Geomorphological features caused by glacial activity in the forefield of Sólheimajökull glacier in Iceland

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Pictured left to right: Antoine, Sigrún, Caitlin, Marzena, Erica and Kevin.

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Geomorphological features caused by glacial activity in the forefield of Sólheimajökull glacier, Iceland

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Abstract- *The forefield of the Sólheimajökull outlet glacier displays numerous examples of geomorphological features caused by jökulhlaups and the advancement and recession of Sólheimajökull. This report elaborates on these glacial features in order to gain a greater understanding of glacial geology. Observations and interpretations were made at a variety of different locations around the glacial forefield. Landform features such as drumlins, eskers, flutes, moraines, and signs of jökulhlaup activity were analyzed by numerous methods to understand how these forefield landscapes were created.*

INTRODUCTION

Glaciers are extremely dynamic in nature and leave traces of their past throughout the landscapes they have retreated from. Across the globe, glaciers are currently retreating and such is the case for the outlet glaciers of Myrdalsjökull in South Iceland. Their retreat allows us to study the landscapes they used to advance upon in order to have a greater understanding of their geomorphological processes. Our group, as well as other groups participating in the glacial geology field trip in spring of 2013, studied the forefield of Sólheimajökull, an 8 km long outlet glacier of Myrdalsjökull. We set out to analyze and understand the glacial landscape by observing and measuring different components of their features, then interpreting our results. Sólheimajökull experienced an advance until the end of the Little Ice Age, followed by general retreat until a relatively small advancement from 1970-1995. The outlet glacier has been retreating since then. In 1999, a jökulhlaup ran through the valley creating many features (Schomacker et al, 2012). During our 3 days in the field at Sólheimajökul, we divided our tasks into six workstations. Each station had components to be observed and measured for different landscape features. At Station 1, we examined and described the Little Ice Age end moraine and its sediment and structural appearance. Station 2, the 1995 ice margin was described and analyzed. Station 3, we examined recessional moraines formed during the last thirteen years. Station 4, a drumlin was analyzed internally and a profile made of its external structure. Station 5, the current ice margin was described. Station 6, the features of the 1999 jökulhlaup were observed and analyzed. Our findings helped to confirm many of the discoveries in the Schomacker paper recently published in 2012.

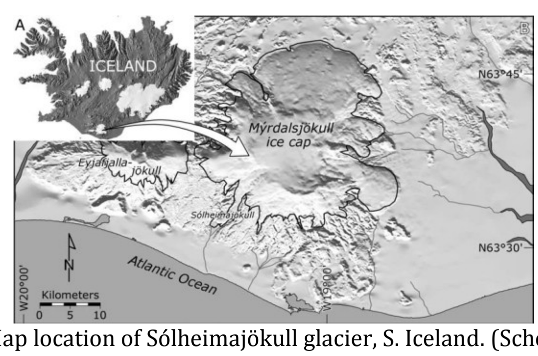


Figure **1**. Map location of Sólheimajökull glacier, S. Iceland. (Schomacker, 2012)

STATION 1
Little Ice Age Moraine

The Little Ice Age (LIA) occurred between 1300 – 1900 AD. In the forefront of Sólheimajökull, the LIA moraine is believed to have been formed in 1890 AD (Bjarki, 2011). Our location was the portion of the LIA moraine that was least affected by a jökulhlaup. The moraine was relatively large compared to the other observed annual moraines seen the previous day. The most prominent end-moraine ridges represent the major LIA glacier advances (Krüger et al, 2010). We noticed that behind the moraine there was a depression often filled with water. Some drumlins and drumlinoids were noted in front, behind and underneath portions of the moraine. The moraine seemed to have a hump-like shape with varied height throughout. There appeared to be a small moraine branching from the larger moraine. In order to observe the structure of the moraine, we utilized a dug out section made by previous groups, which displayed roughly 3 m of the interior of the moraine. Different layers of sediment could be seen in the exposed section of the moraine. The layers from top to bottom are as follows: a course grained layer, a clay layer with pebbles within, an ash layer, another clay layer, and another coarse-grained layer (Figure 2). The first clay layer appeared to be disturbed, as it looked pushed up (Figure 3).

The moraine was large because it was an end moraine. The depression filled with water can be explained by the hill-hole pairing caused by pushing of the sediment by the glacier. Drumlins and drumlinoids were located around different portions of the moraine because they were deposited before the moraine was formed. The saw-tooth shape of the snout of the glacier can explain the hump-like shape of the moraine as well

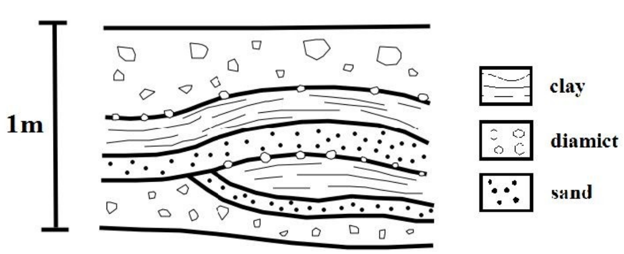


Figure 3. Profile drawing of thrust structure in LIA moraine.

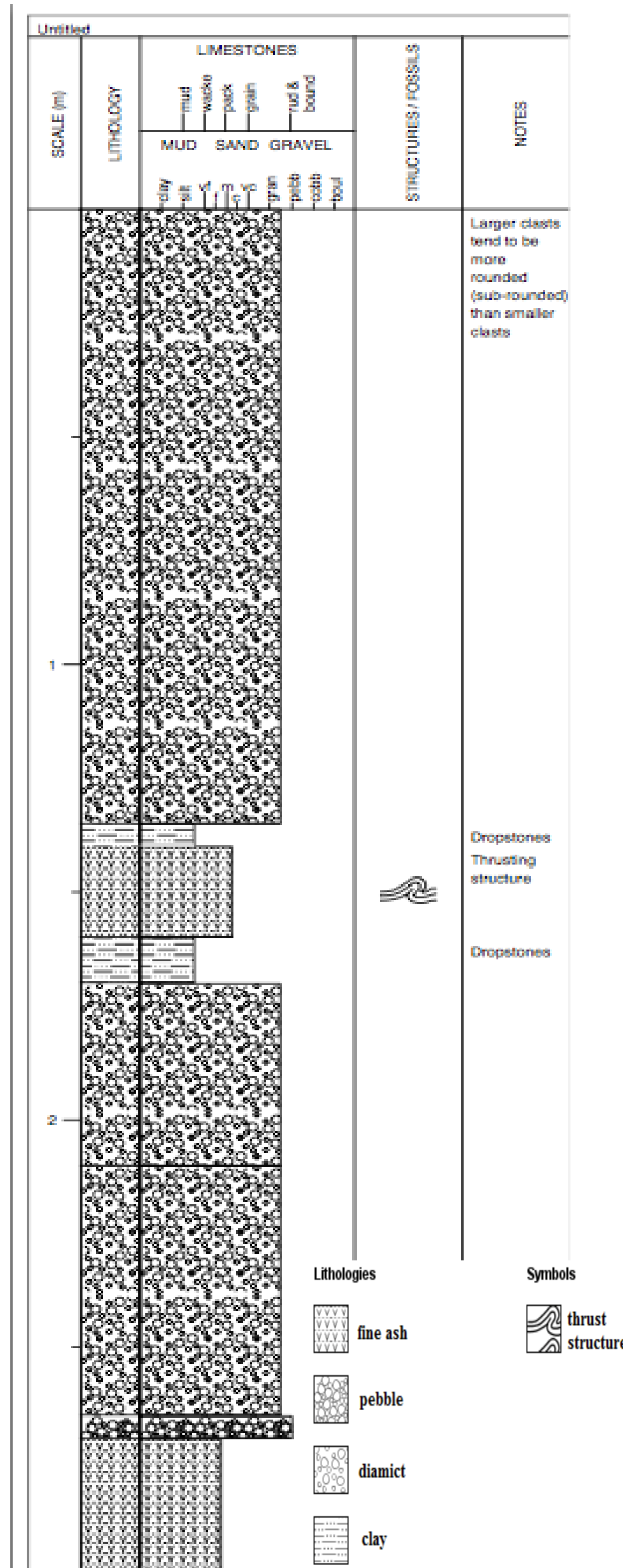


Figure 2. Sedimentological log of profile in LIA moraine.

as the branching portion of the moraine. The clay is characteristic of a low energy environment such as a proglacial lagoon. We recognized that the separation of the clay layers was the result of a shear plane fracture and are indeed the same layer (Figure 3). The ash layer was thrusted between the clay layer as a result of winter glacial advance. The clay was wet because during wintertime it is a frozen body allowing shear fracture. The pebbles can be interpreted as dropstones that fell out from ice melting in the glacial lagoon.

STATION 2
Sólheimajökull 1995 Moraine

Our location was the 1995 advance moraine on the eastern side of the valley at the border of the jökalhlaup carved streambed. The moraine was relatively large compared to other annual moraines. Large boulders could be seen situated on top of many parts of the moraine (Figure 3). We dug out a one-meter deep and one-meter wide section of the moraine and were able to observe clasts of all sizes floating in the sediment matrix of the moraine. The clasts were also of all shapes, some being rounded and some angular but most were rounded. The sediments were poorly sorted within for the most part. However, a layer of finer material, possibly ash with sand could be seen as the top layer of the section, with a finer silt layer observed below it, and finally another ash sand layer below that. No real evidence of push could be seen within the sediment section. We observed that the side of the moraine facing the glacier had a slightly shallower slope than the side facing away from the glacier.

Figure 4. Walking on the 1995 moraine with annual moraines to the left side of its peak; large boulder on top of moraine.

Three separate ridges could be seen near the 1995 moraine on the side facing the glacier. The 1995 moraine was 1.8m from first ridge, 5.9m from the second, and 11.8 m from the third. A road made by construction cut through the 1995 moraine and the three ridges but they could be observed again on the other side of the road. On the other side of the road, the 1995 moraine was 5m from the first ridge, 8.3m from the second, and 16.4m from the last (Figure 4). Successional retreat produced noticeable annual moraines after 1995, therefore, by measuring annual moraines from 1996, 1997, etc, the rate and angle of retreat may be better known.

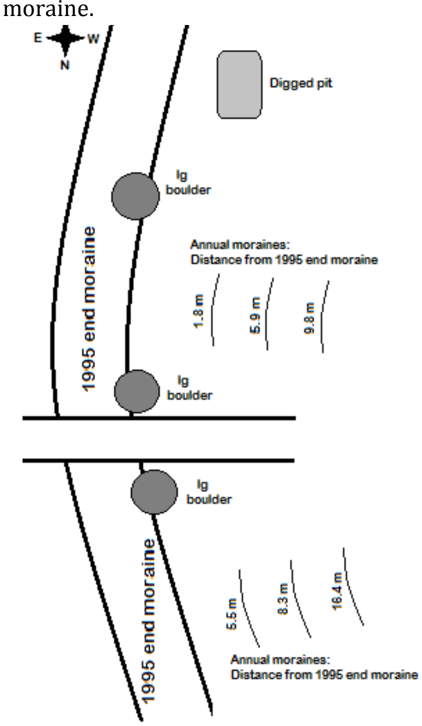


Figure 5. Measurements and locations of annual moraines.

The moraine was most likely larger than other previous observed annual moraines because it was the last advance of the 1970-1995 advancement period. We can imagine that the glacier had a much steeper wall at the ice margin during a time of advancement, therefore depositint more material. The steep walls of an advancing glacier margin can also explain the large boulders that are situated on top of the moraine, that likely fell supraglacially by gravity. Both are signs that the 1995 moraine can be considered a dump moraine. The shallower side of the moraine can be explained by the push aspect of the moraine as it made its advancement in the winter months and retreated in the summer. The poorly sorted sediment is perfectly natural for a moraine feature in general. The layer of silt protruding through the two layers of ash could possibly be a thrusted layer pushed by the moraine but that cannot be entirely determined by the small section analyzed. The ridges observed near the moraine could be annual moraines. The measurements on both sides of the road are similar and indicate consistency in the ridge distances from the 1995 moraine. These distances are small relatively for the distance between annual moraines closer to the ice margin. However, smaller gap between annual moraines closer to the 1995 margin can be explained by a less intense retreat period for a few years. Melting has accelerated for the last 18 years and the intensity of the melt would have been less intense closer to the 1995 margin.

STATION 3
Sólheimajökull recessional moraines

Station three was the annual moraines visible on the eastern side of the valley within the 1995 moraine. The first examined annual moraine was near the present glacial river and between the current illegal parking lot and the Sólheimajökull coffee house. The moraine was 65 cm high at the center, 2.3 m wide from the top to the side facing away from the glacier and 2.0 m wide from the top to the side facing the glacier. We dug about half a meter into the moraine to view its internal structure. At first glance there appeared to be lenses of clay within a sandy ash matrix. Clasts were both large and small throughout the matrix. There seemed to be a deposit layer of smaller rocks through the middle of the section. An ash layer made an "s" shape from the base of the moraine to the surface facing away from the glacier. The lenses of clay now appeared to just be separated because the ash layer ran through and around them. The other section, a meter away from the previous section, showed three distinct ash boundaries clustered in the side of the moraine facing away from the glacier as well.

The second annual moraine studied was in front of the illegal parking lot and behind the current glacial lagoon still on the east side of the valley. A one-meter internal profile dug out showed an extremely wet clay sediment at the base covered in a layer of small pebbles. On top of the pebbles was a layer of ash/sand that was below a top layer of silty clay. This moraine was 30 cm high at the center, 2.3m wide from its center on the side facing the glacier and 2.5m wide on the side facing away from the glacier.


Figure 6. Clay layer thrusted above ash layer.

The "s" shaped ash layer can be explained by the thrusting or even folding of the clay layers around it. The three distinct ash layers on the opposite section display an even more obvious sign of thrusting as the ash layers are each spaced but most likely derive from the same layer. The wet clay layer at the base of the second moraine is evidence of a low energy environment such as a lacustrine environment or glacial lagoon which deposited such fine clay. The pebbles on top of the clay are also probably deposited from floating ice on top of the lagoon environment. The clay on top of the ash layer is a thrusted region of the base layer from a winter advancement of the receding outlet glacier. The varieties of clast sizes are, again, a perfectly natural deposit of an annual moraine.

STATION 4

Drumlin in Sólheimajökull glacier forefield

Our first work in the field was located on and around a drumlin lying relatively centered between the glacier valley and within the 1995 glacial boundary about half a kilometer from the ice margin. It faced in the northeast to southwest direction. We intended to create a vertical profile of the drumlin and to measure the orientation of the clasts within the sediment matrix. The drumlin was relatively large compared to other surrounding drumlin features and was dissected by water erosion. This gave us easier access to analyze the internal structure of the drumlin. The drumlin contained a variety of sized clasts throughout the sediment matrix. The exposed interior of the drumlin had a dry and brittle exterior most likely due to weathering. Once the surface was broken off, the sediment was moist and compact and much harder to dig into. It appeared to have at least three layers but they were harder see once the dry surface was removed.

We created a profile of the drumlin using a TopCon laser tripod (Figure 7). We set our point of reference at the estimated highest point of the drumlin parallel to the ice flow. Roughly every two to three meters we measured the vertical displacement of the drumlin along a straight line to both ends of the drumlin.

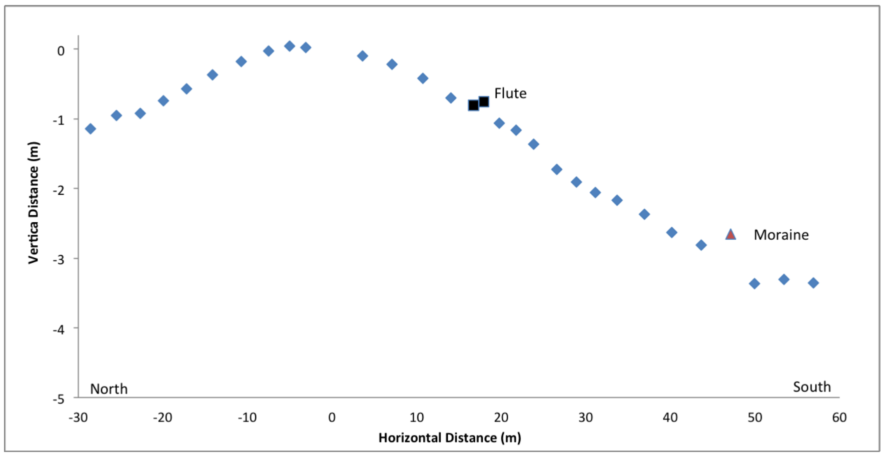
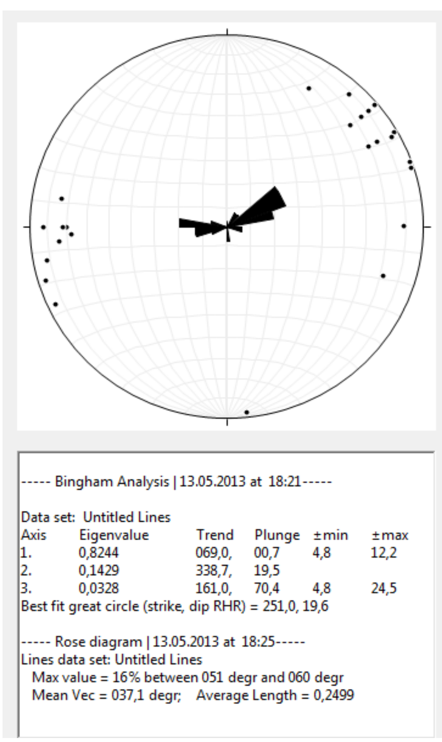


Figure 7. Profile of drumlin.



In order to measure the fabric, we scraped the weathered surface of the drumlin away using a trowel and shovel. The clasts we chose to measure had to be within 6-60 mm and touching no other clast in the matrix. The clasts had to be twice as long as they were wide in order to prove their orientation. We then measured the length, strike, and dip of the clast using a compass. We measured 25 different clasts, removing an already measured clast to insure it was not recounted. The clasts were very difficult to locate within our parameters of an appropriate clast.

We described the face of the drumlin in the section. We discovered three flutes on top of the drumlin as well as an annual moraine that overlaid some of the drumlin. These glacial geological features are prone to erosion, thus some of the flutes were not as prominent.

Figure 8. Rose diagram of the orientation of 25 clasts in the drumlin.

The TopCon data was plotted on an excel spreadsheet and made into a graph displaying vertical displacement over a horizontal distance. On the graphed profile we observed an anomaly due to flutes and the annual moraine on top of the drumlin which can be seen in the graph. It is also noticeable that the drumlin has a lee side and stoss side (Figure 7). The strike and dip of the 25 clasts were plotted in a rose diagram in order to compare their orientations (Figure 8). The rose diagram shows that a significant majority of the clasts are oriented in the northeast direction. The strong orientation axis had an eigenvalue of 0,8244 with a trend of 069,0 , a plunge of 00,7 , ±min of 4,8 and a ±max of 12,2. Group 3, who also conducted research on this drumlin today has similar results with a 0,96 eigenvalue and a trend of 69,0.

STATION 5
Sólheimajökull ice margin

The station 5 field site includes the area directly in front of the ice margin on the eastern side. The western side of the ice margin is inaccessible by foot because it is submerged in a newly formed glacial lagoon. Our focus was to analyze the annual moraines, landforms and try to interpret the past and present processes occurring during glacier retreat and advance at the ice margin.

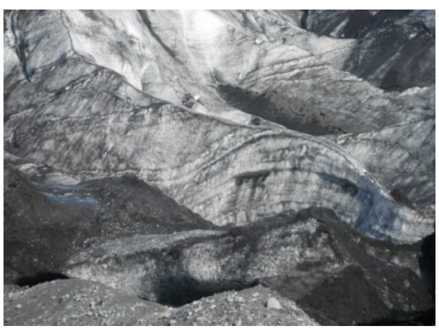


Figure 9. Active ice margin with thrusting, saw-tooth front and ash both supraglacial and englacial.

On the eastern side of the ice margin, a moraine can be seen that is partially covered in ice (Figure 9). A fine layer of sediment and ash can be seen on top of the ice as well as piles of sediment beneath the ice with a variety of clast sizes. One section under the ice appeared to have very rounded clasts. Walking parallel to the ice margin towards the eastern slope of the valley, two smaller moraines were seen that were nearly parallel to each other but almost perpendicular to the ice margin. A significant amount of dead ice could be seen under thick layers of sediment, up a fair amount of the eastern slope of the valley near the ice margin. The silty clay on much of the surface of the ice margin can be easily rolled into a ball. Some parts of the ground surface were dry and covered in larger sediments but once dug into, a moist, fine sediment layer was seen again. Large boulders were seen in the forefront of the ice margin with striations on them.

Other moraines could be seen on the accessible side of the eastern ice margin, spaced about 10 m from each other. Dead ice could also be seen in the glacial lagoon and some ice chunks were covered completely in ash or sediment in the lagoon. We dug into the thrusted sediment in front of the melting dead ice to get a profile view of the push moraine. We hoped to find some type of thrust structure in the sediment, but were unsuccessful. We found three different types of sediment in the profile. The sediment that was closest to the melting ice at the surface was wet, poorly sorted, medium grained, and contained very few clasts. This wet layer was sloped parallel to the ground surface slope and created by the thrusting of sediment. The second layer of sediment was beneath the wet layer. This layer was dry, poorly sorted, and coarser grained than the above layer. This layer also contained lenses of well-sorted, very cohesive, fine-grained clay. There was only one clast in the profile, which was sub angular. We observed that clasts tended to appear outside and on top of the thrusted sediment, but few clasts were typically within the sediment. We identified some fractures on the surface of the sediment behind the melting ice. These fractures were of interest because they were parallel to the melting ice margin.

Figure 10. Moraines from 2011 and 2012 at the ice margin, where the 2013 moraine is presently being developed. (Photo, courtesy of glacial geology group 3).

We can assume that the moraine forming directly at the ice margin that is still overlaid by some ice is the 2013 annual moraine. The ice pushed up against the sediment and tephra material until it moved above it during the winter months. As the summer approaches, the ice will retreat and melt displaying more clearly the 2013 moraine without the overlying ice. Further up the slope, a 2012 and 2011 moraine are recognizable from retreat over previous years (Figure 10).

The variety of clast sizes seem natural for a moraine structure. The rounded clasts are a good sign of glacial erosion on the clasts. We can deduce that the ash near the ice margin is from 1918 Katla eruption which is englacial, whereas Eyjafjallajokull eruption in 2010 produced ash that is supraglacial. It can be inferred that the two smaller parallel moraines observed come from a retreated tongue of ice that shows the saw-tooth pattern of the ice margin area, as opposed to the text book arc-shaped definition of a moraine. The saw-tooth shape of the ice at the ice margin can easily be seen as the cause of these moraines. A lateral moraine at the far eastern side still contains thick ice within it.

At the western side of the ice margin, a high, large structure exists due to insulation of a thick ash layer (Figure 11). When rain washes ash into depressions, 'reverse' structures such as ash cones on the glacier surface or thick insulated sediment covering dead ice, can be created. This is the result of tephra thicker than ~ 5 cm insulating the ice, thus protecting areas from melt underneath.


Figure 11. Ash-covered, high structure on eastern side of ice margin, due to insulation by ash.

Retreat is occurring more rapidly in the glacial lake area direct in front of the glacier, and a slower rate of retreat on the eastern side where we worked. As the glacier retreats further into its basin at lower elevation, the lagoon will grow, facilitating a positive feedback system that will likely increase melt and retreat rate.

STATION 6

Sólheimajökull 1999 Jökulhlaup

Station 6 was located near the 1995 end moraine on the east side of the valley, where the 1999 jökulhlaup occurred. Our task was to describe the erosional and depositional features of the jökulhlaup, as well as the intensity of the flow. We observed a fairly deep and wide channel, which seemed to be the main conduit of the jökulhlaup (Figure 12). The channel had steep walls and had small boulders in the center of the channel and fine sediment composing the walls. There were also smaller cobbles and boulders within the fine sediment. As we walked up the channel valley in a northerly direction, the boulders in the center were larger. There was no grading of the clasts, they ranged from well-rounded to angular.

Figure 12. Jökulhlaup conduit.

We attempted to measure the volume of sediment removed from the jökulhlaup conduit. First, we separated the conduit into two halves by length, 90 m and 72 m. In the 90 m section, we measured the length from bank to bank and also the length from the top edge down to the center of the conduit at four equally spaced locations along the conduit (Figure 13). The depth was difficult to estimate using only a measuring tape so we used Pythagrius' theorem. The hypotenuse of the triangle was the distance from one of the banks to the center of the conduit and one base of the triangle was half the length of the conduit. Once the depth was calculated for each of the four locations they were averaged together to equal about 7,5 m high. The average width of the conduit was 30.5 m using measurements from all four locations. We then treated the conduit as half of an ellipse. The area of an ellipse can be determined by the length of its two axis' (a & b) multiplied by π. The conduit is the shape of half of the ellipse, which equals 57,2m². This area is then multiplied by the length of the entire conduit area that we dissected, 90 m. The result is a volume of roughly 16000 m³ of sediment removed in the farther, southern section of the conduit. The same process was done for the second, more northerly half of the conduit resulting in a volume of roughly 15000 m³. Adding these two volumes together gives a total volume displaced of approximately 31000 m³. A summary of calculations:

Area of V_1:	$ab\pi = (15{,}25m)(7{,}5m)\pi = 359{,}3\ m^2$
Conduit is ½ oval:	$359{,}3\ m^2/2 = 179{,}7\ m^2$
V_1 = (Area)(90 m):	$(179{,}7)(90m) = 16169.5\ m^3$
Area of V_2:	$ab\pi = (13{,}5m)(10m)\pi = 424{,}12\ m^2$
Conduit ½ oval:	$424{,}12/2 = 212\ m^2$
V_2 = (Area)(72 m):	$15268\ m^3$

Conduit Total Volume estimate:

$$V_1 + V_2 = 16169{,}5 + 15268 = 31437{,}4\ m^3$$

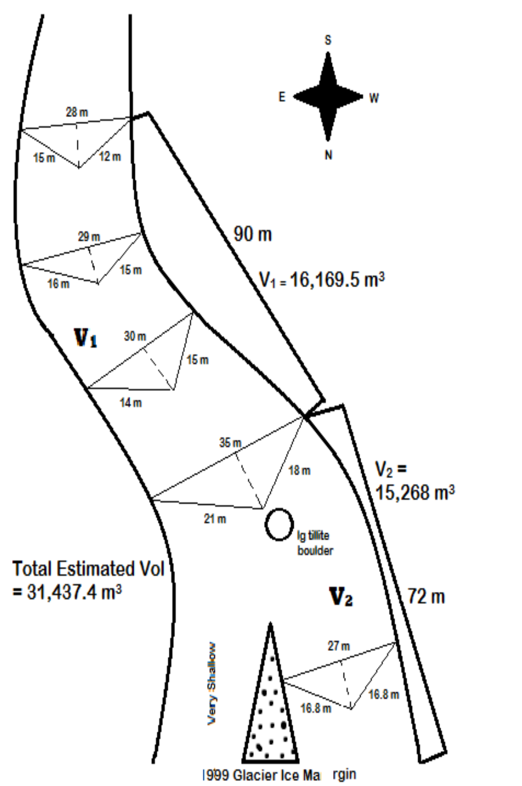


Figure 13. Conduit measurements and calculations.

This is a very rough estimate but gives us a good idea of the immense size and intensity of the jökulhlaup. Scientists have estimated the 1999 jökulhlaup to have a peak discharge rateof 3000 m3/s, as pointed out by our professor, Ólafur Ingólfsson, during the field trip. Although significant, is relatively small compared to previous jökulhlaups. The Sólheimasandur was built up by 8 large jökulhlaups during the last 4000 years with estimated discharge rates varying from 10 000 m^3/s and 100 000 m^3/s (Bjarki, 2011).

Figure 14. Leaving the south-end of jokulhaup conduit.

The jökulhlaup conduit ended when it dispersed into a braided stream system that proceeded the 1999 glacier margin. This stream valley is still an active braided glacial river system. The entire length of the jökulhlaup conduit was around 200 meters, and is narrower than the braided stream valley. At the boundary between the jökulhlaup conduit and the broader braided stream valley there was an increase in the size of clasts. This increase in clast size was contained to the boundary region. In this broad jökulhlaup valley the larger clasts deposited are located at the margins of the stream valley. The finer grained material was located closer to the center of the stream valley. There were many kettle holes in the braided stream valley, indicating chunks of ice travelled in the jokulhaup, settled and melted. In the braided stream valley there were many elongated deposited of sorted fine grained material that were surrounded by sorted coarser grained cobbles and boulders.

Figure 15. Kettle hole.

It was also observed that there was another jökulhlaup conduit located on the west side of the glacier. This conduit also terminated in the braided stream valley. Evidence of erosion from the jökulhlaup was seen from the steepness of the braided stream valley banks. Ripples were preserved in a rock (Figure 16), and possibly in the sediment. In the elongated section of sorted fine-grained material there are structures appearing to be lunate shaped ripples. Coarser pebbles were at the crest of the ripples and fine-grained sediments at the base. The distance between the ripples was around 30 cm, height of ripples are around 0,5–1 cm, and the width of the ripples about 15 cm.

Figure 16. Rippled rock.

We observed rocks, with indication of fractures associated from contact. As the boulders leave the conduit channel they arrive in a larger system that implies a lesser transport capacity, therefore, a deposit of larger boulders. There are larger boulders in the center of the valley because the jökulhlaup derived from conduits on each side of the valley and met in the center region where its energy decreased. This led to the dropping out of coarse and large material. Kettle holes are likely associated with ice deposits transported by the jökulhlaup. Since jökulhlaups have such high flow regime and are turbulent, it is likely the ripples are associated with dried and braided stream beds.

CONCLUSION

The dynamic nature of glaciers is clearly seen in the numerous landforms in the forefield of the Sólheimajökull glacier. Signs of glacial advancement can be seen in the Little Ice Age moraine as well as the 1995 moraine as Schomaker observed and interpreted. Evidence of push and dump moraines are seen within the internal structure of the moraines. Drumlin fabric analysis supports the hypothesis of clast orientation within the drumlin. The current ice margin has a saw-tooth pattern, which supports the imperfect structure of the annual moraines in the forefield. Massive boulders and carved out conduits are clear evidence of the 1999 jökulhlaup and display perfectly the features left behind and erased by such a flood. The features in the land are able to support the recorded history of the glacier as well as lead to interpretation about the unrecorded history of the outlet glacier.

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