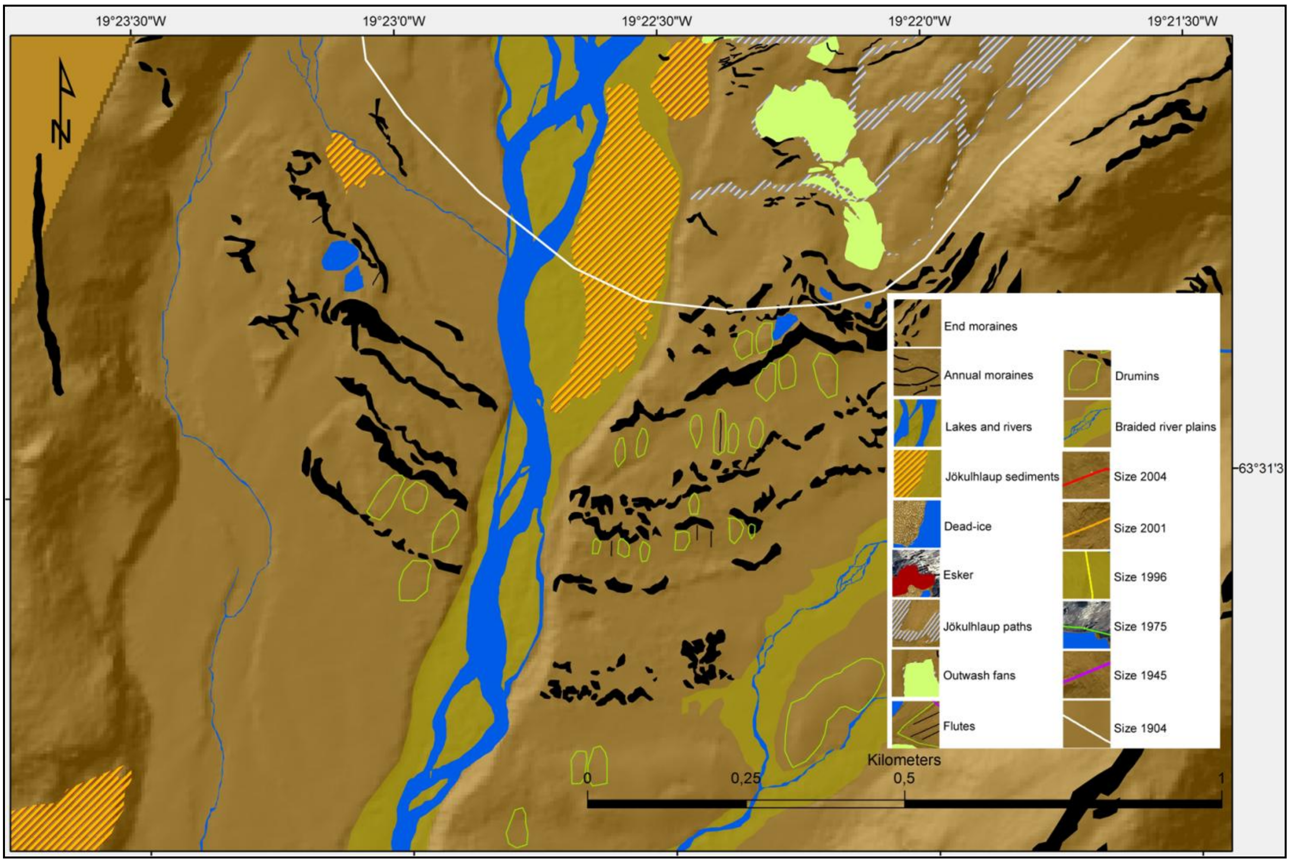


Figure 33. Map scale 1:5000 of the forefield of Sólheimajökull.

A map in the scale of 1:2500 was made, to get a better view of the details from the forefield of Sólheimajökull (Figure 34). The limits used for this scale was drawn from the present day (2007) glacier margin to the 1996 end moraine.

The thin small black lines are annual moraines situated between the 2007 glacier margin and the 1996 end moraine. The annual moraines are all deposited during a retreat phase of the glacier and are all small, from 10 cm to 100 cm high. Some of these moraines are still ice cored, but melts away in a summer or two. The moraines have a discontinuous and irregular appearance with depressions and peaks in the ridge systems, suggesting different retreat velocities of the glacier margin. It is not possible to distinguish or recognize moraines from all 11 years as some have been wiped out by fluvial processes and other by winter advances. The terrain from the 1996 moraine towards the glacier margin is sloping down-hill as well (Figure 31). Numbering the annual moraines to try to re-create the position of Sólheimajökull since 1996, was made possible by using aerial photographs from different years along with measurements done by the Icelandic Glaciological Society of the frontal movement of the glacier and correction in the field.

The esker marked in thick red colour is described at page 28 but is mostly ice cored covered by sediments. Some places it is ~ 5 m thick. The esker is situated in an active fluvial area and is steadily being torn down by the processes at work.

The drumlins on this map all have distinct flutes on the surface, which is recognizable both in the field and from the aerial photographs. These landforms have been deposited during advances but are too large to have been deposited by winter advances, but could have been deposited when Sólheimajökull was advancing during an earlier period e.g. 1970-1995.

The glacier margins from 1945 to the present day glacier margin are marked as lines with different colours on the map. This was done by using aerial photographs from different years. The 1945 limit is inside the 1996 limit because the glacier was retreating until 1970. From 1970 to 1996 the glacier was advancing moving the 1975 line (green) forward, ending up with the 1996 limit (yellow). Hereafter the glacier has been retreating which can be seen on the 2001 (orange) and 2004 (red) lines.

The rivers in front of the glacier changes from year to year and are here mapped in 2007, but using different aerial photographs it would be possible to map the changes of the rivers and lakes in front of Sólheimajökull through time.

The different outwash fans (light green) consists of fine sand and were deposited as the glacier retreated and melt water flowed down on the relatively flat areas.

Dead-ice is mostly confined to the close vicinity of the glacier margin. This is shown as white dots on brown surface on the map. Some of the dead-ice is pieces of ice which breaks of the glacier margin and later gets covered by sediments, while most of it is in the form of parts of the glacier margin which detaches. This is usually covered in tephra and sediments and disintegrates slowly. The melting takes place by backwasting and downwasting. The rivers and proglacial lake then erodes the sediments away and the dead-ice will then melt easier.

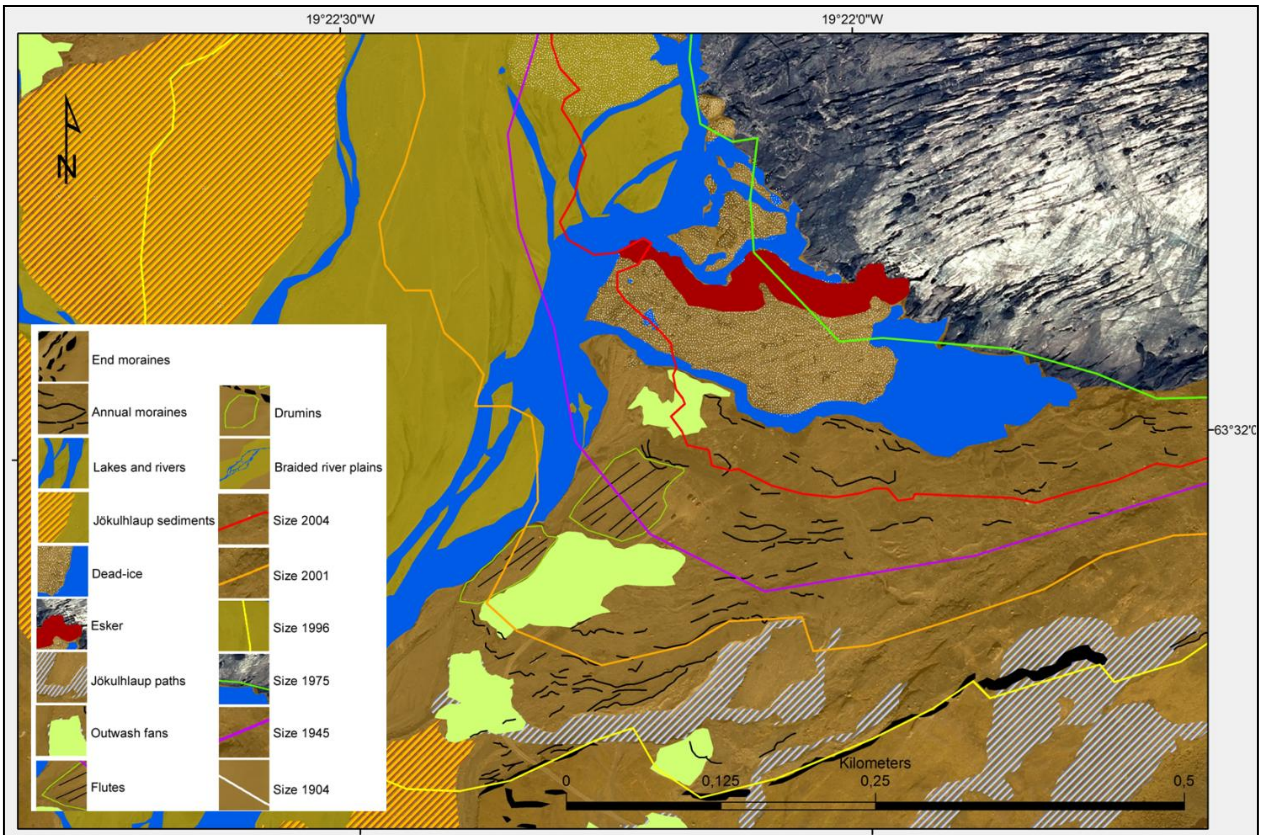


Figure 34. Map scale 1:2500 showing the morphology from the 1996 moraine (yellow line) to the present day glacier front.

The 3D model is a good tool for visualizing how Sólheimajökull was draping the landscape surrounding the glacier both during retreat and advance. Thereby it is possible to see how elevated the glacier margin was at a given time. The glacier margins which are drawn on the 3D model in Figure 35 show the elevation of these lines on the landscape and can be used to compare both areal distribution and the elevation of the given year. Using several lines of glacier margins this can be used to see how the glacier changes through time.

The 3D model shows that the best preserved moraines (white lines) are situated at high elevations, most of them at the east side of Jökulsá. The southernmost moraines on the west side are from around 1890, while the eastern side have moraines almost 2000 years old. Using the terrain model it is possible to see that the west side of Jökulsá is at lower altitudes than the east side, which is the probable cause to why the moraines are not preserved during the same time span as the east side. They have been destroyed by jökulhlaup and other fluvial processes.

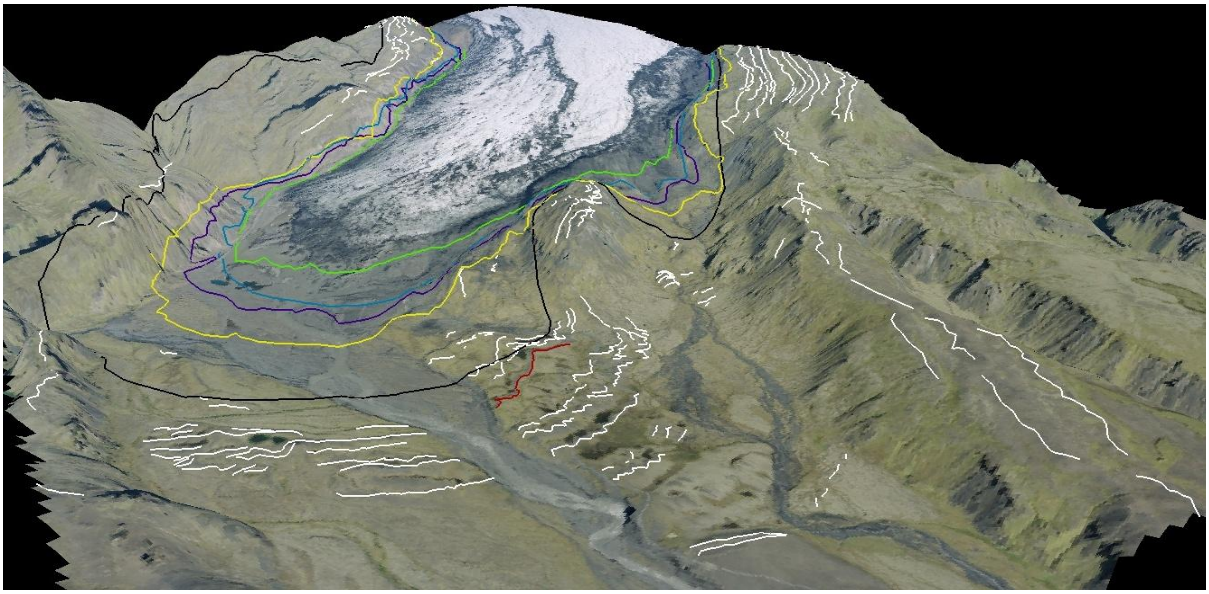


Figure 35. 3D map of Sólheimajökull. Aerial photograph from 2009 draped over a 2004 DEM, vertical exaggeration is 2.

Area calculations

The area used in the calulations is the frontal part of the glacier. The limit is the white area on the 2009 aerial photograph in Figure 36. Everything East of the black field is not included in the calculations. The calculations (Table 5) were performed in GIS with the aerial photograph from 2009 as base.

The table shows the area and perimeter and change of glaciated area, from the four different years. Lines in red, green and yellow colours mark the glaciated area at the given time, of Sólheimajökull from 1904-2009. All lines were measured in length (perimeter) and in area, from the white division line to the coloured lines. The green line from 1904 is drawn on a georeferenced map, while the yellow line from 1945 and the red line from 1996 have been drawn on georeferenced aerial photographs.

The uncertainties of the aerial photographs are between 1 and 10 meters, while the map from 1904 has a large uncertainty due to the tools of measurements available at that time, this is explained in the table and figure below.

The frontal part of Sólheimajökull reduced from 3,09 km^2 to 0,85 km^2 (68-72.5%) from 1904-2009, depending on the uncertainty of the 1904 map.

Table 5. Change in area and perimeter pr. time-slot, of Sólheimajökull 1904-2009.

Change in area and perimeter of Sólheimajökull 1904-2009				
Year	1904	1945	1996	2009
Area (km^2)	3,09	1,33	1,87	0,85
Perimeter (km)	8,1	5	6	4
Change (%)		-57	40,6	-54,5
Uncertainty 1904 (km^2)	0,46			

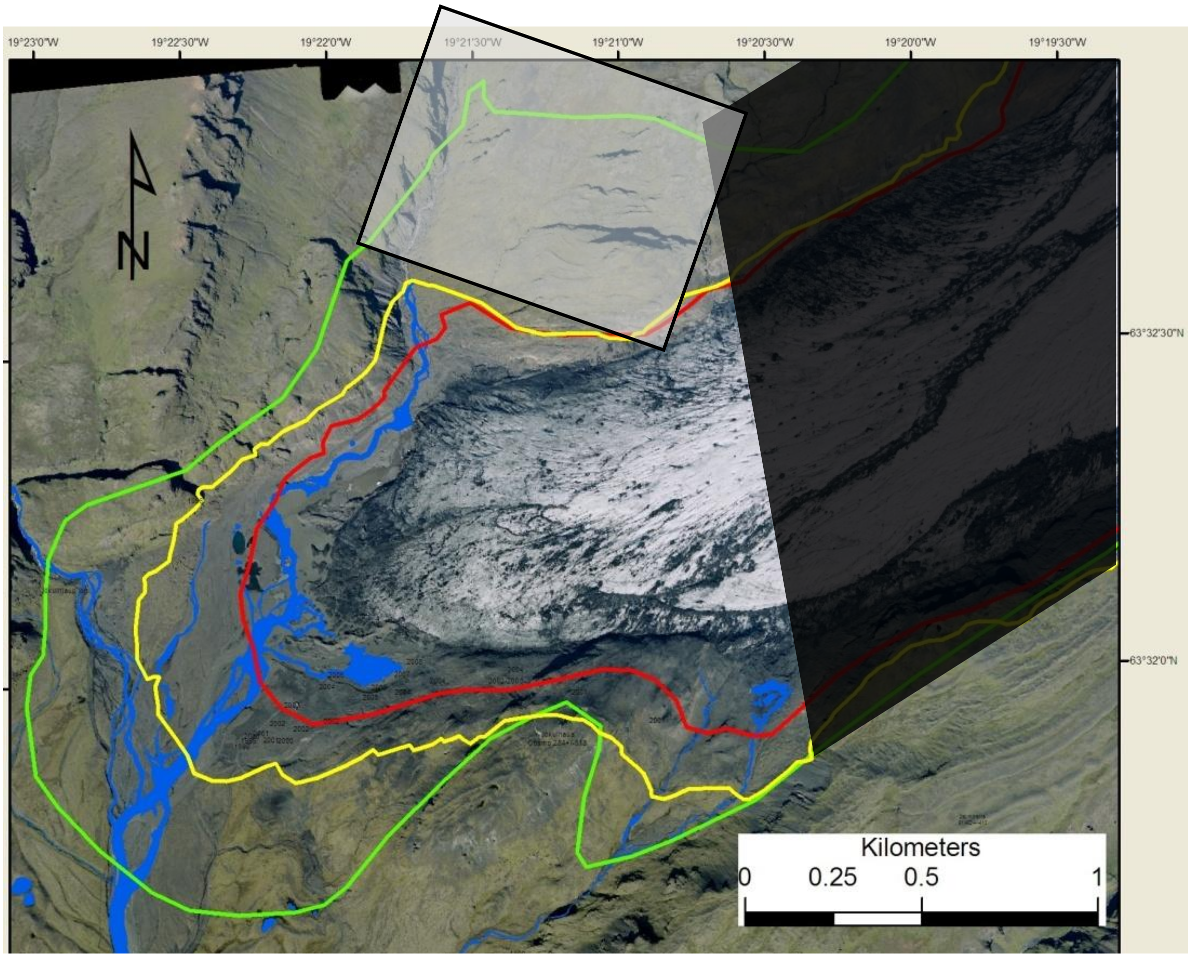


Figure 36. Map of Sólheimajökull from 2009. Red line show size of glacier in 1945, yellow line in 1996 and green line in 1905 Only the area west of the black area was used in the calculations. The grey inserted box shows the area of uncertainty in 1905.

3.2 Sedimentology

The forefield of sólheimajökull is divided into a western and eastern part, parted by Jökulsá. Along the river, which has cut down through the sediments, it is possible to find sections for logging and studies of the stratigraphy. Five logging site sites and three section sites were cleared and used during the field work (Figure 37). The purpose of making the sedimentological logs was to achieve a detailed record of the geological sediments in the forefield of Sólheimajökull and to gain a better knowledge about the glacial history of the area. The logging site sites were chosen because of interesting surface topography or close connection to some of the described sections.

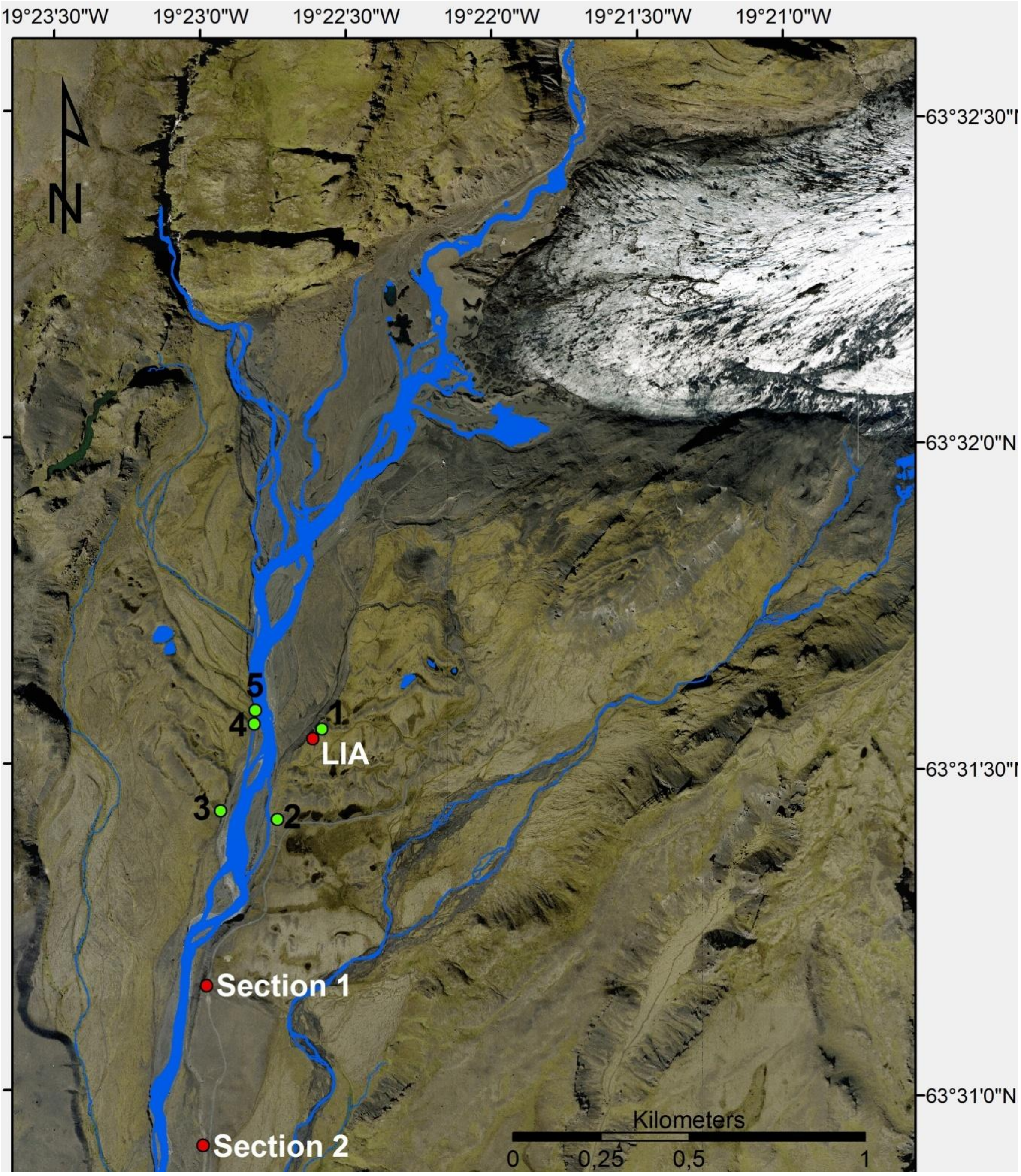


Figure 37. Map of the forefield of Sólheimajökull with red dots showing the position of sections and green dots showing position of logs. Aerial photograph from 2009 is used as background.

3.2.1 Section one

Description. - The section (Figure 37) is situated on the east side of Jökulsá, 1.9 km in front of the present day glacier. The section is 50 meter long and 16 meter high (Figure 38).

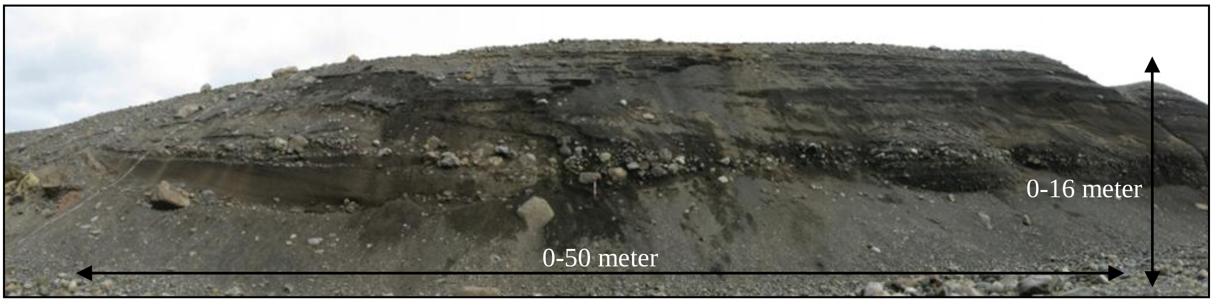


Figure 38. Photograph of section one. The section is 50 meter long and 16 meter high.

From the bottom of the section and 3.2 m upwards the unit consists mostly of matrix-supported tephra (Figure 39). The grain size of the tephra is up to 0.5 cm thick and mostly angular in form. Within the tephra there are some boulders, some bigger than 1x2 meters and dropstones up to 2 cm thick. The tephra layer is dipping towards he south, thus the sediments are thicker in the western part of the section. ~ 90 cm from the bottom with a sharp basal contact, there is a 10 cm unit of horizontal silt and fine sand with lenses of tephra. ~ 2 meters from the bottom of the section wedge-shaped sediments penetrate the sediments. These sediments consists of finer material than the surrounding sediments, like clay, silt, sand and gravel. The length of the intrusions are a couple of meters and up to 20 cm wide. The sediments inside the intrusions consists of clay, silt, sand and gravel, with a grain size from a few mm up to 1 cm.

Overlying is a ~ 20 cm thick tephra with grain size up to 2 cm. This unist is coarsing upwards. Next is a ~ 30 cm thick boulder unit with clasts up to 10 cm in size, in a matrix of fine sand and tephra.

On top is a ~ 40 cm thick grey-black tephra unit up to 5 mm in size and dropstones up to 1 cm. A 4 cm thick medium-coarse sand is next with a grain size around 4 mm.

Overlying is a ~ 35 cm thick massive matrix-supported diamict. It has a brownish colour, banded in places, fine-grained and the matrix has a clayey-silty composition. It is clast rich, firm and difficult to excavate. Some of the clasts are larger than 20 cm.

Next is a 70 cm sequence consisting of first a laminated silty, clayey layer which is coarsening upwards, with a light brown colour. Then there is an unconformity consisting of mainly clast-supported coarse sand to fine gravel up to 5 mm. On top is another coarsening upwards laminated layer of clay, silt and fine sand, with a light brown colour. A second unconformity lies on top consisting of the same material as the lower unconformity.

Next is a layer of clay, silt and medium sand, coarsening upwards. The colour of this layer is more grey-blue. Then a third unconformity consisting of clast-supported, fine gravel with a grain size of ~5 mm. This is overlain by ~ 20 cm thick laminated fine to medium sand which is coarsening upwards. The laminations are many and very thin changing from a few mm thick to ~ 1 cm thick (Figure 40).

Following is a ~ 50 cm fine to coarse gravel layer with gradational contacts to both upper and lower boundaries. The beds in the gravel layers are between 1-3 cm thick and the grain size is from 0.5-2 cm thick.

Overlying is a ~ 3 meter thick laminated, coarse sand unit, with beds. Gravel size clasts (2-5 cm) lie around in the coarse layers. Most beds are less than 1 cm thick and the thicker beds around 2 cm thick. In the middle part there is a slight variation in sand grain size, from medium to coarse sand, thus giving bedding to the unit. The lower beds are more or less horizontal, and then the beds start to dip towards the south, until they reach ~ 40° and a thickness of ~70 cm. The upper sand beds are then levelling out and becoming horizontal again.

On top is a ~ 1.7 meter matrix-supported diamict with a sharp basal contact. The diamict is fissile with angular to subangular clasts, up to 15 cm long, with a moderate content of striations on the clasts, the smaller clasts are from 2-4 cm. Some of the clasts has chattermarks. The colour of the diamict is ranging from brown to grey. The sediments are firm and difficult to excavate.

Capping the section is a medium to coarse sand, with a gradational basal contact. Most of the clasts on the surface are striated.

Wedge-shaped sediments penetrate the whole section from the top to the scree at the bottom. These sediments consist of finer sediments than the surroundings, like clay, silt, sand and gravel. The length of the intrusions is from a few meters up to 10-15 meters and they have a thickness from a few cm to 30-40 cm. Most of them are moving towards the same direction, dipping to the south.

25 samples were collected from the top of the upper diamict in section one, for fabric analyses (Figure 41). The orientation and dip of elongated clasts were plotted in *Stereo32*, which is a program to plot structural data in.

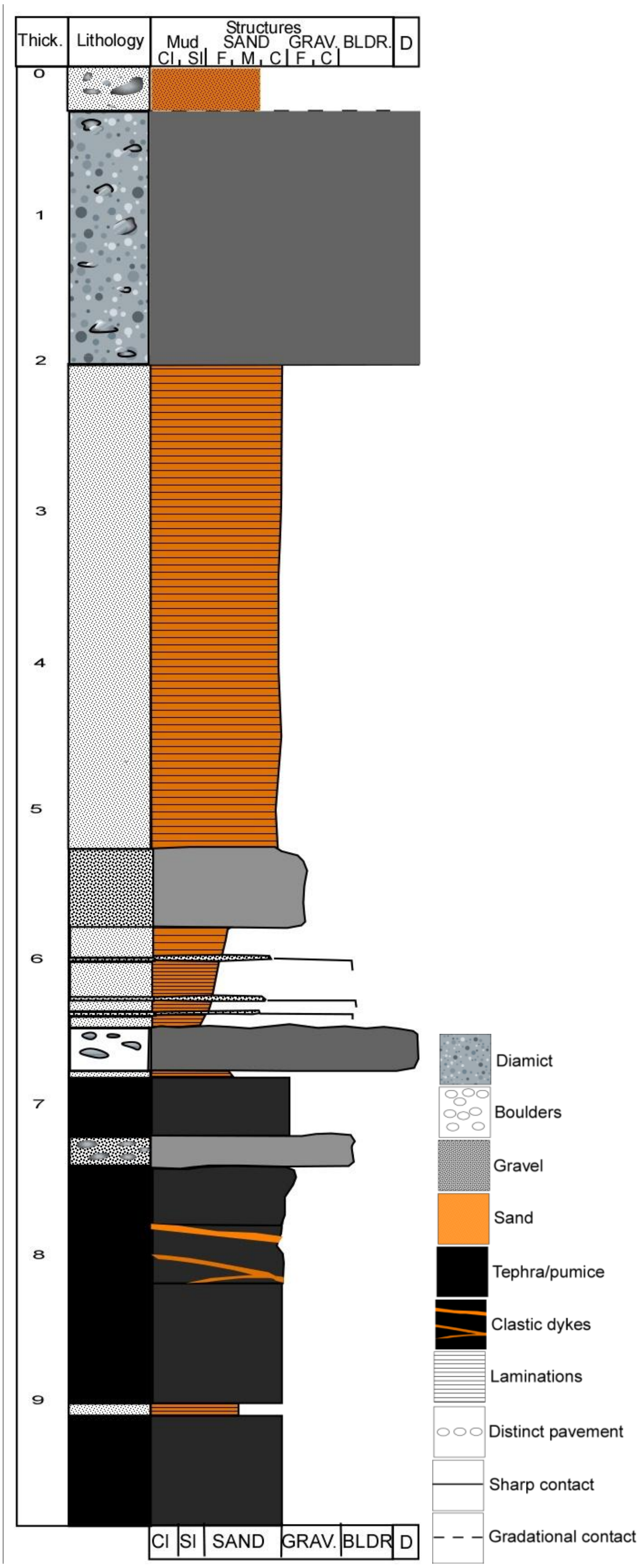


Figure 39. Logging site section 1. Scale is in meters.

*Interpretation***. -** The lower ~ 3 meters of the section is interpreted as jökulhlaup deposits and show many of the criteria's of a jökulhlaup, e.g. massive layers, fines in the bottom and coarsening upwards with large boulders and clasts are indicative of a fluvial origin (Benn & Evans, 1998). The massive amount of tephra in the section is interpreted as pumice, which is tephra mixed and transported by water, thus supporting the jökulhlaup interpretation.

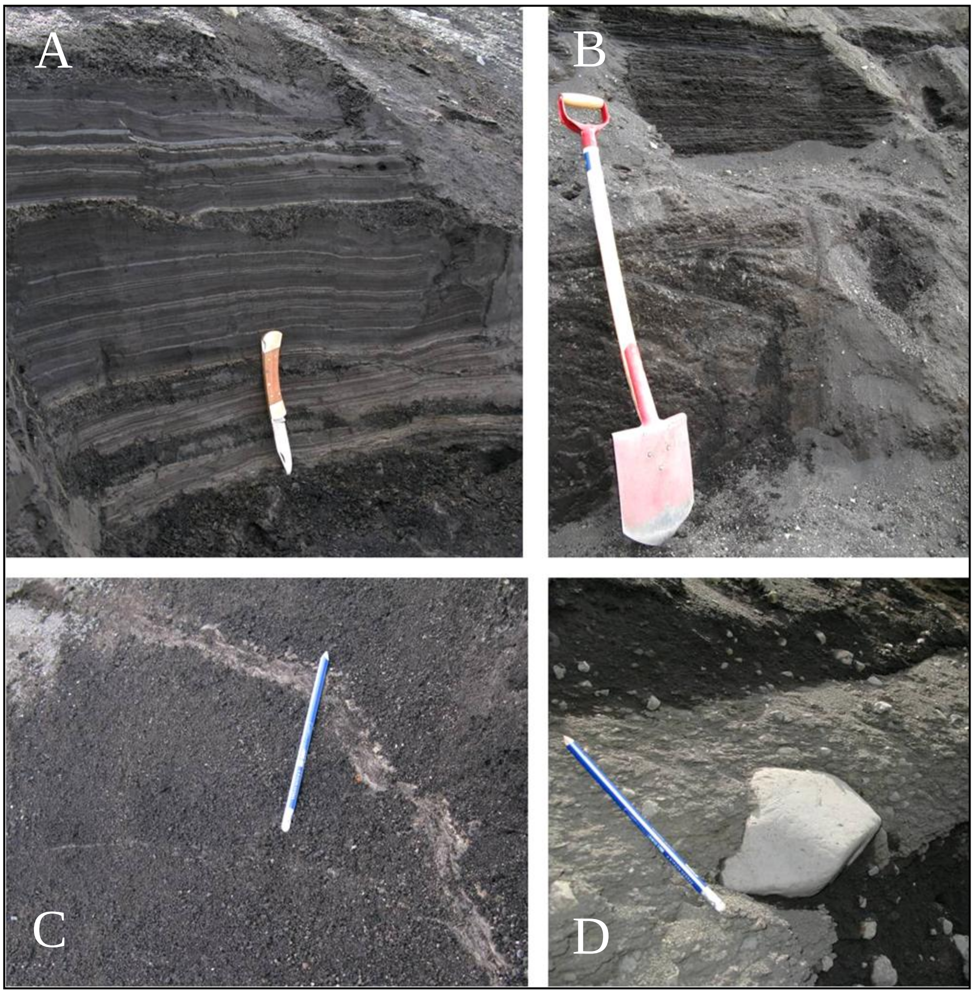


Figure 40. A shows laminated coarsening upwards bottomsets. B shows the transition from foresets to topsets. C a clastic dyke penetrating sandy sediments and D shows the fissile till on top of section 1.

The laminated beds with transitions from fine material like silt into coarse sand and the change from horizontal to dipping and back to horizontal laminations are indications of fluvial origin. This is interpreted as bottomset, foreset and topset, components of a Gilbert-type delta.

Topsets are deposited by braided streams on the subaerial delta top, foresets represent sediment that avalanches down the steep frontal slopes of deltas, and bottomsets are deposited from sediment-laden underflows (turbidity currents) which intermittently extend into deep water beyond the delta front. Progradation of the delta results in foresets being deposited on top of bottomsets, and topsets on top of foresets (Benn & Evans, 1998). It is likely that the delta was fed by glacial meltwater, which prograded into a small lake dammed up by jökulhlaup sediments or ice.

The upper diamict with striated clasts and the sharp basal contact is thought to represent basal till (Benn & Evans, 1998; Krüger and Kjær, 1999).

The result of the fabric analyses, show that V1, which is the principal vector combined with the strength of the maximum clustering in the data was 46.51 degrees (Table 6). The interpretation of V1 show that the glacier was moving south-west out of the valley during deposition of the till, which fits well with the glacial history of Sólheimajökull.

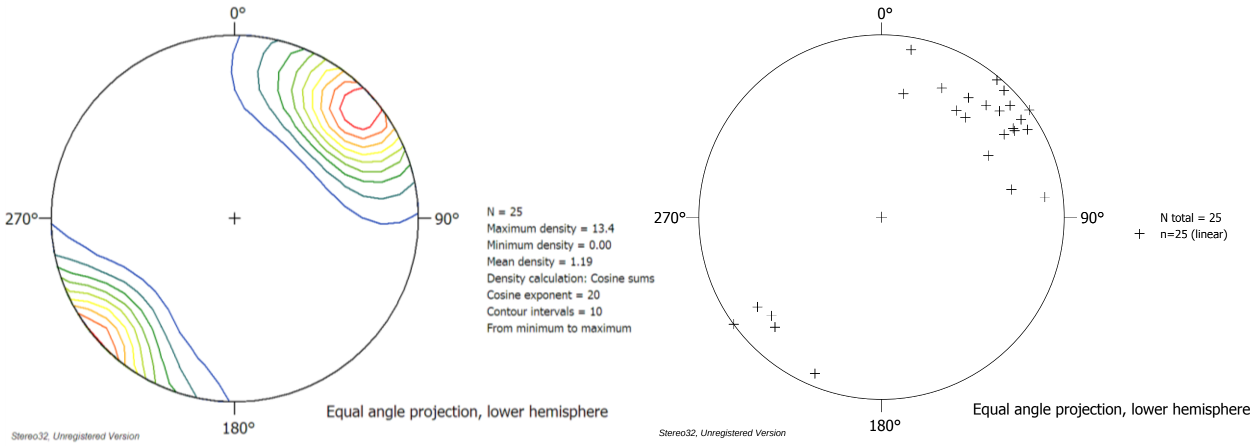


Figure 41. The result of the fabric analyses from section 1. The program Stereo32 was used. Displayed density projection of data (left). Displayed data in projection (right)

Table 6. Eigenvectors and Eigenvalues from section 1.

Eigenvectors	Azimuth	Plunge	Eigenvalues	
V1	46,51	6,88	S1	0,8986
V2	316,2	2,49	S2	0,0753
V3	206,4	82,68	S3	0,0262

The interpretation of section one indicates a changing environments in the forefield of Sólheimajökull with a probable eruption from the Katla subglacial volcano and volcanogenic jökulhlaup, probably during the same event (Figure 42).

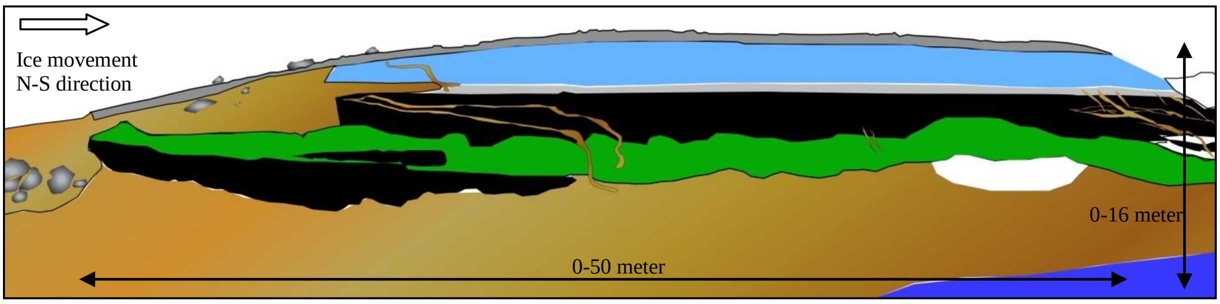
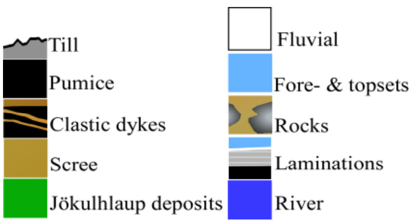


Figure 42. Sketch of section one.



The fine grained and wiggly intrusions which cuts the sediments from the surface of the section are interpreted as clastic dykes. They are formed by loading of the sediments and injected with water from the base of a glacier (Le Heron & Etienne, 2005). Together with the clast fabric the clastic dykes shows the movement of a glacier overriding the sediments moving south, out of the valley (Figure 43).

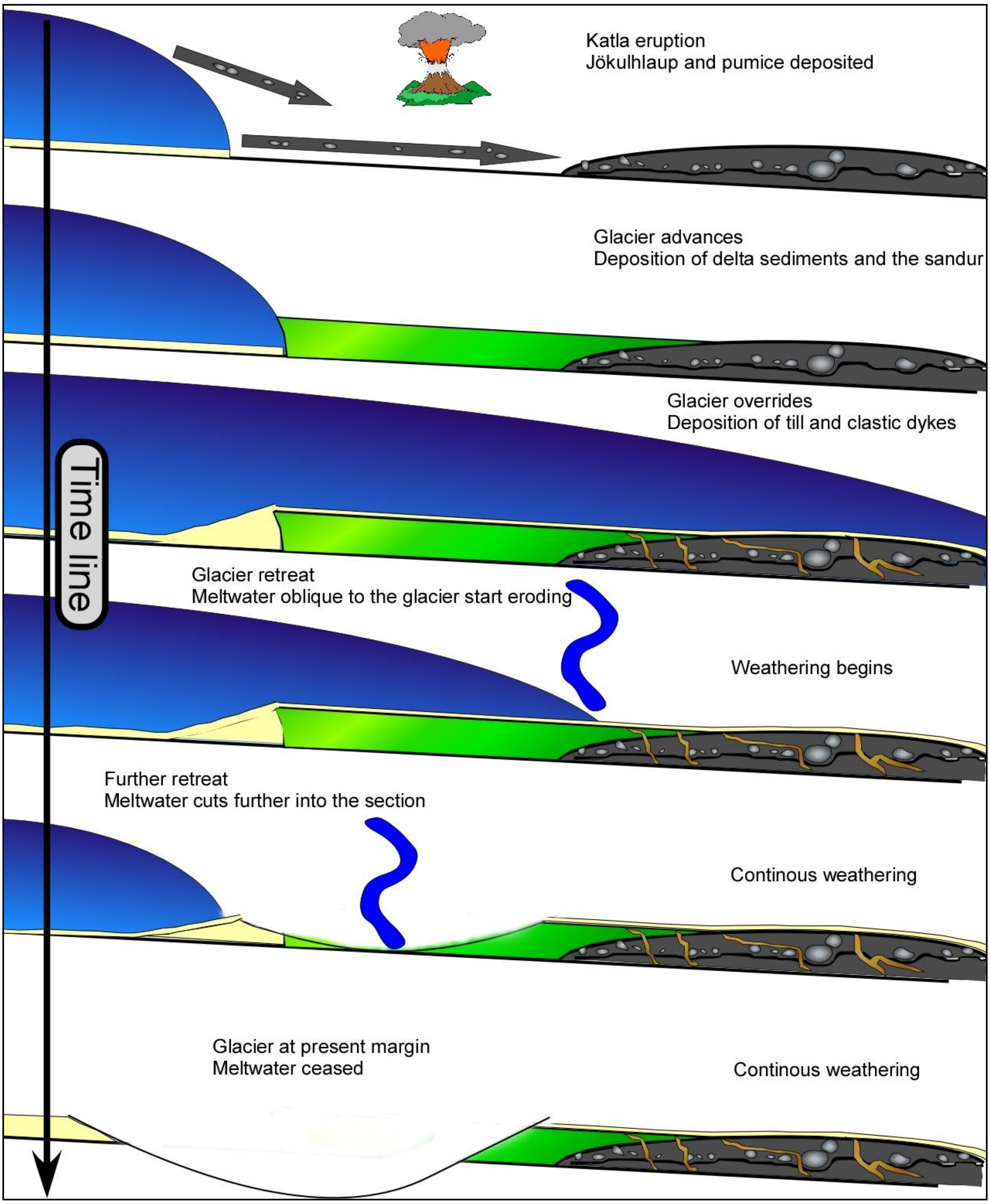


Figure 43. Depositional history of section one.

3.2.2 Section two

Description. - The section (Figure 37) is 10 m high and 20 m wide (Figure 44). The section is 2.4 km south of the present day glacier, on the East side of Jökulsá. The lower part of the section consists of volcanic ash of at least 4 meter thickness. Due to the scree it was not possible to dig further down and see how thick the layer actually was.

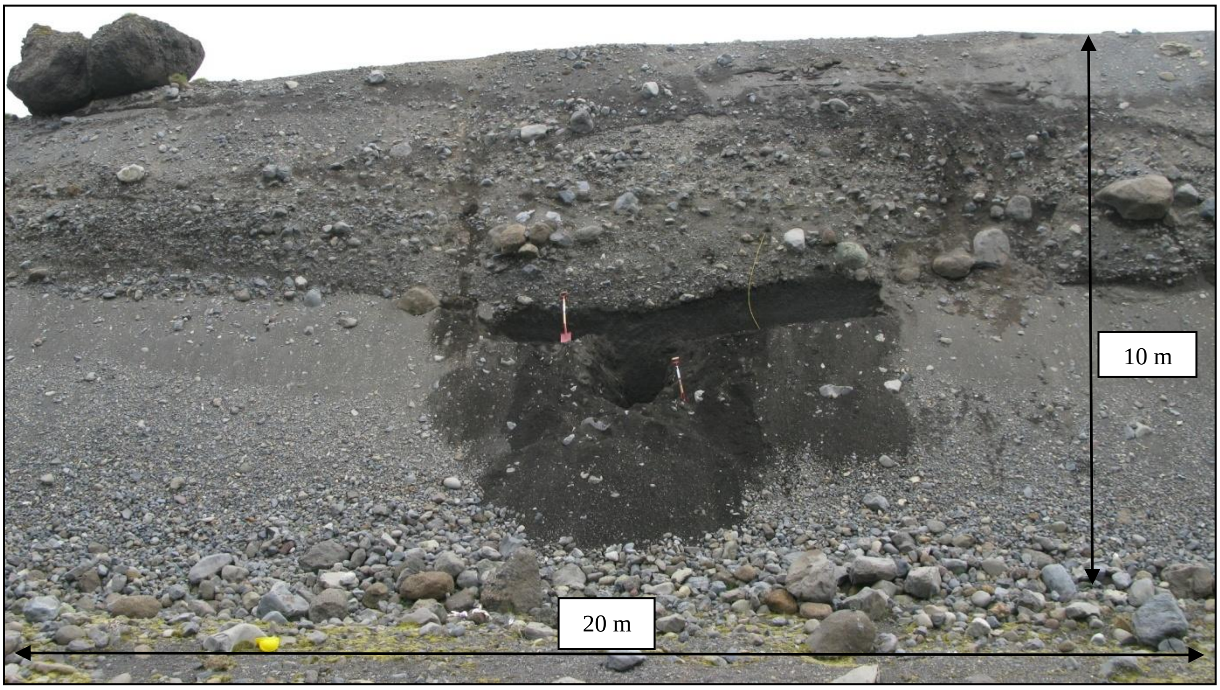


Figure 44. Photograph of section two. The section is 20 meter wide and 10 meter high.

The contact between the ash and the overlying sediments is gradual as ash can be found higher up than the boundary and drop stones falling out of suspension can be found within the ash sediments. The overlying sediments consist of a mixture of big blocks up to 2x3 meters, boulders, cobbles and clasts of different size, from a few cm up to around 50 cm. The sediments on top of the section have been heavily weathered. Thus the abundance of striated rocks is not high and those striated, show weak striations. Some of the bigger clasts have chattermarks. The whole section was loose and easy to excavate.

Fine grained sediments penetrate through the whole section from the surface sediments to the thick ash layer at the bottom, at lengths of more than 10. These sediments have a wiggly pattern following weak structures in the sediments, draping around rocks and pebbles. The grain size inside the form is finer than the material it penetrates through. Most of the material is clay, silt, sand and gravel (Figure 45).

Figure 45. A Clastic dyke penetrating through the coarse jökulhlaup sediments and into the pumice. B is a close up of the clastic dyke with fine material inside the dyke compared to the surrounding material. C shows the contact between the underlying pumice and the overlying jökulhlaup sediments. D shows a cleaned profile of the pumice section sediments and the jökulhlaup sediments.

*Interpretation***. -** The data suggest that ash from an eruption, either on the surface of the glacier or directly beneath the glacier was flushed out of the system. This ash was mixed with water into pumice. As there became less pumice in the system sediments started to be eroded away, flowing on the surface of pumice. The sediments overlying the pumice are interpreted as jökulhlaup sediments, deposited by the same event as the pumice.

The surface sediments are diamict and are interpreted to have a glacial origin, due to weathered rocks with weak striations, along with clasts with chattermarks indicating a subglacial origin. The large blocks on the surface, up to several meters could only have been moved to the site by ice. Thus the diamict is interpreted as a till.

The fine grained sediments which penetrate the sections are interpreted as clastic dykes. The age of the clastic dykes is not known other than it probably occurred after deposition of the entire section, most likely due to loading from an advancing glacier, as the direction of the dykes show the movement of the load causing this feature (Le Heron & Etienne, 2005). The direction of the dykes is out valley which fits well with the glacial history of Sólheimajökull (Figure 46).

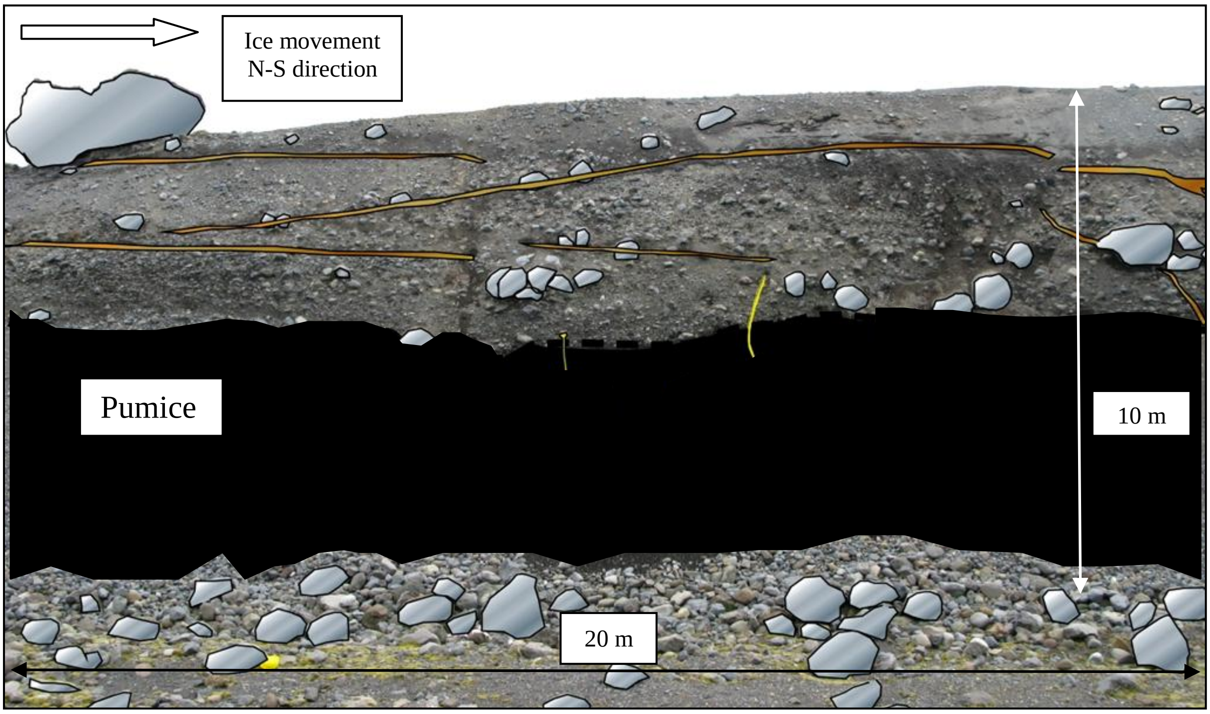


Figure 46. Section two is 2.4 km south of the present day glacier on the east side of Jökulsá. The lower part consists of a 4 meter thick layer of pumice and small pebbles, coarsening up into jökulhlaup sediments of pebbles, cobbles, rocks and boulder size. The section is cut by clastic dykes (orange), penetrating into the pumice layer. The top is capped by coarse gravel and pebbles with a till on top. A large rock is situated on top, probably deposited by a glacier. The section is 10 m high and 20 m wide. A 2 m measure tape (yellow) for scale.

3.2.3 LIA section

The LIA (Little Ice Age) section (Figure 47) is situated 1.1 km south of the present day glacier margin, on the east side of Jökulsá (Figure 37). The section is 20 m wide and 28 m high. Organic material was found beneath the surface of the diamicton. The organic layer is ~ 10 meters long and almost horizontal although some folds appear in the layer.

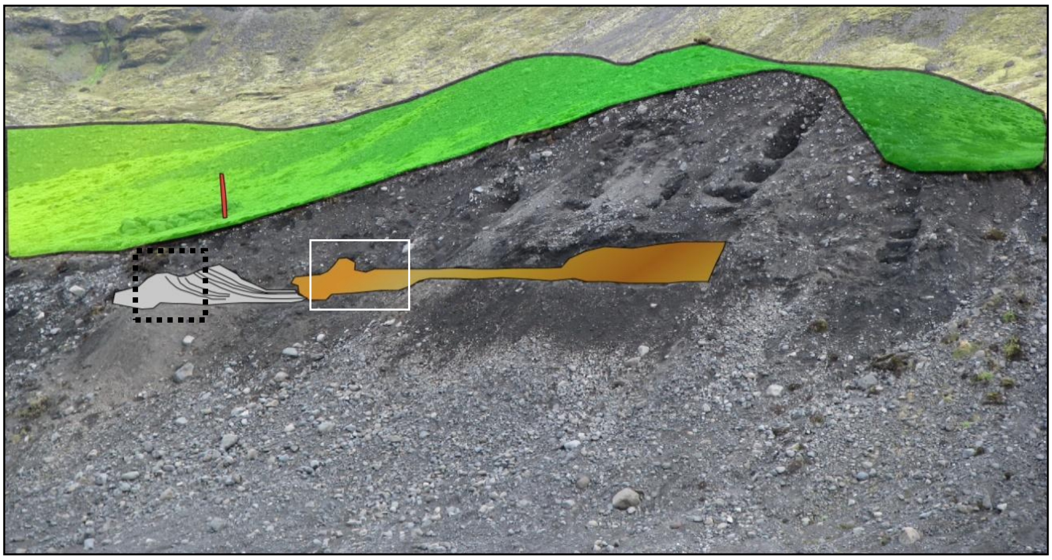


Figure 47. LIA 1.1 km in front of the present day glacier. Brown colour is the organic material that was radiocarbon dated, the white box is the sample site and dashed box is logging site no.1. The green colour is the surface of the diamicton and the red stick is a one meter scale. The section is 20 m wide and 28 m high.

*Description***.** – The section is 435 cm thick. The upper 10 cm of the section is very firm and comprises unsorted sediments, with pebbles, gravel and rocks from 5 cm to tens of cm size, medium sized boulders and lenses of sand. Striations can be found on several clasts found in the unsorted sediments. Next is a 175 cm thick graded, coarse-grained, sandy-gravelly, matrix-supported clast rich diamict. The boulder size increases with depth.

The following 150 cm consists of a graded coarse-grained, sandy-gravelly diamict. It is matrix-supported, with a moderate amounts of clasts and firm to excavate. The size of the clasts has a diameter between 5 and 10 cm and are decreasing in size downwards in the section. The sandy layer is banded. The next 25 cm consists of a loose heterogenous fine-grained, clayey-silty matrix-supported moderate clast diamict. This can be divided into an upper darker band and a lower lighter band. The layer below is a 20 cm thick, clast supported loose diamict. It is homogenous, coarse-grained and in a sandy gravelly-matrix.

A sharp boundary of 2 cm thick clay is overlaying the lowermost sediment layer of 50 cm thick, massive, fine-to-medium-grained, matrix-supported, clast-rich, fissile and firm diamict (Krüger et al., 2010). The lowermost diamict is cut at base of the backslope of the moraine and towards a depression on the upglacier side. Slightly below the backslope surface, there is an upglacier-dipping slab of diamict showing the same characteristics as the diamict below. A coarse-grained, matrix-supported, loose diamict with moderate amount of clasts forms the top-layer of the backslope and the distal part of the moraine ridge, and also occupies the space beneath the dipping diamict slab. Clasts were mostly angular to sub-rounded and many of them were striated, but with no preferred orientation of striations.

On an aerial photograph of the section and landform, the landform is 10-15 meters wide and ~ 3 meter high and has a saw-tooth shape (Figure 48). The landscape surrounding the landform seems to be hummocky in some places, with depressions in the form of small lakes on the northern side of the landform. As well as a river flowing parallel to the ridge and surrounded by depressions. The morphology of the landform appear to be irregular in shape and size.

The amount of organic material is quite extensive, covering about half the width of the section with a thickness from 5 to 40 cm. The western part of the organic material is heavily folded, compared to the central and eastern part which is almost undisturbed. The material has a light brown to dark brown colour and is surrounded by dark silty-sand and clay both below and above. Two samples were collected ~ 2 m below the surface in the western part, with a distance of 50 cm between. Radiocarbon ages for the samples were calculated and calibrated (Figure 47).

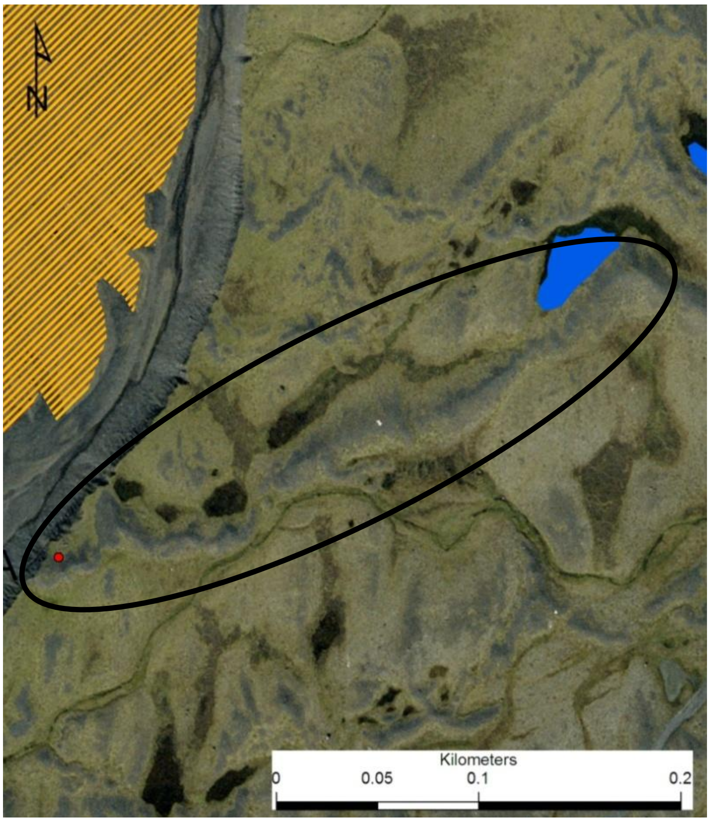


Figure 48. Aerial view of the LIA-moraine with a saw-tooth shape. Blue colour is lakes and orange colour is jökulhlaup sediments. The Red dot mark the LIA section. Basemap is an aerial photograph from 2007.

Interpretation. **-** The landform on the aerial photograph is interpreted as an end moraine. The landscape surrounding the end moraine suggests localized dead-ice melting and the morphology of the end moraine implies a steadily fluctuating ice margin throughout the period of deposition.

The lowermost diamict is interpreted as a basal till (Benn & Evans, 1998). The basal till lies horizontally below the moraine ridge and on top of sandur deposits that can be traced undisturbed in the forefield beyond the moraine ridge, therefore predating the formation of the moraine ridge. Due to its properties, the upper diamict is interpreted as a re-deposited diamict (Krüger et al., 2010).

Around 1910 Sólheimajökull advanced and pushed up pre-existing sediments to form the moraine ridge as seen today (Figure 47). At the end of the advance the glacier detached a part of the pre-existing basal till, which was covering the underlying sandur deposits pushing it upwards, producing the moraine ridge. During this movement the underlying sediments of sand, gravel and the organic layer (^{14}C dated to AD 1495+/-45) was folded. When the advance ceased the debris melted out of the glacier snout and dumped down-slope the ice front onto the marginal moraine ridge. This is an ongoing process at the present day front of Sólheimajökull.

The saw-tooth shape of the moraine indicates splaying/radial crevasses due to lateral extension in an advancing ice margin (Benn & Evans, 1998), which fits well with an N-S advancing glacier depositing the basal till (Figure 49).

The results of the radiocarbon dated samples came out with AD 1445 +/-30 and AD 1495+/-45. This means that the moraine situated on top of the dated material is younger than AD 1495 (Schomacker, pers.comm. August 2009).

It is most likely that the surface moraine of this section was deposited around 1910. A photograph of the glacier margin from the west side of Jökulá is following the same moraine ridge all the way to the east side where this section is situated (Figure 65).

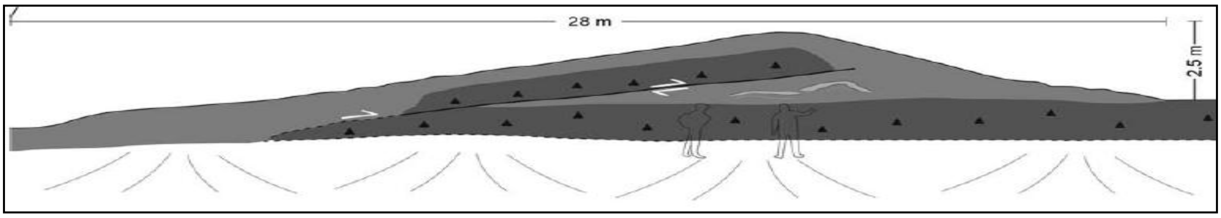


Figure 49. The LIA marginal moraine ridge, illustrating the composition and a simple model of the formation. Model adapted from (Krüger et al., 2010).

3.2.4 Log no.1

Description. **-** The logging site is on the eastern side of Jökulsá, within section one **(**Figure 37**).** The log is ~ 100 cm thick (Figure 50). The bottom layer is a 10 cm thick heterogeneous diamict, with a coarse-grained and sandy-gravelly matrix. The layer is matrix-supported with a moderate content of clasts and few striations. Most of the clasts are subrounded to rounded. The layer consistence is friable and easy to excavate.

Overlying a 13 cm massive and matrix-supported gravel layer. The clast content is rich and they are subrounded to rounded. The layer is very loose and easy to excavate. Grain size ranges from a few mm up to 10-15 mm. The layer is gradational.

Next is a 5 cm thick heterogeneous, coarse-grained and sandy-gravelly diamict. The diamict is matrix supported and easy to excavate. The clast content is poor but striations are common on those present. Most of the clasts are subangular to subrounded.

Following is a 2 cm thick layer of gravel, clast-supported, consisting of coarse sand to fine gravel, with a grain size up to 6 mm. The clasts are mostly rounded. Striations were not observed.

Overlying is a 7 cm diamict layer with a banded and massive appearance. It is matrix supported and easy to excavate. The clast content is poor, but striations are common. The clasts are mostly subangular with a grain size up to 2 cm.

Next is a 2 cm gradational gravel layer with sharp basal and upper contact. The clasts are subangular to subrounded and range in size from 5 to 10 mm. Striations are not present.

Overlying is a ~ 10 cm layer of medium-coarse sand, subangular to subrounded with laminations dipping south. The laminations are getting finer, more undisturbed and thicker towards south. The grain size is up to 5 mm and the layer is very loose to excavate. Drop-stones up to 15 mm are within the layer. The colour of the sediments is darker, than in the lower layers

The section is capped by a 25 cm thick heterogeneous diamict, with a sharp lower boundary with few striations in the lower part. It is massive and easy to excavate, coarse-grained, sandy-gravelly and matrix supported with a moderate content of clasts. The clasts are mostly subangular. Boulders between 10-15 cm long are scattered within the layer, subangular to subrounded in shape. ~2/3 up in the diamict there is a sharp contact to some organic material. The organic material has a light to dark brown colour and has been torn apart, turned around and mixed with gravel and clay. The upper part of the diamict is relatively stiff, but not overconsolidated. There are more clasts in the upper part than in the lower part, with striated clasts common. The section is capped by scree deposits (Figure 51).

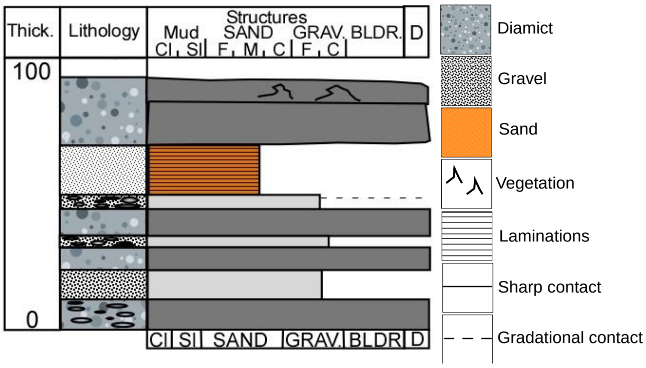


Figure 50. Logging site no.1 from the Little Ice Age moraine.

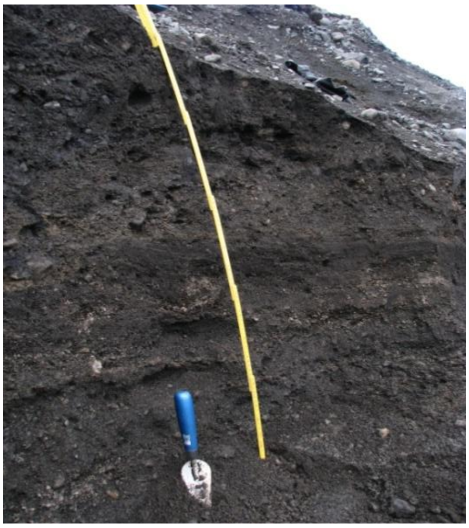


Figure 51. Photograph of log no. 1.

Interpretation. - Based on the descriptions of the sediments the upper diamict is thought to represent basal till which incorporated organic material as the glacier advanced over vegetated surface (Benn & Evans, 1998).

The laminated sand dipping towards south is interpreted to be of fluvial origin and as the advancing glacier pushed the sediments further west the tilting of the laminations occurred and they thickened.

The lower part of the section with interchangeable gravel and diamict is interpreted to be of fluvial origin and represents changes in flow regime and is thought to be channel infillings.

3.2.5 Log no.2

Description. - From aerial photographs, logging site no.2 (Figure 37) appears to be part of the same moraine as logging site no.3 on the west side of Jökulsá. The thickness of the log is 120 cm (Figure 52).

The lower 30 cm is a heterogeneous, medium-grained, silty-sandy and matrix-supported diamict. The content of clasts is moderate with few striations. Most of the clasts are subanglar to subrounded. The layer is extremely firm to excavate, with a sharp contact to the overlying layer.

The next layer is ~ 45 cm thick massive gravel (Figure 53) consisting of medium-coarse gravel. The gravel layer is clast-supported, very loose, not compacted and easy excavate. The size of the clasts is ranging from a few cm to ~ 20 cm and most of them are subrounded with few striations. In the layer there is unsorted coarse sand and black tephra.

Following is a 20 cm thick grey-brown diamict with a sharp basal contact. It is heterogeneous, medium-grained, silty-sandy and matrix-supported. The clast content is moderate with few striations and subangular shape. The clasts range in size from 1-3 cm with a few larger boulders of ~ 10 cm. The layer is fairly compact and easy to excavate.

Next is a 5 cm black layer of tephra, with banded sand. It is horizontally laminated with a uniform thickness. Grain size is up to 5 mm and the content of clasts is rare.

The section is capped by 20 cm of brown massive medium-sand and the weathered surface is covered in rocks of different sizes with a moderate content of striations. With few subrounded pebbles up to 2 cm thick. The layer is compact but easy to excavate. There are a few clasts of ~ 5 cm thickness is in the upper part of the sand.

On the surface there are clasts and boulders from 3-10 cm in length, with weak striations and chattermarks.

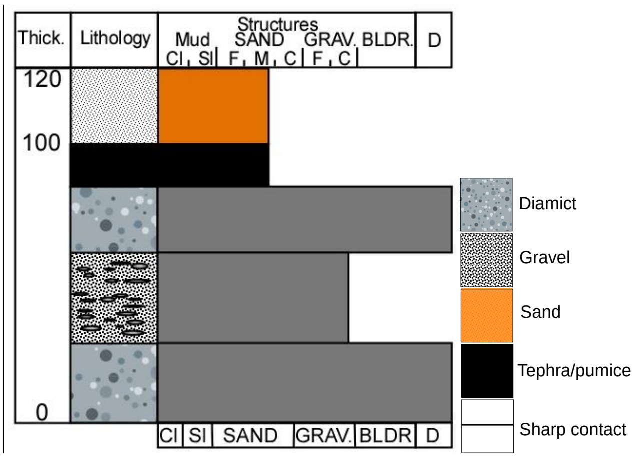


Figure 52. Logging site no25 on the East side of Jökulsá.

Figure 53. Photograph of logging site no. 2.

Interpretation. – The lower diamict with its properties is interpreted as basal till, even though striations were not present, deposited as the glacier advanced (Benn & Evans, 1998).
The heterogeneous appearance, gravel accumulations, sand lenses and medium-coarse grained texture suggest that the layers overlying the basal till is a flow till, deposited by sediments sliding off the surface of ice in the form of a mudflow, during retreat or stagnation of the glacier (Kruger & Kjær, 1999). This process can be witnessed in front of the present day glacier during warm sunny days or during rainfall.

3.2.6 Log no.3

Description. - The logging site (Figure 37) was chosen because it is one of the most southerly moraines on the west side of Jökulsá and has some interesting horizontal features beneath the surface that can be seen from the east side of the river (Figure 54). The thickness of the log is ~ 6 meter (Figure 55).

The lower 50 cm is a heterogeneous clast rich diamict. It is medium-grained, silty-sandy and matrix-supported. It is easy to excavate and striations on clasts are rare. The clasts are mostly subrounded. The clasts and boulders are up to 15 cm long.

The contact to the upper layer is sharp and is consisting of ~ 10 cm matrix-supported coarse sand. The sandy layer is coarsening upwards.

Next is a 12 cm thick layer of matrix-supported gravel. The gravel is mostly subrounded and medium to coarse grained with size up to 25 mm. No striations were found on the clasts.

Following is a 90 cm heterogeneous layer of diamict. It is a medium-grained and silty-sandy layer. It is firm and difficult to excavate. The smaller rocks are rounded while the larger are angular. Striations are rare and there are light-brown clay patches within the layer, which seems to drape over clasts where it is present. The larger rocks are up to 15-20 cm in size.

Overlying is a 30 cm thick clast-supported massive gravel with a gradational basal contact. The layer is easy to excavate. Most of the clasts are subrounded and range in size from 2-10 cm, with few striations.

The next 2.5 m is a heterogeneous diamict that is coarse-grained, sandy-gravelly and matrix-supported. It is clast rich and extremely firm to excavate. Striations are rare and the clasts are mostly subrounded to rounded. Many clasts and boulder up to 40 cm in size is sticking out of the sediment, while the surrounding matrix has been removed. The upper 20 cm of the diamict has a sharp boundary and is more matrix-supported and more fine-grained than the diamict below. The clast content is moderate with a common content of striations. This part is extremely firm to excavate. The layer can be traced undisturbed horizontally for 200-300 meters.

Next is a 40 cm thick horizontally laminated, medium to coarse sand with fines. This is overlain by a 10 cm laminated tephra with fines, with sharp upper and lower contacts.
The section is capped by a 30 cm heterogeneous diamict. It is coarse-grained and sandy-gravelly, matrix-supported and has a moderate content of clasts. Striations are rare and the diamict is easy to excavate. On the surface there is a soil layer (Figure 56).

Figure 54. Photograph of logging site no. 3. The two white circles show the log locations.

Figure 55. Close up of logging site no.3. Showel for scale.

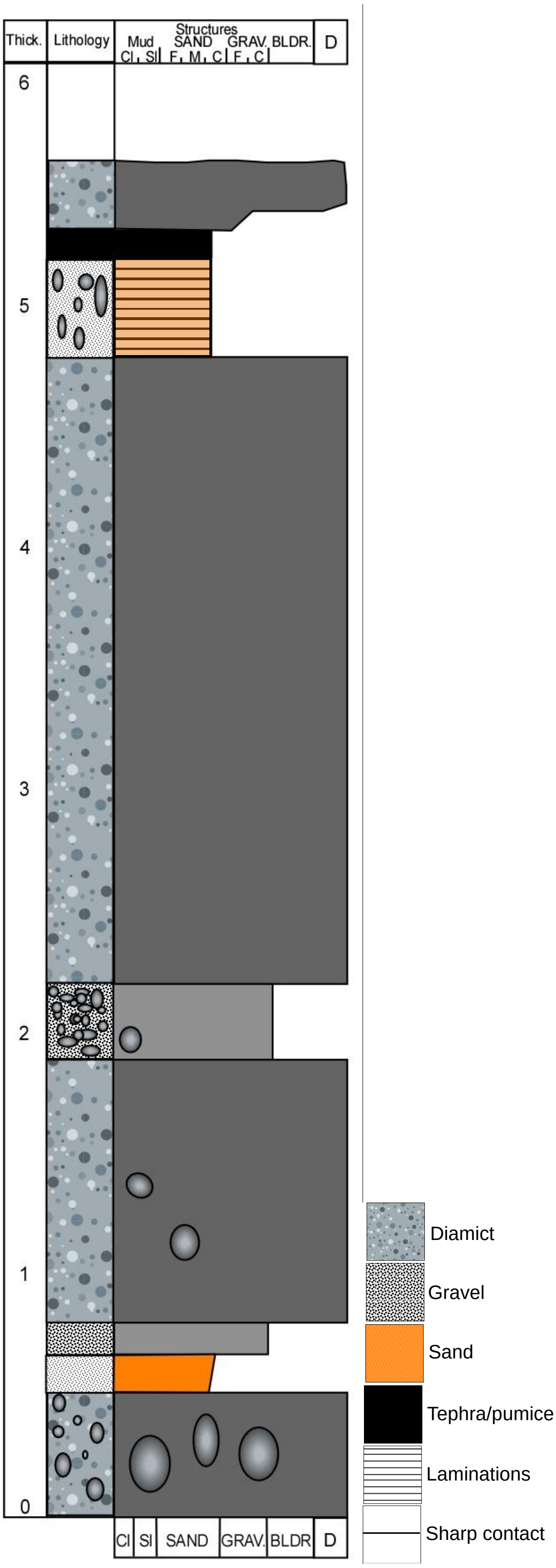


Figure 56. Logging site no.3 on the West side of Jökulsá.

*Interpretation***. -** The lower ~ 4.5 meters of the section show many of the criterias of hyperconcentrated flow deposits, e.g. massive layers, subrounded to rounded clasts indicative of a fluvial origin and crude stratification. This part of the section is interpreted as a sandur (Benn & Evans, 1998).

The interpretation of the 20 cm thick diamict layer at 470 cm is thought to represent basal till and is supported by the description of the sediment properties mentioned above (Benn & Evans, 1998; Krüger and Kjær, 1999).

The laminated tephra and sand in the upper part is indicating that fluvial process took place. During warm and sunny days or days with rain, sand and tephra can be washed down from the slopes of the ice and flow down into depressions on the surface. The interpretation of the laminated sand and tephra is trough-fillings (Krüger & Kjær, 2000).

The landform on top of the section has 2-3 m long rocks situated on the surface and is interpreted as a moraine. The diamict capping the section is interpreted as melt-out till, deposited during a retreat or stagnation of Sólheimajökull (Krüger and Kjær, 1999). Even though striations are rare in this upper part high erosion rates and weathering at Sólheimajökull could have removed these.

The basal till, which lies undisturbed horizontally below the moraine ridge and on top of the sandur, predates the formation of the moraine ridge.

3.2.7 Log no.4

*Description***. –** The logging site is on the west side of Jökulsá (Figure 37) and was chosen because it appeared to be part of the same moraine as the LIA section. The height of the section is 2.75 meter (Figure 57) (Figure 58).

The lower 100 cm of the section consists of a heterogeneous massive diamict. Most of the pebbles are covered with a thin layer of brown clay. It is matrix-supported and clast rich with few striations. The matrix consists of coarse sand and gravel with size from 4 mm to 3 cm. Large boulders up to 30 cm are situated in the bottom part. The diamict is firm and difficult to excavate. The unit has a brown colour (Figure 59).

Overlying is a 40 cm thick heterogeneous and coarse-grained diamict. It is sandy-gravelly, matrix-supported, clast rich, easy to excavate and striations are rare. The clasts are subrounded to rounded.

Next is a 15 cm thick massive gravel. There is a distinct lower basal contact. The layer is heterogeneous, coarse-grained and sandy-gravelly. Grain size is from 4-20 mm. It is matrix-supported with a poor content of clasts, few striations and easy to excavate. The clasts are subrounded to rounded. Most of the clasts have a thin coating of light-brown mud draping over them.

The upper ~ 100 cm is a massive, matrix-supported diamict, with a moderate content of clasts and few striations in the lower part. The matrix consists of medium-sand to coarse-gravel. Some thin roots are found within the layer. The upper part of the unit is homogeneous and coarse-grained. Striations on clasts are common. The unit is clasts supported, loose and easy to excavate. The clasts are subangular to subrounded. Soil cover is capping the section.

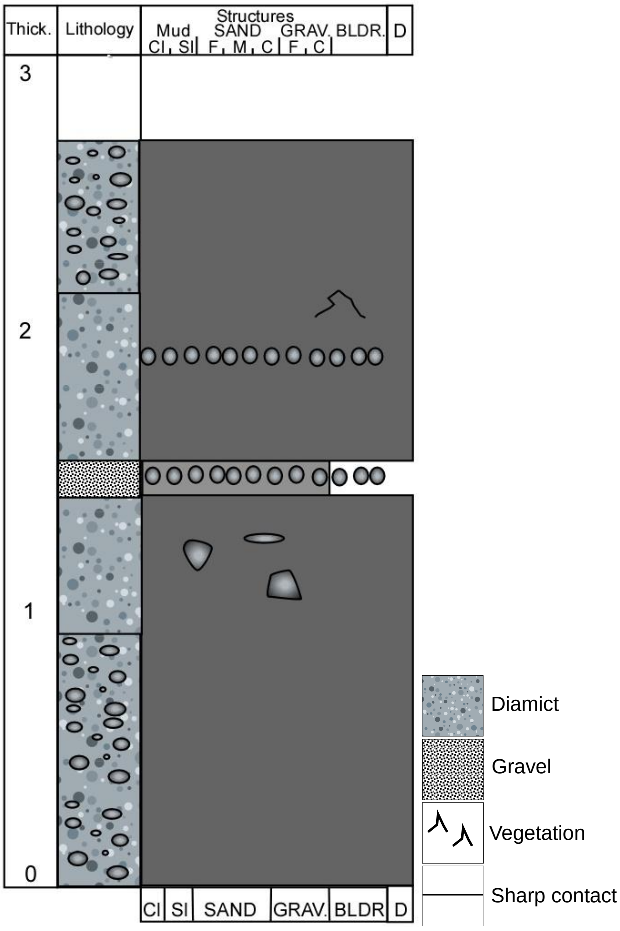


Figure 57. Logging site no. 4 on the West side of Jökulsá.

Interpretation. **-** The interpretation of the lower diamict is supported by the sediment properties mentioned in the description and is thought to represent basal till (Benn & Evans, 1998). The brown clay found on clasts in the lower diamict and on the gravel layer is probably coming from a pool of stagnant water which was left in an abandoned channel. This allowed fine suspended sediment to settle without being entrained as bedload. This sediment forms drapes of mud, silt and sometimes very fine sand which drape the underlying deposits. The beds are commonly massive, but can be laminated if sediment delivery occurs in pulses (Benn & Evans, 1998).

The gravel layer with the sediment properties from the description is thought to have a glaciofluvial origin. It is thought that melt-water from the glacier flooded over this area for some time removing the fines and leaving the gravel on top of the diamict.

The upper diamict is due to its properties in the description thought to be a melt out till, deposited during retreat or stagnation of the glacier (Krüger & Kjær, 1999).

The roots in the upper part of the section which are penetrating down through the sediments from the surface is to be part of the surface vegetation.

Figure 58. Photograph of logging site no. 4.

Figure 59. Lower part of logging site no. 4 showing massive boulders.

3.2.8 Log no.5

Description. - The logging site is on the west side of Jökulsá (Figure 37). The thickness of the log is 2.5 meters (Figure 60). The lower 60 cm is a heterogeneous, coarse-grained, sandy-gravelly diamict. It is matrix-supported and clast rich, but with few striations. The unit is firm and very difficult to excavate. There are large boulders up to 30 cm in diameter is within the layer. Most of the clasts are subrounded.

Overlaying is a 20 cm uniform diamict with sharp boundaries to the upper and lower units. The unit is massive but not compacted, consisting of fine-grained and clayey-silty materials. The boulders are clast-supported and striations are rare. The clasts are subangular to subrounded, with a light-brown mud draping and easy to excavate.

The next unit is a 40 cm thick heterogeneous, coarse-grained diamict. The unit is consisting of coarse sand and gravel, matrix supported and has a moderate content of clasts with few striations. The diamict is not compacted and clasts are subangular to subrounded.

Overlying is a 5 cm thick massive diamict. The unit is massive, coarse-grained and sandy-gravelly. It is clast-supported and easy to excavate. Striations are rare and clasts subrounded to rounded.

The upper 1 m is a heterogeneous diamict with a gradational basal contact. It is coarse-grained, sandy-gravelly and matrix-supported. The unit is clast rich with striations common. It is easy to excavate and clasts are subrounded to rounded. Large boulders from 20 cm to 100 cm are within the unit. The section is capped by soil (Figure 61).

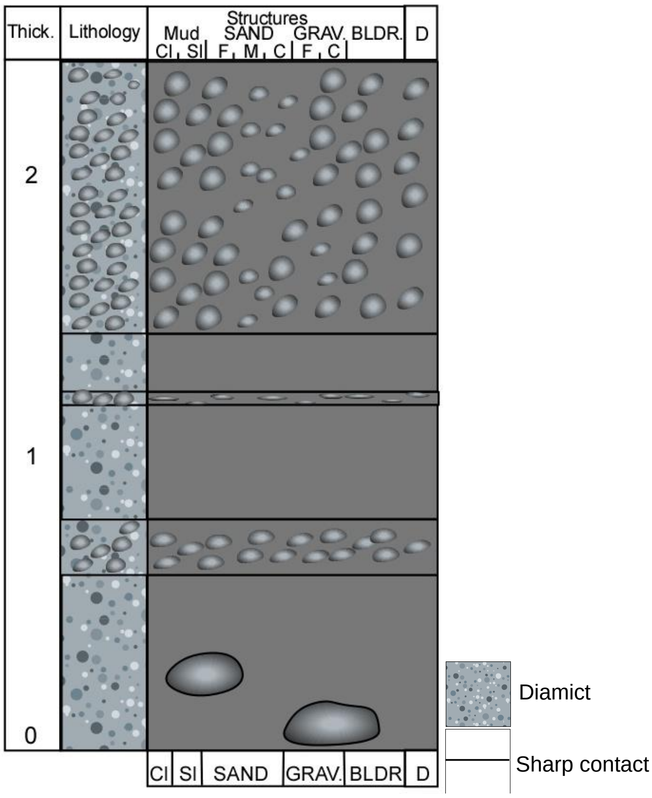


Figure 60. Logging site no. 5 on the West side of Jökulsá.

Figure 61. Photograph of logging site no. 5.

*Interpretation***.** – Some of the criterias for being a jökulhlaup are not fulfilled for the section, but there are still indications e.g. matrix-supported diamict and change in structures. This part of the section is being interpreted as sandur deposits.

The brown clay draping clasts in the lower diamict is interpreted to come from a pool of stagnant water which was left in an abandoned channel. This allowed fine suspended sediment to settle without being entrained as bedload. This sediment forms drapes of mud, silt and sometimes very fine sand that drape the underlying deposits (Benn & Evans, 1998).

Only the upper one meter of the section has clasts with common striations and together with large boulders of different sizes indicates a glacial origin. The sediments were deposited by a retreating or stagnant glacier and is interpreted as melt-out till.

3.3 Cosmogenic Exposure Dating

Four cosmogenic exposure samples were collected in 2008 (Figure 62) and sent to Prime Lab, Purdue University in the USA.

The first sample was taken at the top of Jökulhaus. A large piece was chipped of a rock of firm basalt, with striations on. Position is in UTM 27N, 581831E, 7045881N. The result was AD 284 +/-513.

The next three samples were collected from the eastern flank of the glacier on high ground. Sample two, at position 582779E, 7045486N, resulted in AD 858 +/-313. Sample three, at the position 582849E, 7045521N, resulted in AD 56 +/-606. Sample four, was taken from the penultimate moraine with the position 582899E, 7045606N, resulted in AD 91 +/-410.

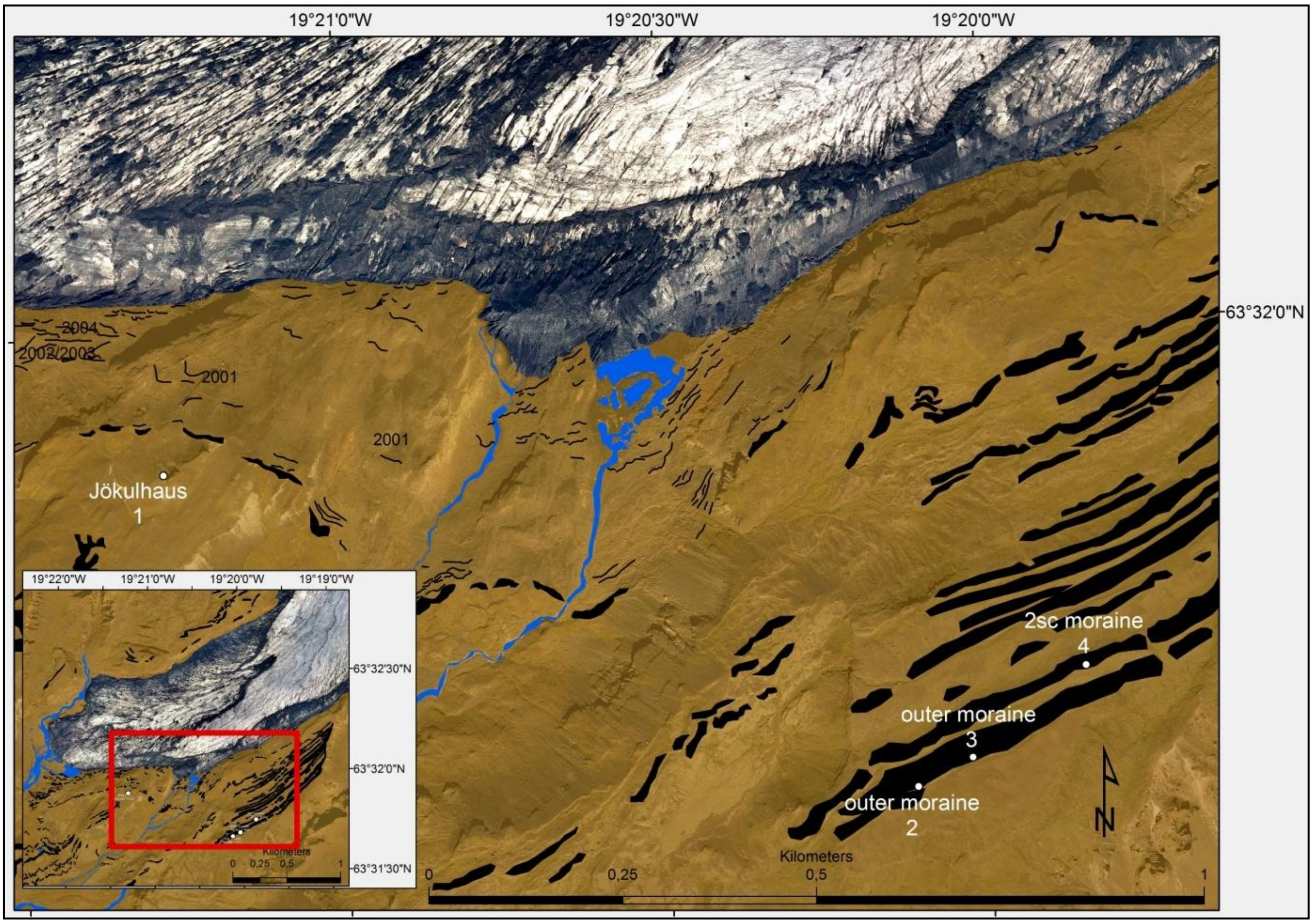


Figure 62. White dots show the position of cosmogenic exposure dating at Sólheimajökull and black lines are end moraines. The map is made from a 2007 aerial photograph.

The results from the cosmogenic exposure dating, along with radiocarbon dates and information from written sources were compiled into a summary and is presented in Table 7.

Table 7. Summary of oscillations of Sólheimajökull last 2000 years. Data was compiled from written sources, dating results and the Icelandic glaciological society.

Year	Position
56	Glacier reached the outermost moraine on the East ridge
91	Retreat to the second outermost moraine on the East ridge
284	Jökulhaus probably not covered by ice since this time
1445/1495	Reached end moraines 200 m infront of 1904 moraines
Preceding 1705	Advance
1705	Glacier same position as 1904, snout presumably a bit thicker
1783	Glacier significantly smaller than in 1705
1794	Glacier about as large as in 1705
1820	Glacier at least as large as in 1705
1820-1860	Stagnation
1860-1883	Retreat, possibly due to the 1860 Katla eruption and jökulhlaup
1883-1893	Stagnation, 1890 thought to be LIA maximum
1893-1969	Retreat
1969-1995	Advance
1996-2010	Retreat, 1999 jökulhlaup

3.4 The retreat history of Sólheimajökull last 100 years

The chapter shows a combination of old and new photographs, time-lapse series and their positions on maps of Sólheimajökull, for the last 100 years. During this time span the glacier has retreated ~ 1.5 km. Older maps of the glacier can be found in chapter 1.4 and aerial photographs of the glacier margin, from 1938 to 2010 can be found in the appendix.

The photographs to the left in Figure 63 were taken by Magnus Olafsson in 1910 and the right one was taken in October 2010 by me. They show Sólheimajökull and are the oldest photographs of the glacier. The glacier was in a retreat/melting phase in 1910. The front of the glacier is ~ 12 meter high, calculated from the height of the people in the river. The front is steep and the surface has few and shallow crevasses. In the western part of the photographs thrust sheets are being pushed up, creating a small moraine. The ice is clean with few traces of tephra.

Using the terrain in the background, the 1910 photograph was taken in the western part of the valley. The 2010 photograph show that the position of the 1910 photograph is 1.5 km from the present day glacier front (Figure 65). The photograph is taken from the surface of a moraine. The terrain towards the rock face consists of mostly old river channels and a few smaller moraines. The old river channels are orientated towards the south-east. The topography is quite low, with changes up to five meters. The location of the photograph fits with Figure 21, which shows two rivers flowing from Sólheimajökull in 1930. A western river which used to flow in the area, and a more central river which is still flowing in the centre of the valley today (Figure 65). The glacial limit of 1904 is inside the 1910 position, probably due to inaccurate measurements in 1904, thus inaccurate georeferencing of the same map. It is also possible that Sólheimajökull advanced from 1904 to 1910, even though it is thought to have been retreating during that time.

Figure 64 shows a photograph from 1910 of a river flowing from Sólheimajökull. The photograph was taken from surface of the glacier in Figure 63. The moriane infront of the glacier is easily recoqnizable today, both on aerial photographs and in the field, thus pinpointing the excact location of the glacier margin in 1910. The area behind and infront of the moraine in Figure 64, is without vegetation, indicating a quick retreat through the valley and/or a fluvially dominated terrain.

Figure 65 shows a map of Sólheimajökull from 2009, with the position of the glacier margin in 1910, as seen in Figures 63 & 64.

Figure 63. Sólheimajökull 1910 (left) by Magnus Olafsson and the same position 2010 (right).

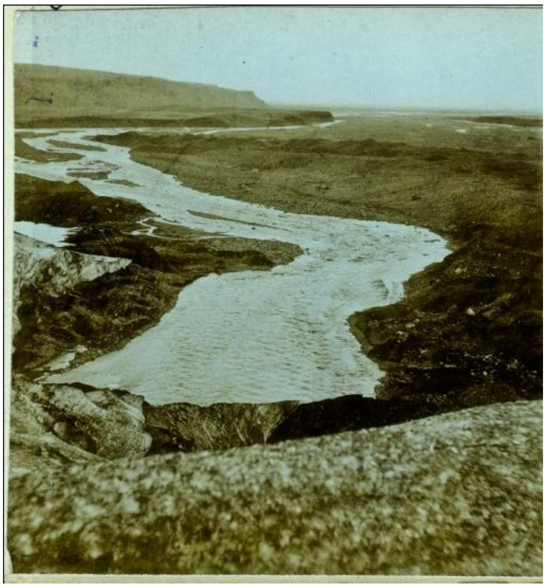


Figure 64. Sólheimajökull 1910, view towards south, by Magnus Olafsson.

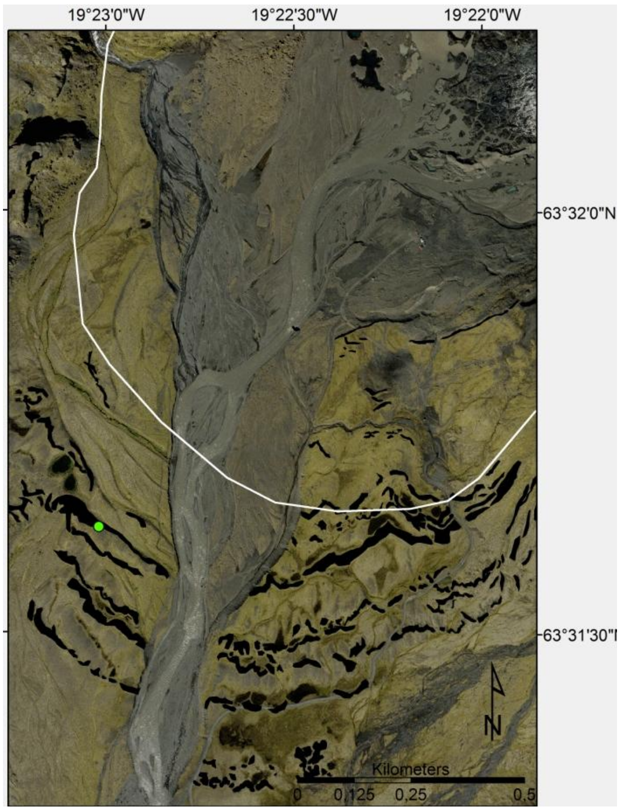


Figure 65. Position of Sólheimajökull in 1910 as green dot. White line is the 1904 limit. The present day glacier margin is in the NE corner. Base map is a 2009 aerial photograph.

An overview photograph of Sólheimajökull taken between 1915-1920 (Figure 66) shows a large glacier. The protection wall in the middle of the photograph was built prior to the construction of the bridge over Jökulsá in 1921. The ice is clean and white with little tephra, thus the photograph must also be prior to the eruption of Katla in 1918 which covered the whole area with tephra. The glacier tongue to the east of Jökulhaus is wide and reaches far into the valley. The western tongue reaches far into the valley with a low sloping surface. Jökulhaus is not completely covered with ice at this stage. Tephra bands can be seen in the glacier ice, from the surface dipping towards the east.


Figure 66. Sólheimajökull 1915-1920, view towards north, by Geir Zoega.

The mixing of a photograph from 2009 (Figure 67B) and 1921 (Figure 67C) was done in the drawing program *Canvas*. It is difficult to exactly place the site from which the 1921 photograph was taken because of changes occurring in the terrain over the past 90 years. A small jökulhlaup in 1999 is the possible source of moving or burying the two large rocks seen in the 1921 photograph. This spot was probably only a few tens of meters away from the spot used in 2009. Using cross points from mountains on the photo and foundations from the old bridge which can still be seen, the reconstructed photo (Figure 67A) is quite accurate. The new bridge is ~ 10 meter from the south-side of the old bridge. The approximate position of the 1921 glacial position is shown in Figure 68.

Figure 67C shows that Sólheimajökull was much larger than today. The glacier was much thicker, reaching high above Jökulhaus. It did not cover Jökulhaus completely, but ice was covering both sides and a part of the summit of Jökulhaus. The glacier reached as far down-valley as Votagjá, ~ 900 meters west of present position. The thickness of the present glacier has lowered more than 300 meters in some places. Apart from some tephra at the glacier margin and in the eastern part, the glacier is quite clean, even though there was a large Katla eruption in 1918.

The old bridge over Jökulsá was opened on September 3rd, 1921 and the new one opened in 1968. These two bridges were only ~ 20 meters apart from each other. Two large rocks can be seen in the 1921 photograph, but in the 2009 photograph they are gone. They have probably been removed or buried in sediments by the river or the 1999 jökulhlaup.

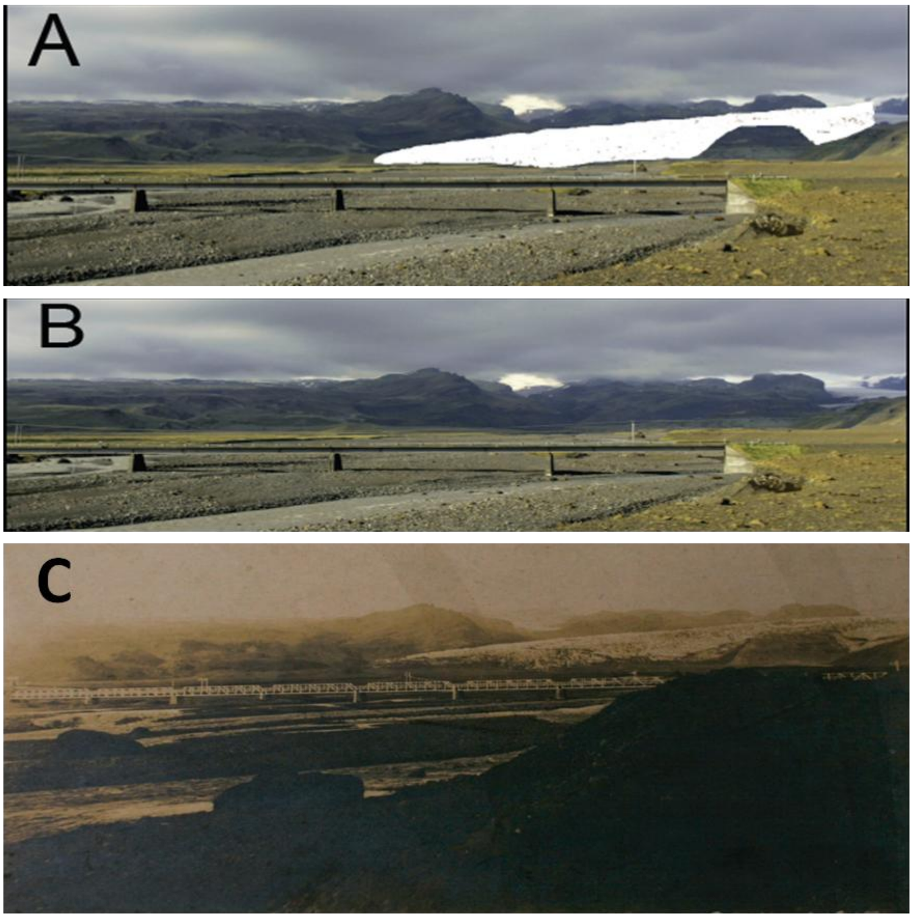


Figure 67. Sólheimajökull reconstructed to 1921 (A), (B) the reconstructed photograph from 2009 and the original from 3 September, 1921, stored at the museum in Skógar.

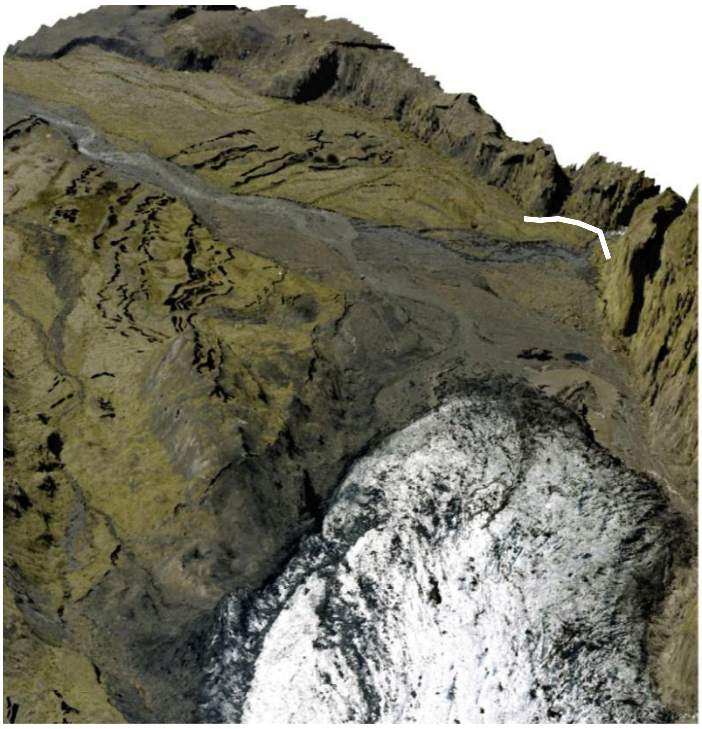


Figure 68. The white line shows the ~ position of the extent of the 1921 glacier. Base-map is a 2009 aerial photograph draped over a 3D model.

An aerial photograph from 1938, taken on behalf of the Geodætisk Insitut in Denmark by the Royal Danish Air-force is the oldest aerial photograph of Sólheimajökull (Figure 69A). This photograph can be can be compared with a photograph taken by Oddur Sigurðsson in 1985 (Figure 69B), to show the melting of the upper part of the glacier. The red and yellow rings on the photographs show areas where melting or retreat has occured since 1938. In the lower SE corner of (A) there is glacial ice covering the bottom of the valley, but in the same corner of (B) the ice is completely gone. The yellow western circle shows a small nunatak, but in (B) this is now a ridge with steep and high sides.

The western yellow circle (A) shows several small nunataks and in (B) they have turned into a rock-face with a steeper gradient almost free of ice. The eastern red circle (A) show an almost snow and ice covered surface and in (B) the same surface is more or less snow free.

Large tephra bands are covering Sólheimajökull, probably deposited from the 1918 Katla eruption, but in (B) these tephra bands are completely gone, drifted away with the movement of the ice.

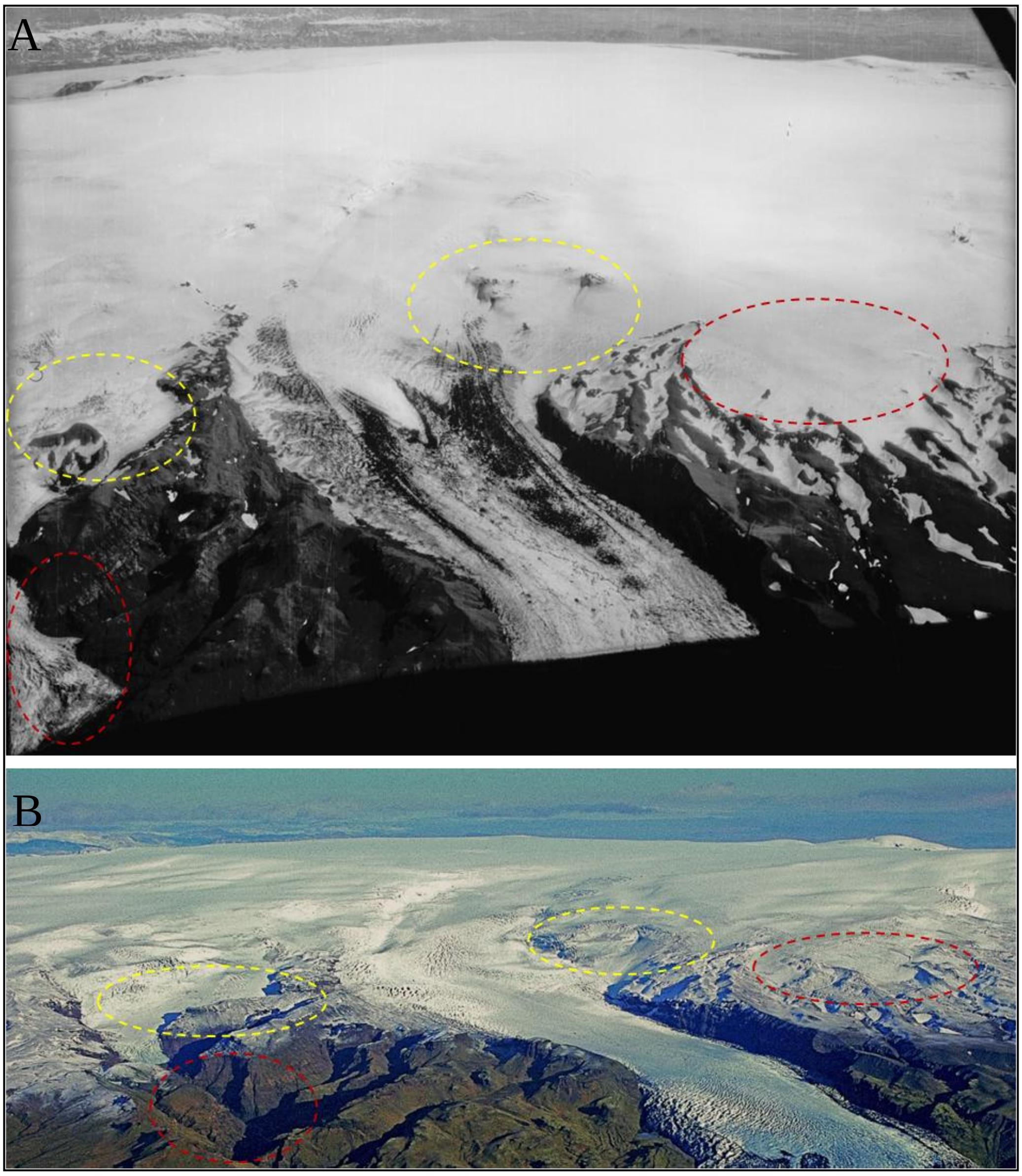


Figure 69. Sólheimajökull 1938 (A) (Geodætisk, 1938) and 1985 (B) (Sigurðsson, 1985). Red and yellow coloured rings shows areas of melting/retreat of the glacier.

In the years between 1938 and 1969 the glacier mostly retreated. From 1970-1995 the glacier advanced ~ 500 meters, but has since 1996 been in a retreat phase.

Photographs of Sólheimajökull, taken by Oddur Sigurðsson in 1997 (Figure 70A) and 2006 (Figure 70B) show the fast retreat of the glacier both in frontal length and thickness.

What is seen in (A) is a high glacier with steep sides and many crevasses. In (B) the glacier has melted and is now thinner, shorter and has a lower gradient than it had in 1997.

Crevasses on the surface are less than in 1997 and there is almost no tephra on the ice. From 1997-2006 the glacier retreated 430 meters and lowered 100 meters in thickness, showing that the glacier is retreating at a rate of almost 50 meters per year (Sigurðsson, 2006).

From 2006 to 2010 (C) the glacier had retreated ~ 400 meters and thinned extensively. The glacier can not be seen any more from the position of A & B, showing the rapid rate of retreat of Sólheimajökull.

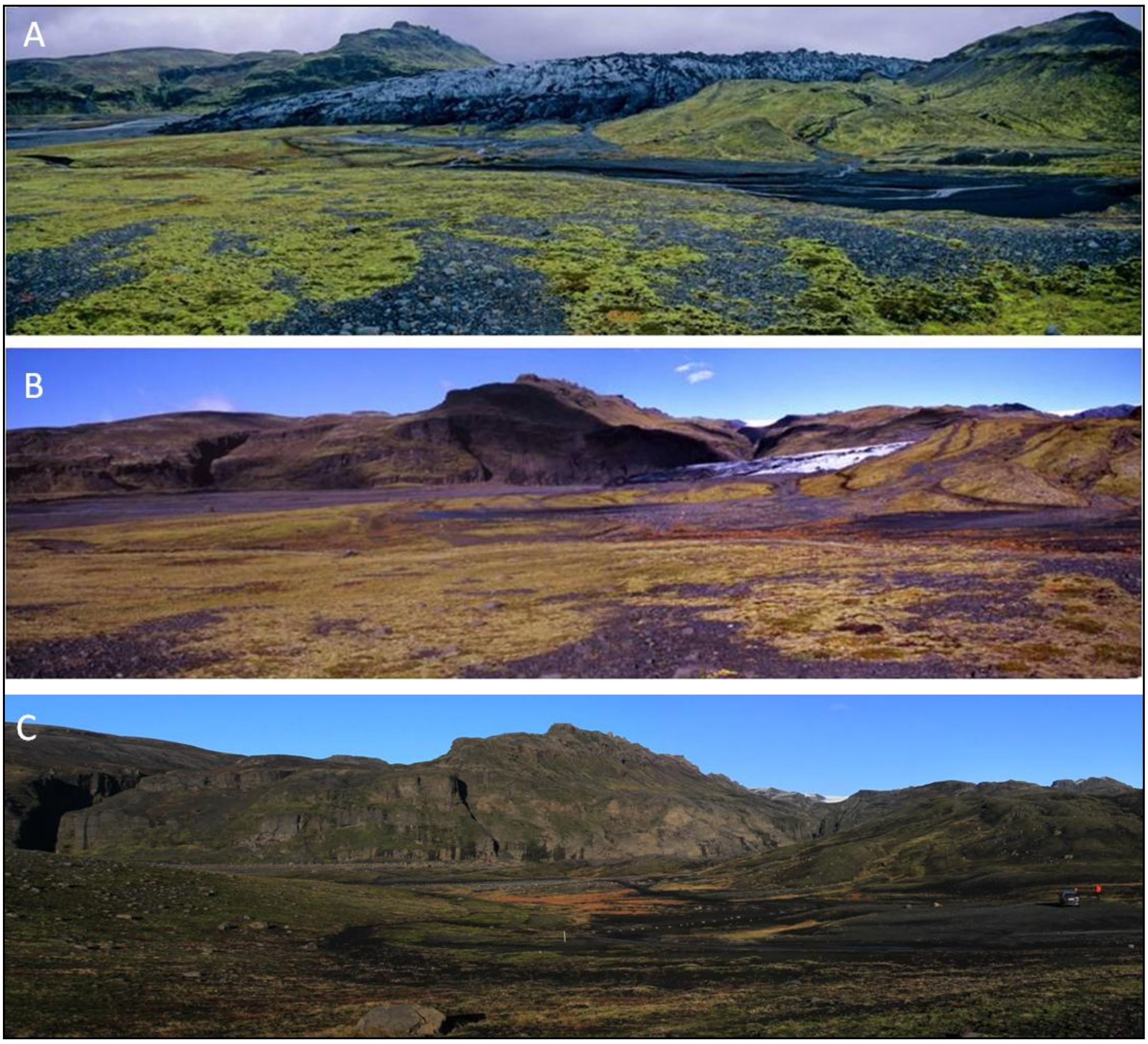


Figure 70. Sólheimajökull in 1997 (A) and 2006 (B). The glacier retreated ~ 500 m in this time and the thinning of it on this place is ~ 100m (Sigurðsson, 2006). (C) is from 2010, the glacier has retreated 300 meters more and thinned so much as the glacier can no more be seen from this position.

Photographs taken from Jökulhaus in 2000 (A) and 2009 (B) (Figure 71) also show the quick retreat of Sólheimajökull. The deep channel on the left side of the photograph (A) was dug out by the 1999 jökulhlaup which only lasted for a few hours. The channel is ~ 2-3 meter deep and up to 10 meter wide. The gradient of the glacier is low and crevasses are few. This is because of five years of retreat prior to this photograph. Meltwater can be seen flowing from three different places of the glacier in 2000 (A), while in 2009 (B) this is reduced to one place. The glacier has retreated around 700 meter from 2000 (A)-2009 (B) leaving annual moraines and drumlins.

Figure 71. Glacier front at Sólheimajökull in 2000 (A), this was the year after the 1999 jökulhlaup, the large channel on the left side of the glacier was dug out by the flash flood. In 2010 (B) the glacier front had retreated around 700 meters.

Time lapse photographs ranging from April 2007 to June 2010, (Figure 72) was very helpful to get an understanding of how Sólheimajökull reacts during retreat and how fast it happens. Six photographs from three different cameras and angles on the western side of the glacier. During this time interval the glacier has retreated ~ 330 m. The river is changing its flow pattern quite often, probably following the retreat pattern of the glacier.

Looking at the aerial photograph from 2007 (A) the glacier is flat and moderately crevassed in the frontal western part. The glacier foreland consists mostly of dried up river beds consisting of sand and gravel. The changes to 2008 (B) are large, the river coming from the west has started cutting down into the sediments. Large areas of ice have melted away and a small proglacial lake has started to form. Crevassing on the western part has increased. Dead-ice areas, which used to be thrust planes/sheets in the glacier, now covered by sediments are left behind in the proglacial area as the glacier melts. The river is following the western side of the valley.

In 2009 (C) the river has changed its course closer to the glacier, removing more sediments and dead-ice from the frontal part. The proglacial lake in the forefield has increased by ~ 100%.

In January 2010 (D) the river from the west has moved under the glacier and is no longer flowing in its old path. The proglacial lake has continued increasing, leaving a "peninsula" of dead-ice in the northern part. Crevasses and break-up in the north-western part of the proglacial lake has increased. The western river is still flowing beneath the glacier, coming out just west of the "peninsula"

Late April 2010 (E) the volcanic eruption of Eyjafjallajökull has covered the glacier in black tephra. The water level in the proglacial lake has diminished but calving/break-up of the central and western part has continued to increase. Some sort of bay can be seen starting to form in the central part of the glacier front.

In late August 2010 (F) the water level of the proglacial lake has increased again and it has extended in size. The glacier is still heavily crevasses in the western part and the bay to the north of the "peninsula" has extended further into the glacier front. The tephra is still covering the glacier and some of this material has polished the time-lapse camera, thus the low quality of the photograph.

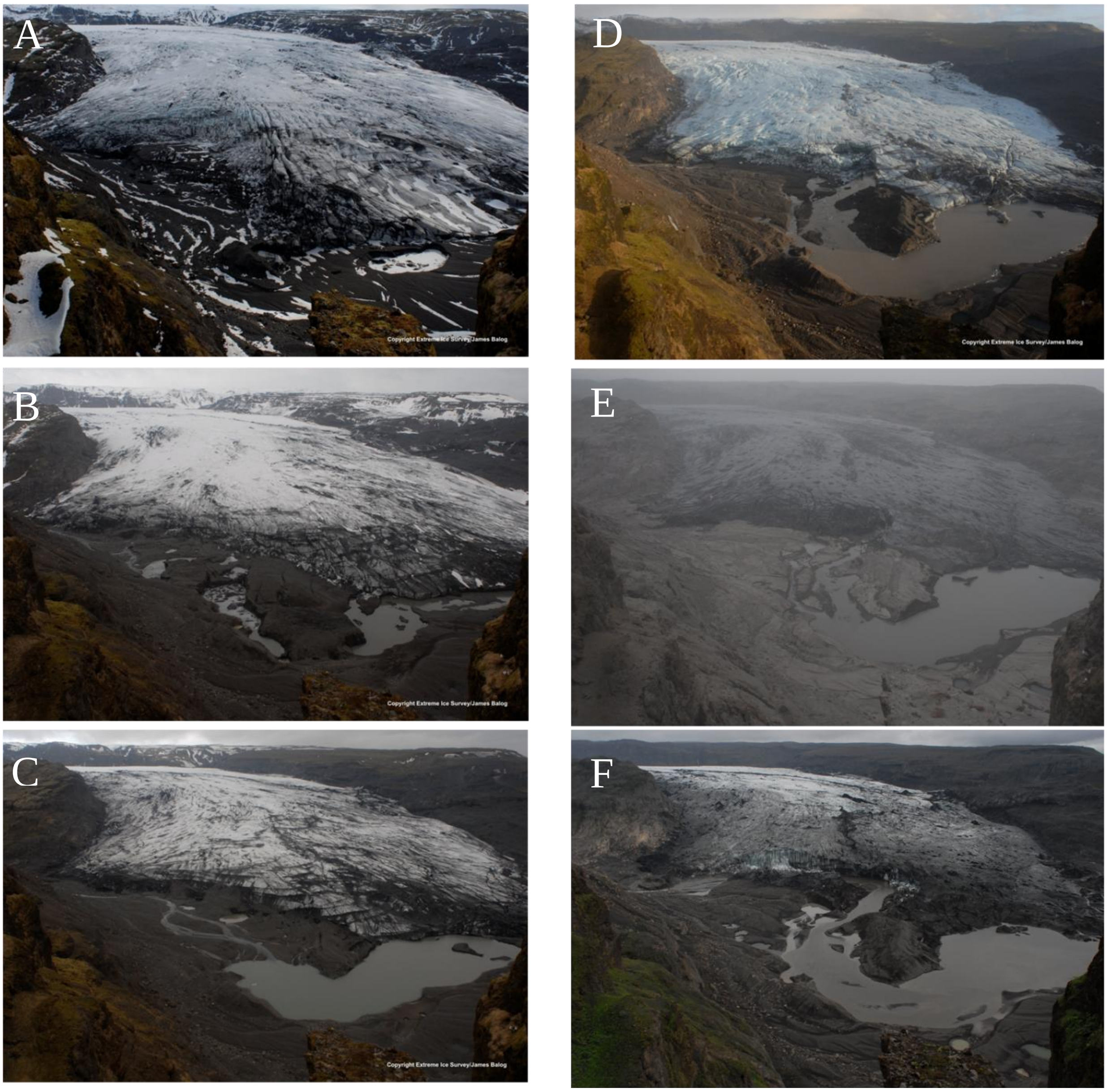


Figure 72. Four years of pictures taken from north-south at the same interval from April 2007- Sept 2010, courtesy by James Balog/Extreme Ice Survey.

Figure 73 is showing six photographs taken from the same place from 2007-2010. Jökulhaus is the mountain to the East. In 2007 (A) the contact between the heavily crevassed glacier ice and the thrust-sheet/plane beneath can be seen. The river flowing from Jökulsárgil is seen in the lower part of the photograph.

In 2008 (B) large parts of the thrust plane/sheet has disappeared and the crevasses does not have the jagged peaks as in 2007. The glacier surface is more smooth and has also lowered considerably.

The camera had to be moved a bit in 2009 (C) due to faster retreat than expected. The surface is smoother than in 2008 and the river has moved closer to the glacier margin. The lowering of the glacier surface has continued. There is a clear contact between the upper glacier ice and the thrust-sheet/plane below.

In January 2010 (D) the glacier lowered more and has gotten a steeper gradient. The river stopped flowing along the glacier and is now flowing under the glacier. Crevasses and break off has increased significantly. A small pond can bee seen in the western part of the photograph, created by melting or collapse of dead-ice.

In April 2010 (E) the tephra from the eruption of Eyjafjallajökull is covering the glacier and the forefield. The small pond in the western part of the photograph has grown and water level has gone down. Lowering of the glacier surface has continued and crevasses and break off continues.

The last photograph from September 2010 (F) show a continued lowering of the glacier surface and crevasses and break off of the glacier margin. The forefield is changing due to melting or removal of dead-ice.

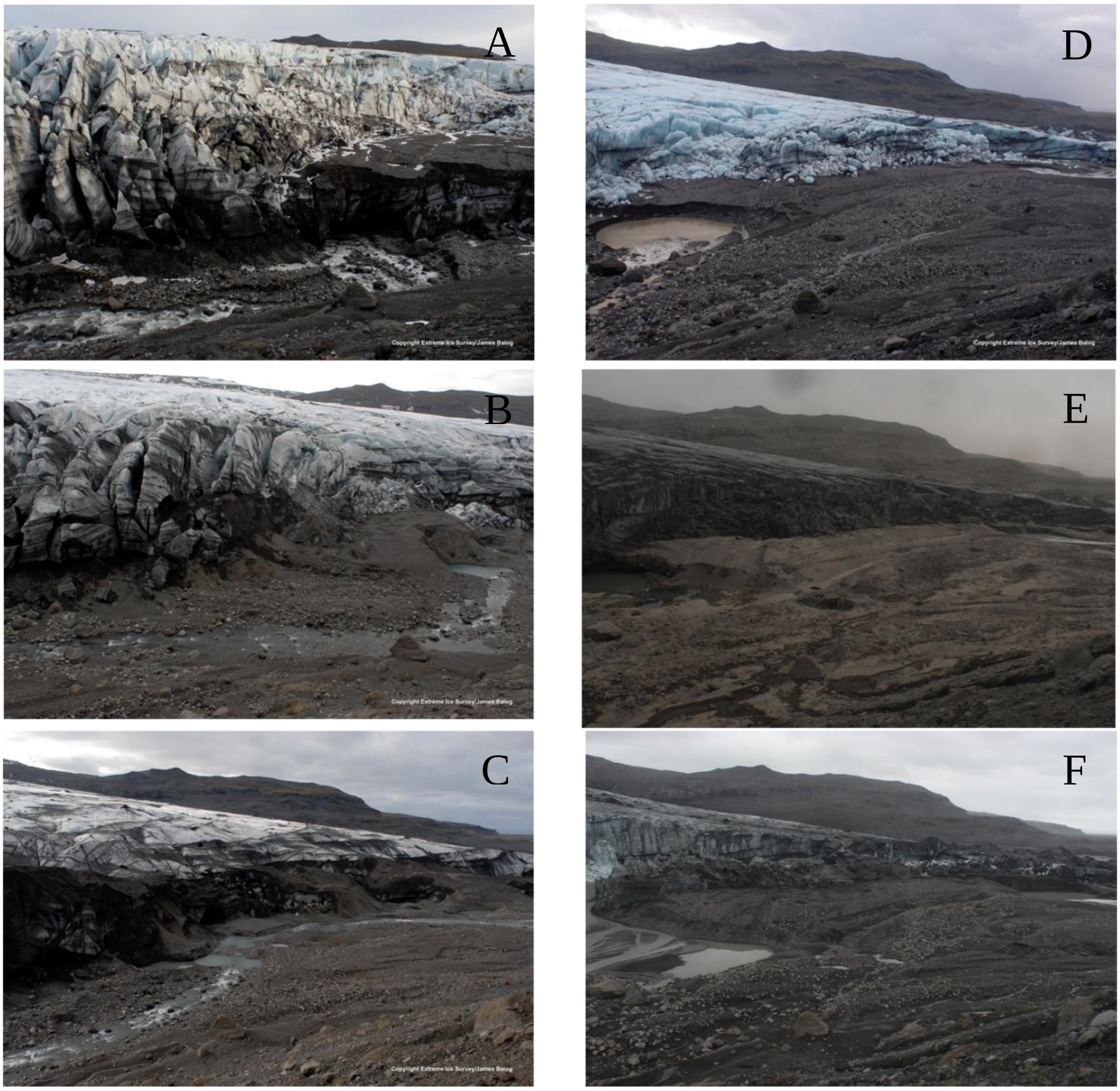


Figure 73. Four years of pictures taken from west-east at the same interval from 2007-2010, courtesy by James Balog/Extreme Ice Survey.

From the time series it is very clear how much the glacier is retreating every year. A proglacial lake has started to form. This could be expected from echo-sounding measurements in 1996/1997 (Mackintosh et al., 1999). They show that a depression beneath the glacier could probably turn into a lake. Calving of the front of the glacier could be expected in the near future, enhancing further retreat. This could be what is happening in Figure 73F.

Figure 74 shows a summary of the size of the glacier margin of Sólheimajökull, from 1905 to 2010. The size in 1910 is larger than in 1905, even though the glacier is thought to have been in a retreat phase. The 1905 size is based on a map made in 1905, while the 1910 limit is based on photographs of the glacier margin and surroundings from 1910. Until 1970 Sólheimajökull retreated, thus the small size in 1945. From 1970 to 1995 the climate changed and the glacier grew until 1996, when the glacier started retreating again and has continued until present day. Figure 75 shows a close-up of oscillations from 1996-2009.

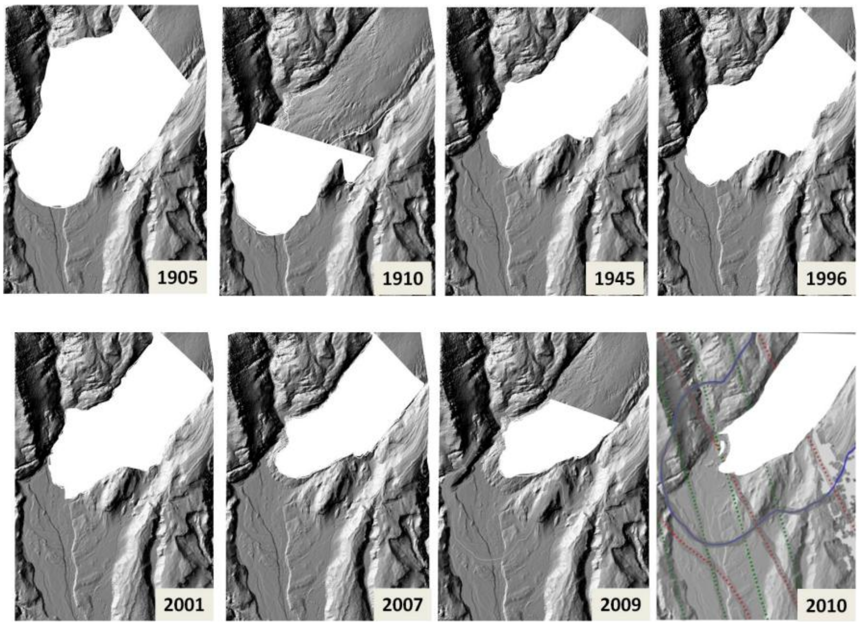


Figure 74. Summary of oscillations of Sólheimajökull from 1905-2010. Base maps are a 5 m DEM from 2004& 2010.

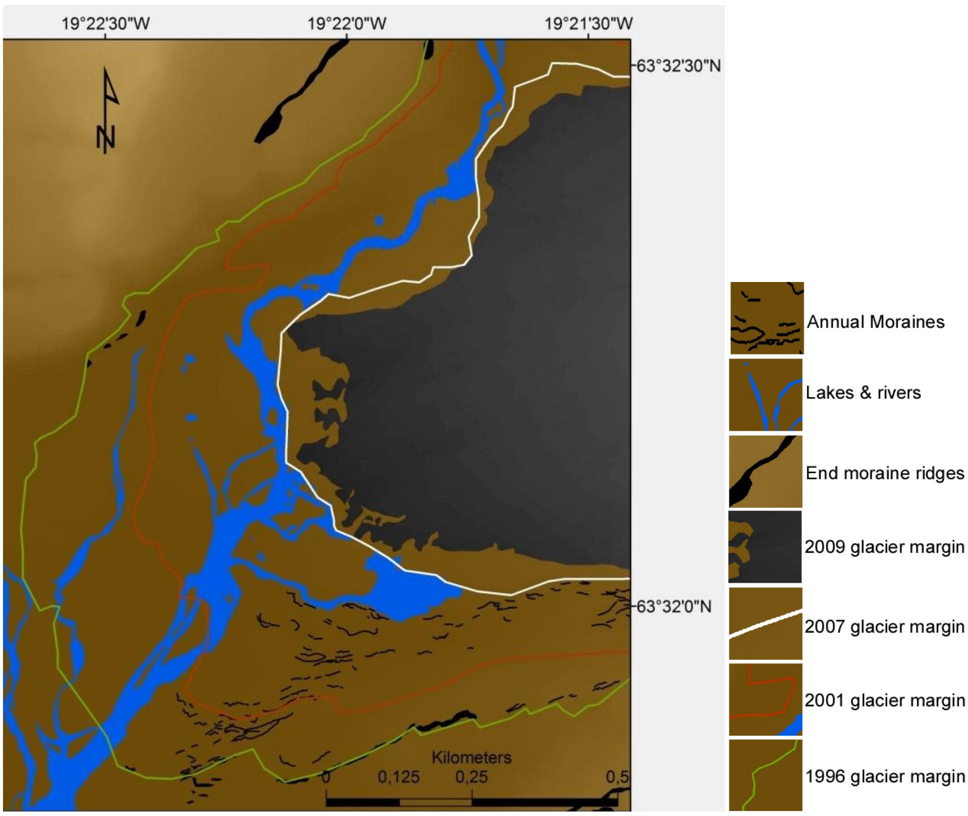


Figure 75. Sólheimajökull map showing glacier margins from 1996 to 2009.

4. Discussion

The forefield of Sólheimajökull has been under influence by many jökulhlaups and volcanic eruptions through time. This has altered, covered or removed landforms in the forefield. It has affected advances and retreats of the glacier, adding more sediments infront of the glacier margin or removing ice from the glacier. Clastic dykes has described in sediments at Sólheimajökull, thought to be created by loading of the sediments by an advancing glacier (Le Heron & Etienne, 2005).

The logs made for this thesis support the huge influence of jökulhlaups in combination with volcanic eruptions in the area. Several of the logs show contents of jökulhlaup sediments, both in area and volume. I have found clastic dykes and described them in several of my sections.

Several of my sections have thick layers of pumice overlain by jökulhlaup sediments and reflects the eruption history of Sólheimajökull. It has not been possible to date these sediments by using tephrochronology due to the pumice, which is a mixture of water-loaded tephra which has been mixed with other sediments. Only tephra which has been deposited by air can be used in this chronology. It could be possible in the future to date the sediments on top of these sections by using cosmogenic exposure dating.

Sediments in one of my sections is described as a Gilbert-type delta (Benn & Evans, 1998), which fits with my descriptions of the sediments. It could be that someone else would describe them as a sandur, but i feel more convinced that my descriptions fits well with the descriptions of a Gilbert-type delta.

In some of my logs i have come to the interpretation of different kind of tills. If more control of these should be established then one should in the future make more clast fabrics.
One of my sections was dated by radiocarbon dating of organic material. There is danger of taking samples which could have been to young and fresh, which would not date the landform I was interested in. (Manz, 2002). I feel certain that i chose the right sample places and the results of the samples also correlates well with each other.

Dating
The tephrochronology dates, radiocarbon datings and leichenometry which has been retrieved earlier in the area are several and give a coarse „picture“ of when the glacier margin was where and when jökulhlaups occured (Jaksch, 1975; Mackintosh et al., 2002 & Maizels & Dugmore, 1985). These datings has shown that the LIA maximum at Sólheimajökull was around 1890, as well as establishing chronology for older end moraines and jökulhlaups.

Former results by the use of tephrochronology and radiocarbondating show that the large lateral moraines on the mountains east of Sólheimajökull are dated to around AD 600 and the LIA maximum is dated from around AD 1800 (Dugmore et al., 2000). These are coarse dates, but narrows the timing of when the margin of Sólheimajökull was at the positions.

My results, shows radiocarbon dates of AD 1445 +/-30 and AD 1495+/-45 for a LIA moraine, but this is 400 m north of the LIA maximum. My results does not move the LIA maximum, but provides a better control of the chronology in the forefield.

The results of the cosmogenic exposure dates came out with ages mostly fitting with the ages of Dugmore & Sugden, 1991. Most of my cosmogenic samples correspond well to each other, except one sample. The reasons could be due to the sampled material, contamination because of erosion or burial of the material. The Sólheimar district has a rapid rate of weathering and erosion on the areas recently uncovered by glaciers. Frost-action is the most effective weathering agent. Almost every boulder is in the process of fragmentation, showing fracture lines, shattered into many pieces but still not fallen apart or split up into plates (Lister et al., 1953). There is also the possibility that this one sample is the correct and the other samples have been exposed to the above mentioned reasons. If this is true then the cosmogenic exposure dates will not fit with former work by Dugmore et al., 2000, resulting in 500-800 year older or younger ages. This can only be proven by taking more samples at the site.

One of the big questions at Sólheimajökull has been if Jökulhaus was entirely covered by ice in the Little Ice-Age or not. Written sources stated that Jökulhaus was covered by ice from 1820-1860 and probably uncovered between 1860-1886 (Grove, 2004). This does not fit with my cosmogenic exposure datings, which says that Jökulhaus has not been covered with ice since AD 284. So either the written sources are incorrect or the sources claim that Jökulhaus was completely covered in ice when it in fact was only parts of it.

Dugmore & Sugden, 1991 states that Sólheimajökull was much bigger during earlier mid-Holocene advances than during the Little Ice Age. One explanation is that the catchment of Sólheimajökull was larger during the mid-Holocene than during the Little Ice-Age (Dugmore & Sugden, 1991). My cosmogenic exposure dates confirm the theory that Sólheimajökull was much larger during early Holocene than during the LIA, by dating moraines much older than the LIA and far outside the LIA maximum.

Photographs

By observing newly found photographs of Sólheimajökull from 1910 and comparing them to the present day landscape it has been possible to establish a new position of Sólheimajökull in 1910. This limit is ~ 200 m further out valley than shown on a map surveyd by the Danish General Staff in 1904 (Grove, 2004). The reason for this could be that the methods used to draw maps in 1904 were coarser and more unprecise than methods used today, thus the actual limit of Sólheimajökull in 1904 is drawn on the wrong place on the 1905 map.

An other reason could be that the survey of comparing the 1910 photographs with the present day landscape has been unprecise, though not very likely due to easy recoqnizable features in the old photographs and comparing them with the present day landscape.

The third reason could be that the photograph is not from 1910 as stated.

I think the most plausible result is that the 1910 photographs of the glaciermargin of Sólheimajökull in 1910 is correct and that the 1905 map is unprecise.

Other photographs like aerial photographs have been helpfull in visualizing the retreats and advances of the glacier, both by area and by volume. Without the photographs to support the geological work, establishing former glacier margins, deposition of landforms and alterations of the forefield would have been more difficult.

The use of time-lapse photography can teach me how much Sólheimajökull will retreat and the time series will help me understand how this happens and how quickly, as well as the huge lowering of the thickness of the glacier. Accurate measurements of the lowering of Sólheimajökull has not been established, but will be possible by using some kind of scale or georeferencing of the photographs and place them on top of DEMs.

Maps

The maps that were made and the following calculations in GIS, show that the snout of Sólheimajökull lost around 70% of its area from 1904-2009. There are uncertainties with these measurements which are done mostly by using aerial photographs, but they are very small. There is a possibility that the georeferencing of the photographs are more imprecise than the 1-10 meters inaccuracy used in the measurements. To fix this problem you can use special work-stations with 3D capabilities and base maps that are almost 100% correct.

Mapping the landforms on the aerial photographs can be tricky, especially small and diffuse landforms. By mapping the landforms on the ground as well it is possible to see how they look like on the ground and then see how they look like on the photograph, thus a better confirmation.

My maps show glacier margins 100 years back in time and is a good tool for visualizing how the glacier margins have advanced and retreated. The landforms I mapped is only mapped for 2007, thus does not show the changes to the landscape and landforms through time. To see these changes maps for several different years have to be made or one could map specific landforms instead of mapping every landform present on an aerial photograph. This is the way to show if landforms have been eroded or deposited.

Older maps of the area has had a low percentage of details and information, e.g. ages of end moraines (Grove, 2004; Jaksch, 1970), so my maps will give people a chance to have a better overview of the area, landforms and oscillations of Sólheimajökull.

Future work

To further advance my knowledge of Sólheimajökull and its history it would be nessesary to take more cosmogenic exposure samples from the large moraines on the mountains east of Sólheimajökull to confirm if the ages I have now are correct or not. It is important to take samples from the other side of the valley to establish a chronology and database of ages and correspond them with the ages of Crittenden, 1975; Dugmore et al., 2000 & Jaksch, 1970.

It would be interesting to study mass balance of the glacier to get a better understanding of how the glacier reacts to changes in precipitation and temperature and how fast the glacier is moving down the valley. This means setting up weather stations at the foot and the top of the glacier. Now the closests weather stations are in Skógar and in Vík.

Lately the margin of Sólheimajökull has started to calve of and a small proglacial lake has started to form. It would be good to use an ice radar like Mackintosh et al., 1999 did in the late 1990s to establish how the bedrock looks like below Sólheimajökull. The grid that was made in the 90s was very coarse, consisting of two lines. In order to get a high resolution „look“ and DEM of the bedrock it would have to be a much tighter grid.

The useage of a georadar over the sediments in the forefield of Sólheimajökull would be interesting to try to see how thick the sediments are and to see if it would be possible to distinguish between the different layers in the sediments.

Comparing satellite images from different days could give me the possibility to see what happens to Sólheimajökull, during a small volcanic eruption with little ash fall (Fimmvörðuháls March 2010) and a larger eruption on with heavy ash fall (Eyjafjallajökull April 2010). In April, Sólheimajökull was completely covered in ash. The interesting thing will be to see how thick the layer of ash is and how it will affect the melting of the glacier for the years to come.

Finally making DEMs from all available aerial maps to try to measure how much the glacier has changed both in area and in volume through time and to do the same with the sediments and landforms in the forefield of Sólheimajökull.

5. Conclusions

- According to the CE dates the eastern flank of Sólheimajökull reached the outer most moraines at AD 56, thereafter it retreated to the second outer most moraine at AD 91. Thus confirming that Sólheimajökull was much larger during the Holocene, than any time of the LIA.
- Jökulhaus has probably been ice-free since AD 284 which seems reasonable with the retreat rate from the AD 56 and 91 moraines, but this is not in accordance with written sources. The written sources might not have been accurate in their definition of a “completely covered” Jökulhaus or the CE date is imprecise.
- Sólheimajökull probably stood at the mouth of the valley around AD 56 +/-606 (4 km south of the present day margin).
- Sampled material for new radiocarbon dates for the LIA moraine was found during field work in the summer 2009. Radiocarbon dates confine the moraine (400 m north of the LIA maximum) to the period after AD 1445 +/- 45 and AD 1495+/-45, which is important for reconstructing the chronology and extent of the LIA glacial advances.
- Several newly found photographs places the1910 margin of Sólheimajökull ~ 200 m further south than the 1904 margin is drawn on a map from 1905. This margin coincides with the LIA moraine.
- Two of the logs show thick layers of jökulhlaup sediments and pumice layers.clastic dykes penetrate both sections from surface to bottom, indicating loading of the sediments by an advancing glacier.
- Large sandur deposits are found in logs on the west side of Jökulsá.
- The GIS maps and 3D models show the oscillations of the glacier margin of Sólheimajökull from 1905 to 2010. The maps show the different types of landforms and their position in the forefield of Sólheimajökull. The area proximal to the glacier margin and close to Jökulsá is very changing and changes and destroys landforms.
- From 1904-2009 Sólheimajökull lost 2.2 km^2 (70%) of its frontal part of the snout.

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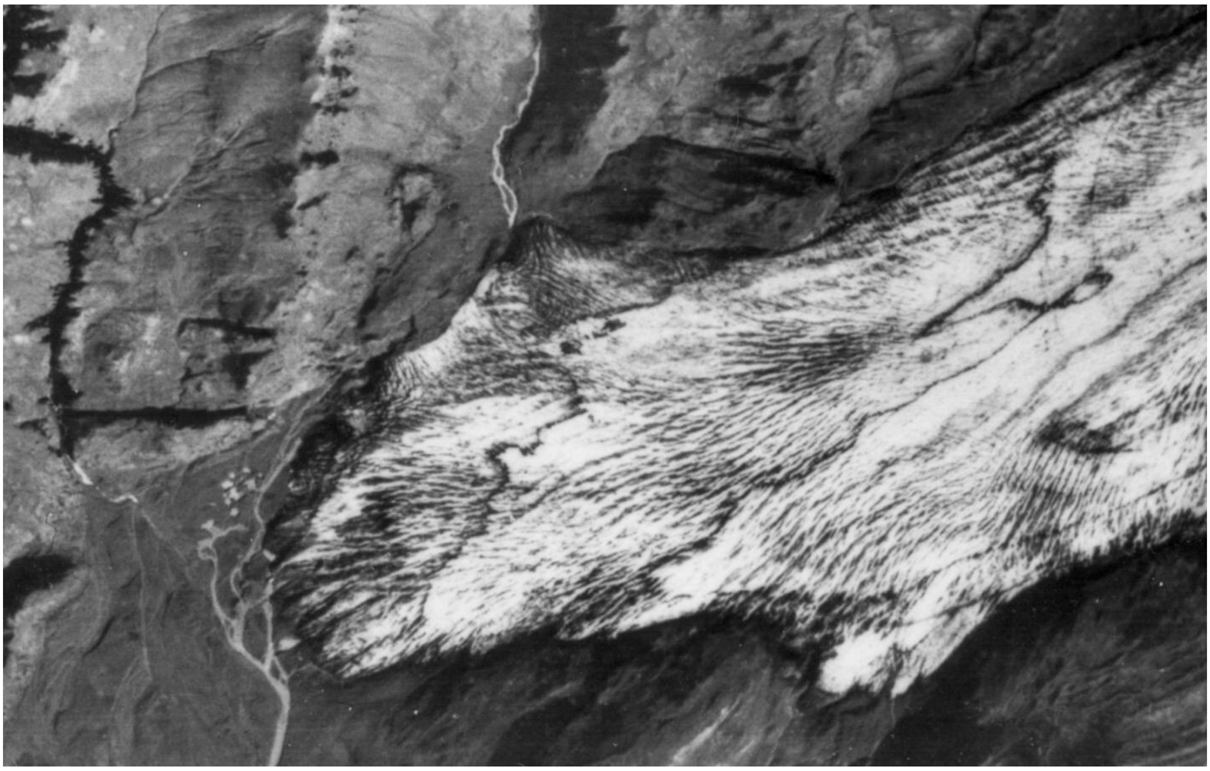
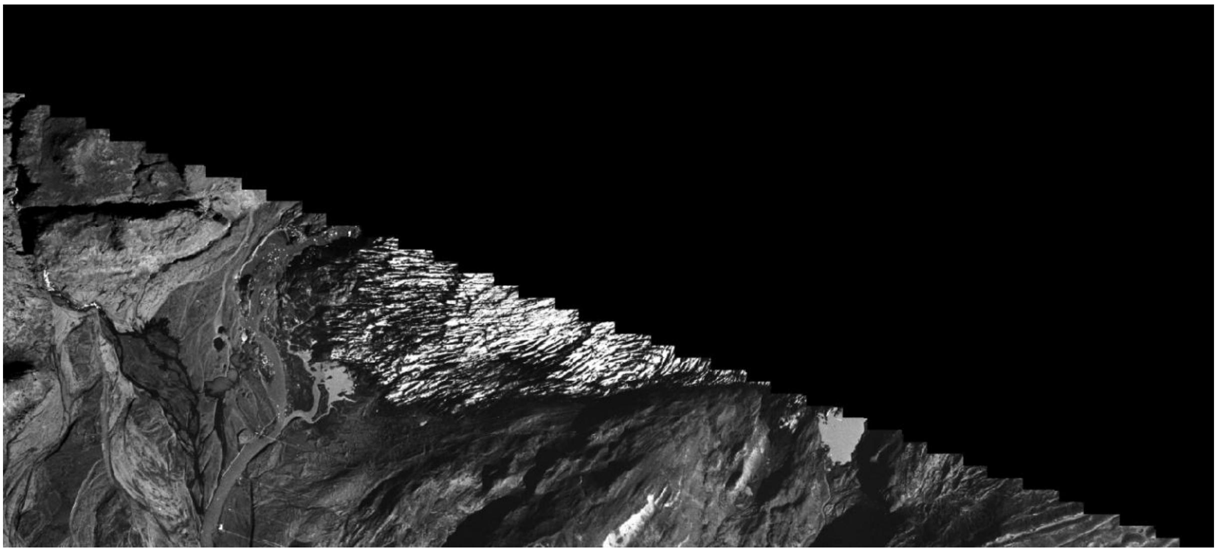
Appendix

Aerial photographs of Sólheimajökull through time

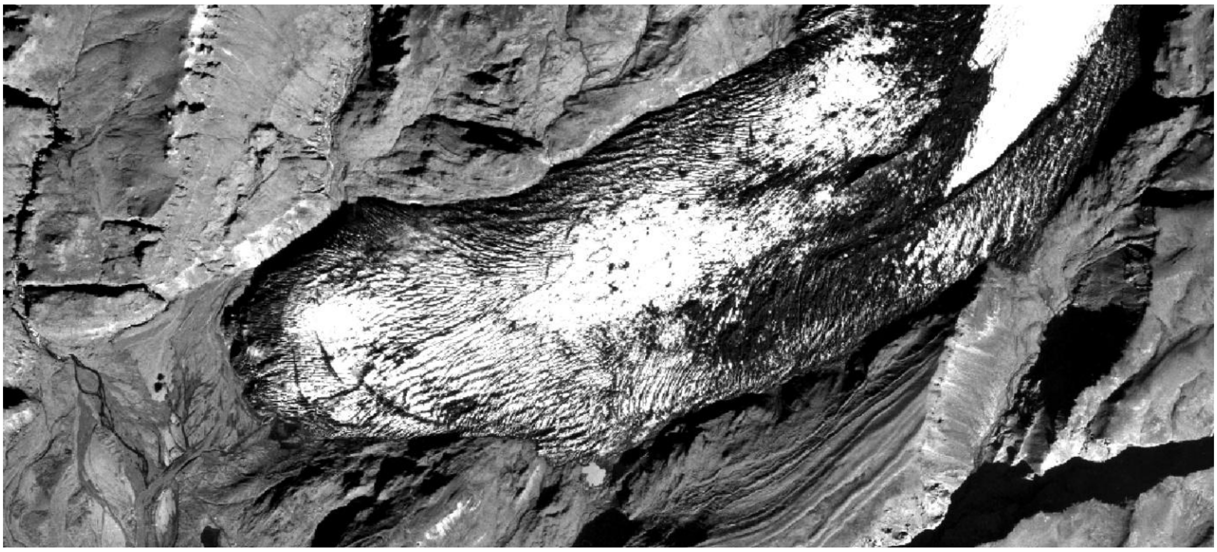
Sólheimajökull 1938, Geodætisk Instiut



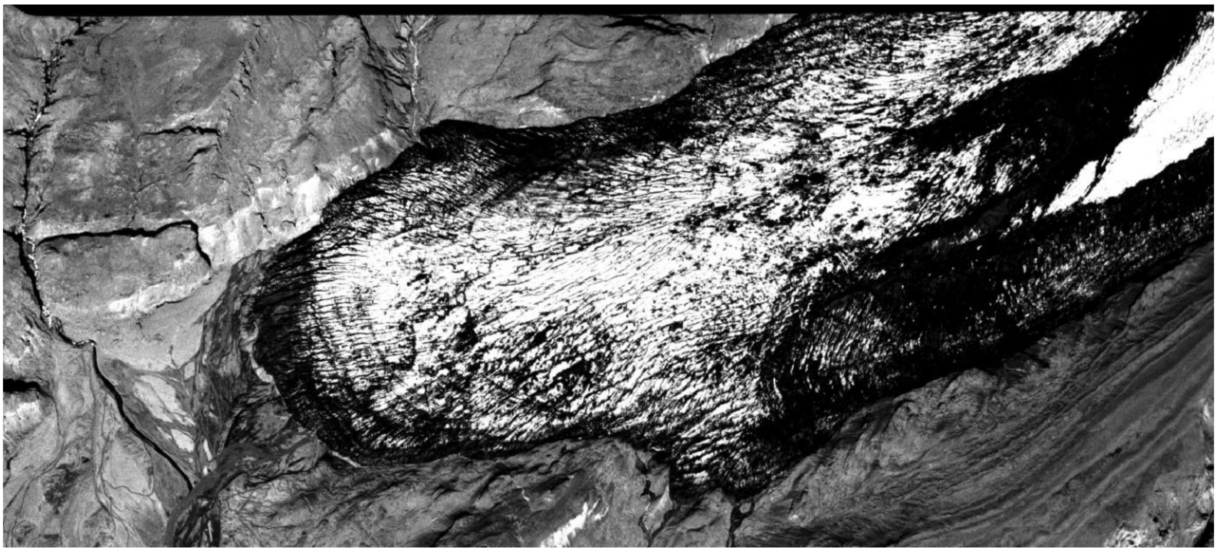
Sólheimajökull August 29th 1945, aerial photograph USAF.



Sólheimajökull 1960, aerial photograph USAF.



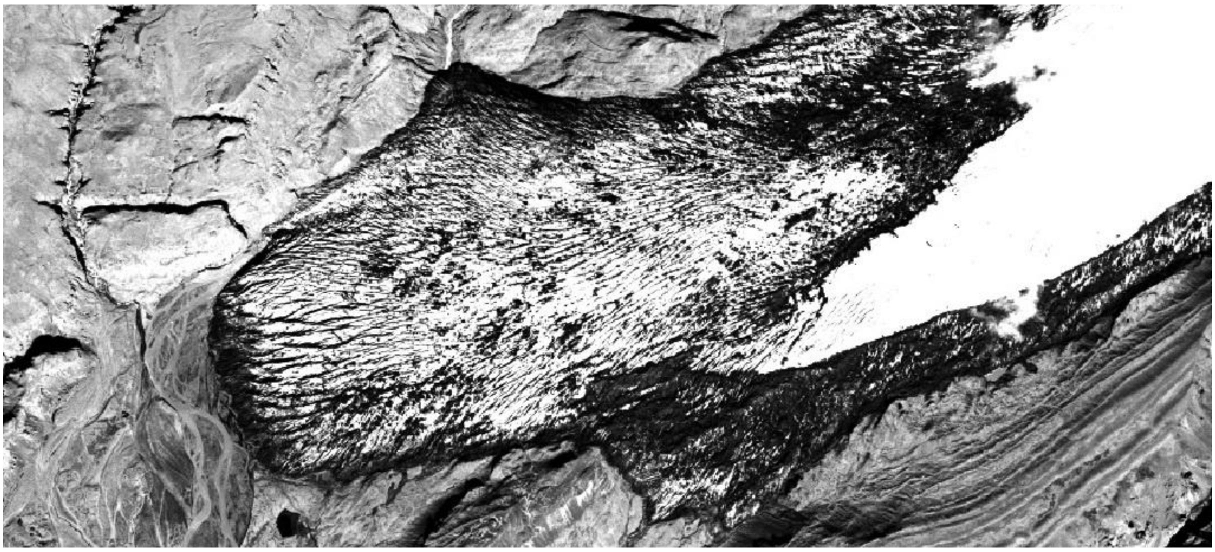
Sólheimajökull 1975



Sólheimajökull 1980

Sólheimajökull 1984

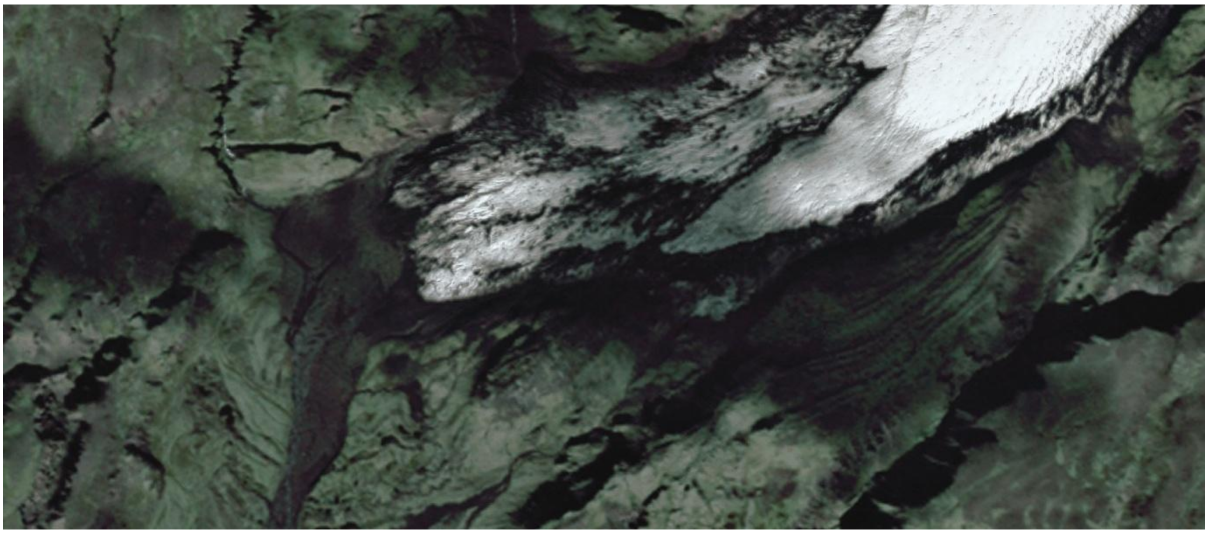
Sólheimajökull 1985, Oddur Sigurðsson

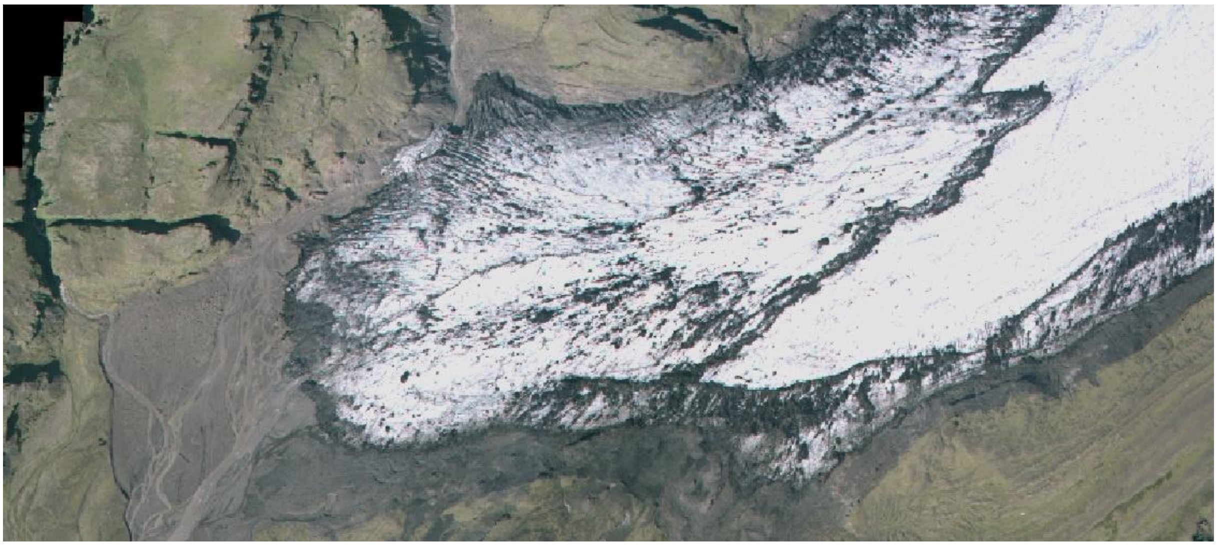


Sólheimajökull 1990


Sólheimajökull 1996


Sólheimajökull 2001

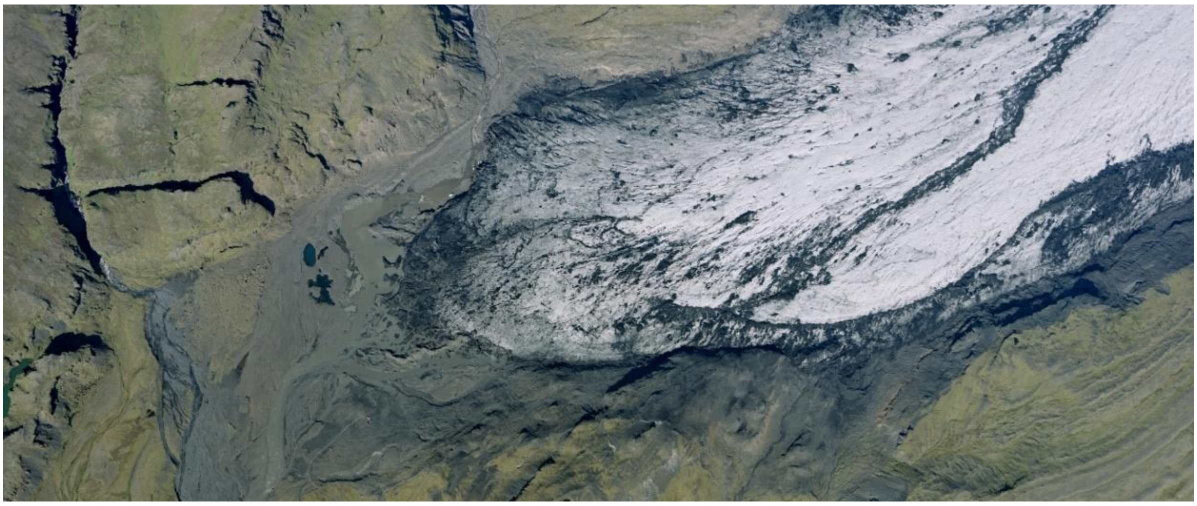

Sólheimajökull 2003, SPOT 5 satellite image



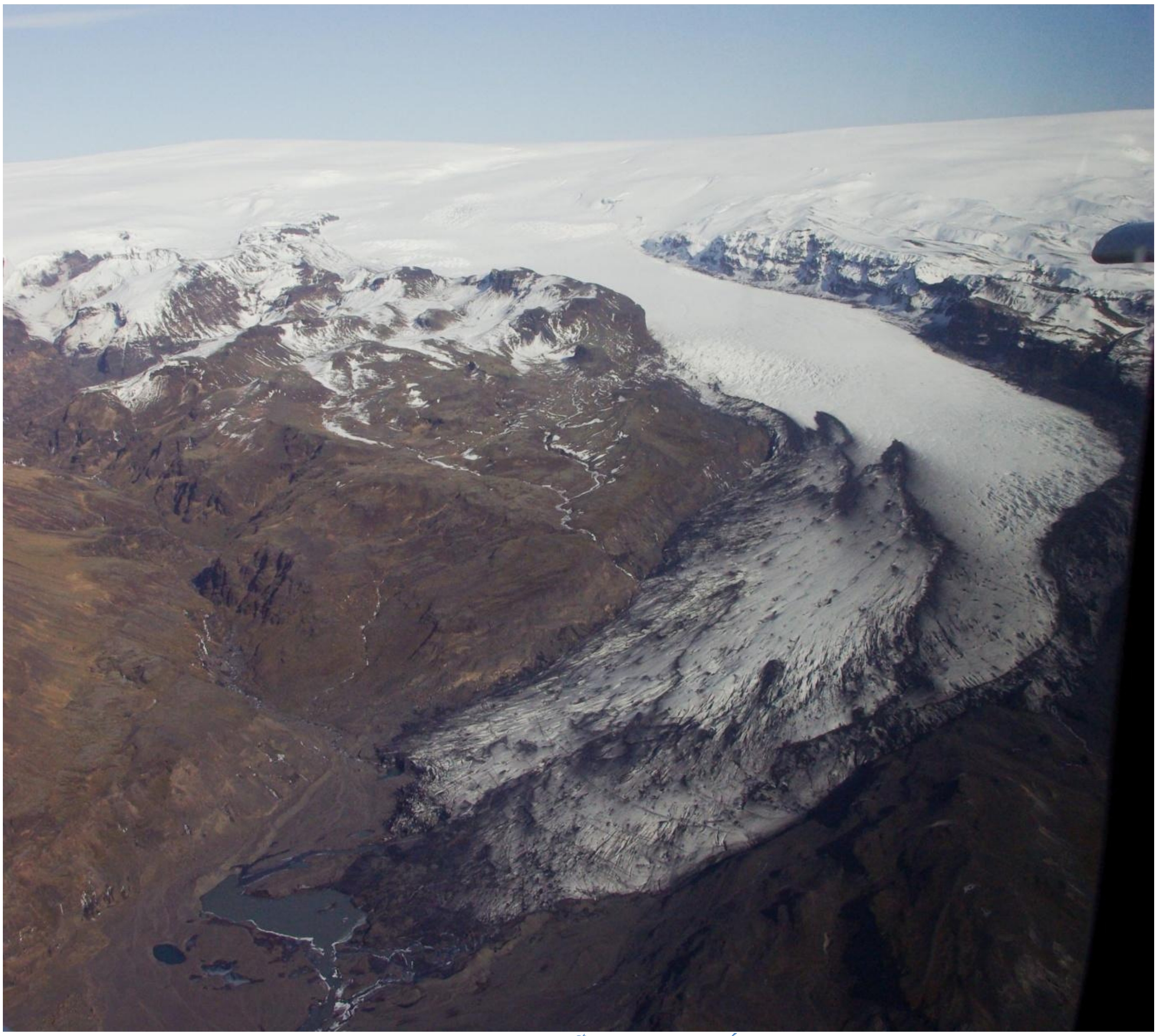
Sólheimajökull 2004

Sólheimajökull 2007, Samsyn ehf

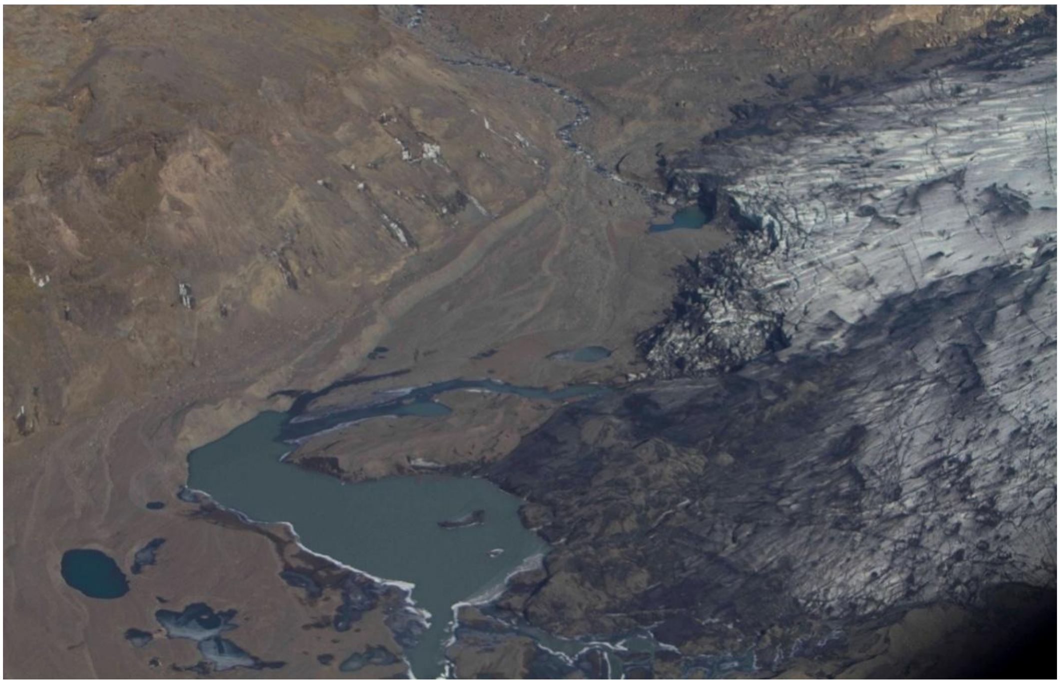
Sólheimajökull February 1st 2008, Quick Bird satellite image



Sólheimajökull 2009, Loftmyndir ehf.



Sólheimajökull March 31st 2010, Eygló Ólafsdóttir

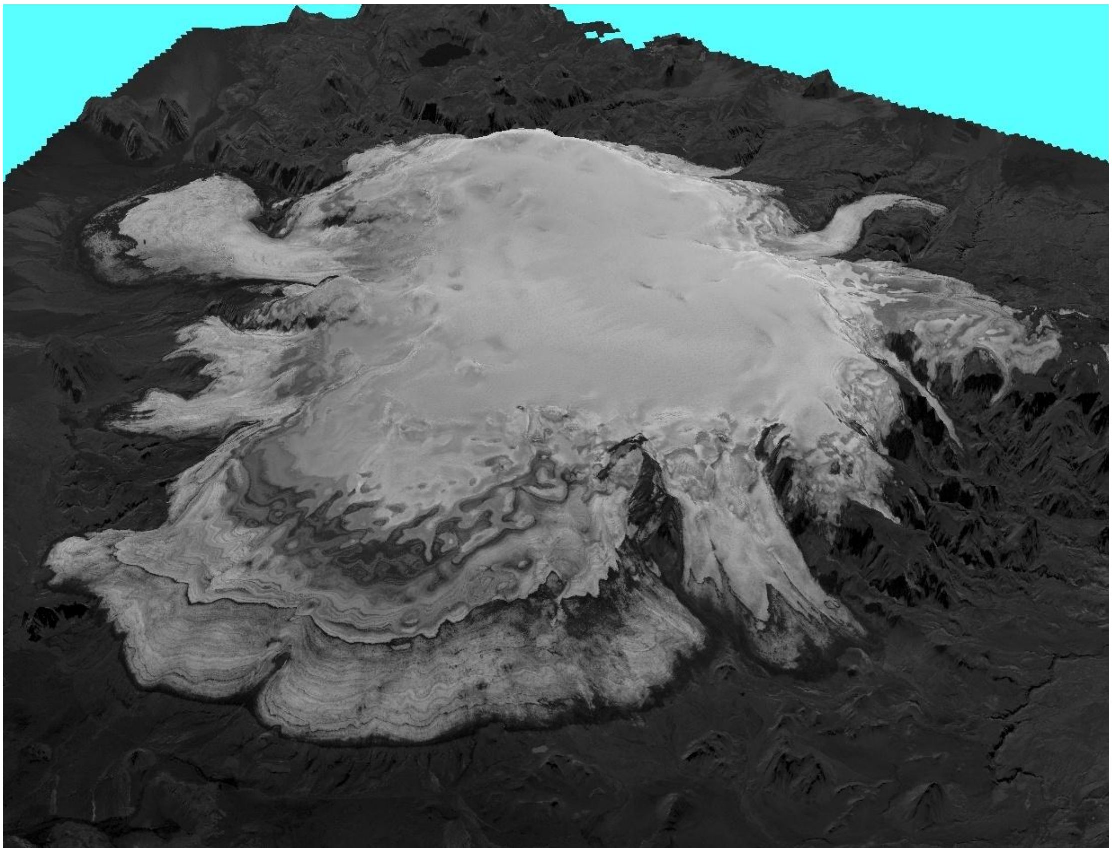


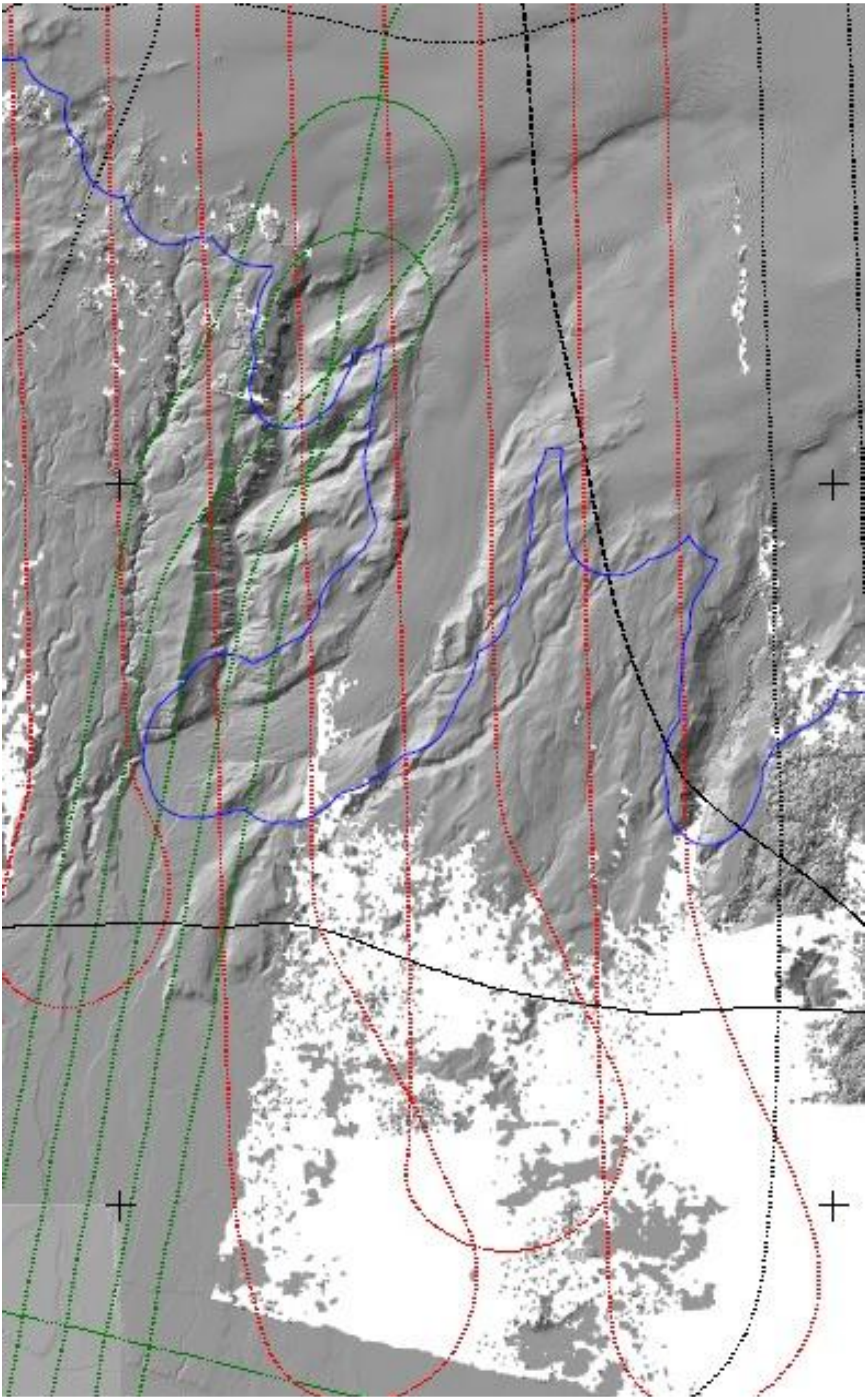
Sólheimajökull March 31st 2010, Bjarki Friis

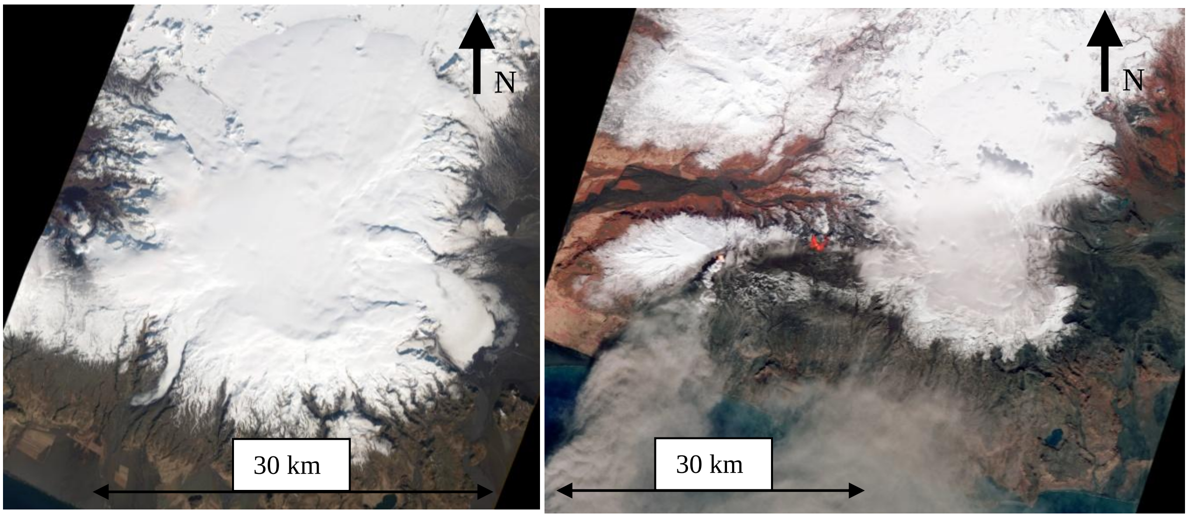
Sólheimajökull panorama October 24th, 2010

Sólheimajökull margin October 24th, 2010.

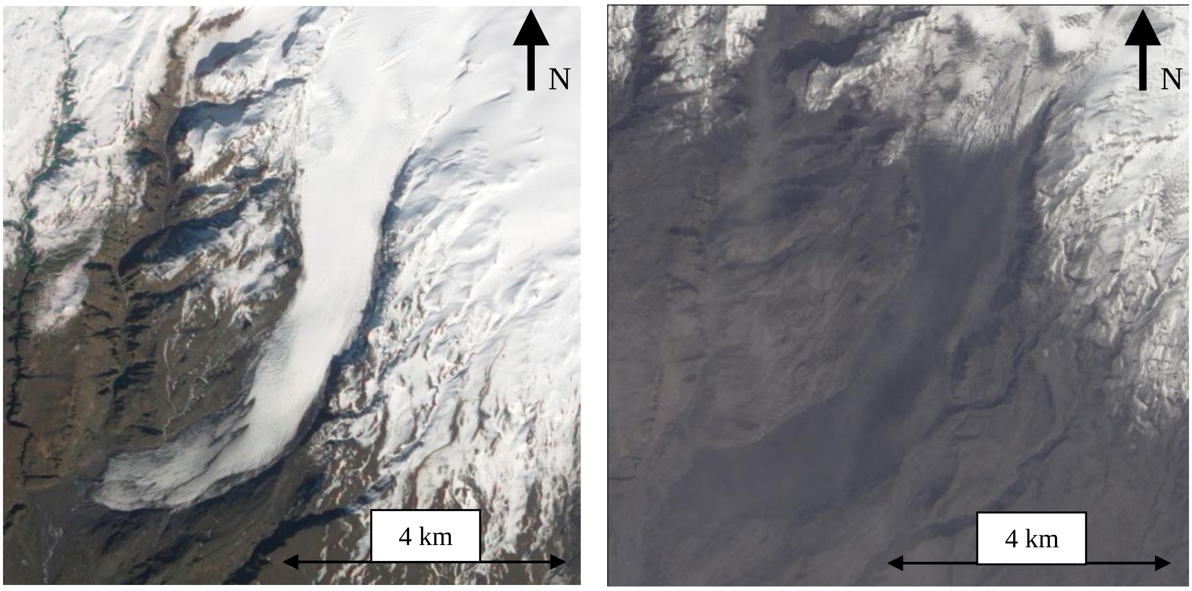
Mýrdalsjökull 2007, SPOT satellite image


Mýrdalsjökull 2008, SPOT HRS 5 stereographic survey





NASA EO-1, 10 m resolution ssatellite picture of Mýrdalsjökull,from April 4th 2010. and NASA ASTER satellite image from April 19th. These images show the small eruption on Fimmvörðuháls ad the larger at Eyjafjallajökull. The latter one showing Kötlujökull and Sólheimajökull covered in black ash (NASA, 2010).

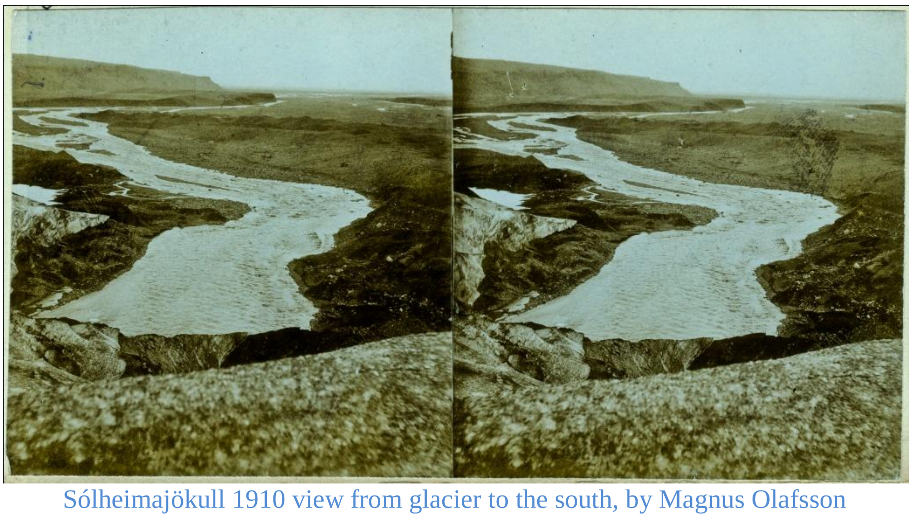


Comparing satellite images of Sólheimajökull. Left one from April 4th and right one from April 17th (NASA, 2010).

Old photographs

Sólheimajökull 1910 by Magnus Olafsson

Sólheimajökull 1910 by Magnus Olafsson



Sólheimajökull 1910 view from glacier to the south, by Magnus Olafsson


West side of Sólheimajökull between 1906-1937, by Thorvald Krabbe


Sólheimajökull between 1915-1920, view towards north, by Geir Zoega


Sólheimajökull 1936, from album of Sveinbjörn Jónsson