Seminar series nr 213

Jökulhlaups: Their Associated Landforms and Landscape Impacts

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2011
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2011

Bachelor Degree Thesis in Physical Geography and Ecosystems Analysis, Department of Earth and Ecosystem Sciences

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Abstract: Glacial outburst floods also known as jökulhlaups are important features connected with glaciers globally. They may induce catastrophic floods as well as new landforms. This review describes and synthesizes jökulhlaup trigger mechanisms as well as associated landforms and landscape impacts of jökulhlaups with a special focus on Skeiðarársandur, south Iceland, and the 1996 jökulhlaup. Important sources of water for jökulhlaups are rapid melting of glacier ice, heavy rainfall, and most importantly the release of stored water from glacial lakes. The release of water may be due to three main initiating processes; overspilling, failure of the dam or changes in the hydraulic pressure. Some scholars divide them into further categories depending on their drainage mechanism.

It is quite hard to draw a strict line between what should be classified as only jökulhlaup induced landforms and what should not. There is one landform that is mentioned together with jökulhlaups more than any other and this is the sandur or the glacial outwash plain.

An abnormally large fissure eruption in conjunction with storage of melt water that exceeded the usual threshold for drainage from the lake Grímsvötn made the 1996 jökulhlaup at Skeiðarársandur to an unusually large event.

Keywords: Physical Geography, Geomorphology, Jökulhlaup, Sandur, Skeiðarársandur

Jökulhlaups: deras associerade landformer och inverkan på landskapet

Martin Bernhardson

Sammanfattning: Denna kandidatuppsats är en litteraturstudie som behandlar jökulhlaups och deras tillhörande landformer samt deras inverkan på landskapet. Jökulhlaup är den isländska termen för störtfloder från glaciärer och används internationellt för att beskriva detta fenomen.

Vattnet som skapar dessa störtfloder kan ha många olika ursprung, såsom kraftig nederbörd, snabb avsmältning av glaciäris, tömning av en glacial sjö etc.

Glaciala sjöar anses ha tre huvudsakliga dräneringmekanismer; att dammen som håller kvar vattnet i sjön brister, att sjön svämmar över eller att vattnet dräneras på grund av tryckskillnader mellan sjön och dess omgivning.

Det är svårt att dra en strikt linje mellan vad som ska klassas som landformer som är skapade endast av jökulhlaups eller som också har formats av en glaciärs framryckningar och reträtter. Dock finns det en landform som förknippas med jökulhlaup mer än någon annan och detta är den så kallade sandurslätten. Sandur är den isländska termen för de slätter som är skapade av utspolat material från en glaciär. Ordet sandur har samma ursprung som svenskans sand och det beskriver dessa slätters utseende förhållandevis korrekt.

I början av november 1996 upplevde sandurslätten Skeiðarársandur i södra Island ett av de största jökulhlaupen under 1900-talet. Smältvattnet som skapade jökuhlaupet dränerades från den glaciala sjön Grímsvötn som är belägen under Vatnajökull, Europas största glaciär. Anledningen till att detta jökulhlaup var så stort som det var anses bero på att det vulkanutbrott som smälte vattnet som skapade jökulhlaupet var ovanligt kraftfullt, samt att mer smältvatten än vanligt samlades i sjön Grímsvötn innan denne tömdes på vatten.

Nyckelord: Naturgeografi, Geomorfologi, Jökulhlaup, Sandur, Skeiðarársandur

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Cover picture: Bernhardson 2010

1. Introduction

Jökulhlaup is the Icelandic term for glacial outburst floods, but since this phenomenon exists in many other glaciated areas around the world they are also known as débâcles in some parts of Europe, chhu-gyümha in Nepal and aluviones in South America (Tweed and Russell, 1999, Vuichard and Zimmermann, 1987). The word jökull is the Icelandic term for glacier, while hlaup in this case might be translated with a run or race. Not everyone have the same criteria for what classifies as a jökulhlaup. Most scientists count all outburst floods with a glacial source as a jökulhlaup, while others only apply it for outburst floods generated underneath a glacier, i.e. sub-glacially (Magilligan et al., 2002). This thesis will use the first of these two definitions.

During the Earth's history jökulhlaups have been responsible for some of the largest freshwater flows in terrestrial environments (Gomez et al., 2000). A good example of this is the drainage of Lake Missoula, north-western USA, during the late Pleistocene, (~12 000 years BP), (Summerfield, 1991). Lake Missoula was a proglacial lake (lake situated in front of a glacier) and at its maximum was thought to have contained 2000 km^3 of water. The water was drained during repeated failures of the lake's dam. The peak discharge during these jökulhlaups is thought to have been close to $21.3*10^6$ m^3s^{-1}, which is nearly as much as 20 times the mean discharge of all the rivers of the world. The jökulhlaups of today are of a much smaller magnitude, but still they can cause damage to infrastructure as well as the loss of human lives (Björnsson, 2003, Holden, 2008, Roberts et al., 2000). In Iceland it is not uncommon that parts of the road network is destroyed by jökulhlaups, especially in southern Iceland (Holden, 2008, Thordarson and Hoskuldsson, 2002). Jökulhlaups are also strong geomorphological phenomena that create and influence landforms by erosion and deposition. They even have the power to erode large canyons. It is therefore important to understand the processes controlling jökulhlaups to be able to predict and minimize damage to communities in jökulhlaup-prone areas. Also, with the increasingly warmer climate the last centuries, the frequency and magnitude of jökulhlaups in a lot of the world's jökulhlaup-prone areas have changed (Evans and Clague, 1994). This means that areas previously spared from catastrophic floods might now be susceptible to jökulhlaups. Therefore it is important to understand what conditions that are necessary to trigger a jökulhlaup. This thesis has deliberately tried to avoid describing the sedimentology of associated landforms as well as the physics of glaciers in too much detail since they are large topics in themselves and might only confuse a reader without sufficient prior knowledge of the subjects.

This thesis is a review and the aim is to describe and synthesize jökulhlaup trigger mechanisms as well as associated landforms and landscape impacts of jökulhlaups with a special focus on Skeiðarársandur, southern Iceland, and the 1996 jökulhlaup.

This thesis will also try to answer the following questions:

- Are the effects of jökulhlaups short-term or long-term?
- Are jökulhlaups regular or sporadic events?
- Does the water from jökulhlaups move from pre-existing outlets and waterways, or do they form new ones?
- Are there any landforms that are unique for jökulhlaup-prone areas, or are they also present at other proglacial sites and outwash plains?
- What factors made the 1996 jökulhlaup at Skeiðarársandur to an unusually large event?

2. Sources of jökulhlaups

There are many different sources of jökulhlaups. Some of them might be due to rapid melting of glacier ice and/or heavy rainfall, but the most common one is the release of stored water from a proglacial/ice-dammed lake or subglacial lake. (Tweed and Russell, 1999) Englacial (in the glacier) and supraglacial (on the glacier) lakes may also cause jökulhlaups (Benn and Evans, 1998). Of course there is rarely only one process at work and they usually interact with each other during a jökulhlaup event. The mechanisms causing the glacial outburst floods are dependent on the position of the water body as well as the kind of physical barrier holding the water back. Benn and Evans (1998) divide these physical barriers into subglacial lakes and ponds, supraglacial and englacial lakes, ice-dammed lakes and lastly proglacial lakes.

2.1. Subglacial lakes and ponds

Subglacial water bodies are stored under a glacier and can range in size from a few millimeters in diameter up to thousands of square kilometers (Benn and Evans, 1998). One of the most effective processes to form subglacial lakes is the presence of volcanic activity and geothermal heating beneath a glacier. This is common in Iceland and Vatnajökull, the largest glacier in Europe, is affected by these processes (Holden, 2008, Thordarson and Hoskuldsson, 2002).

Water under glaciers will flow towards areas of low pressure and/or low elevation (Benn and Evans, 1998). These areas generally form during two conditions. The first condition is when there is a depression in the rock/sediments under the glacier where water can be stored. The second condition where subglacial lakes may form is when the underlying rock/sediments are flat while the glacier contains a cavity surrounded by thicker ice. The lower pressure inside the cavity will cause the water to move towards the surface bed under the cavity and a so called water cupola may form (think of it as an inverted bowl).

2.2. Supraglacial and englacial lakes

In many cases supraglacial and englacial lakes owe their existence to surface melt water (Benn and Evans, 1998). They usually form during the ablation season when melt water is abundant and refreezes later in the year or are drained away through channels and crevasses in the glacier. Supraglacial and englacial lakes are rather shallow and short-lived in warm ice glaciers (glaciers that are close to the melting point at their bases, also known as temperate glaciers), while they tend to be larger and more prevailing in cold ice glaciers (glaciers that are below the melting point, also known as polar glaciers) (Tweed and Russell, 1999).

There have been many suggestions through the years of what mechanics are behind the formation of supraglacial and englacial lakes. Areas full of crevasses in the glacier ice could be responsible for the formation of supraglacial and englacial lakes (Blachut and Ballantyne, 1976). Glacial sinkholes, also called moulins, tend to form when surface water slowly percolates through the small pores between individual ice crystals to such an extent that they eventually form tunnels (Summerfield, 1991). Moulins usually form in pre-existing cavities and cracks in the ice and may serve as sources for englacial lakes. Variations in the topography underlying the glacier might be able to cause subsidence at the glacier surface that would also allow supraglacial lakes to form (Blachut and Ballantyne, 1976).

Sediments transported by aeolian or gravitational processes and subsequently deposited on a glacier may decrease the surface albedo of the glacier surface which will melt the ice and supraglacial lakes may form (Seppälä, 1973). The melt water caused by the changes in surface albedo will in itself have a lower albedo than the surrounding ice which may cause the lake to grow even further by melting the surrounding ice. This process is probably very active in Iceland where the glaciers can experience large depositions of tephra after a volcanic eruption (Thordarson and Hoskuldsson, 2002).

Subglacial volcanic eruptions can melt through the ice without the eruption breaking through to the surface (Thordarson and Hoskuldsson, 2002). This may cause subsidence of the ice at the glacier’s surface and forms an ice cauldron which can store melt water supraglacially (Benn and Evans, 1998).

2.3. Ice-dammed lakes

Ice-dammed lakes are as simple as they sound; they are lakes with barriers of ice. Tweed and Russell (1999) mentioned a lot of different classification models of ice-dammed lakes, but it seems like most of them have in common that they make a distinction between lakes dammed by glaciers in main valleys and lakes dammed by glaciers in tributary valleys. An advancing glacier from a main valley can dam up the stream flow of a tributary valley (or vice versa) and create an ice-dammed lake.

2.4. Proglacial lakes

Proglacial lakes, just as the name implies, are situated in front of a glacier (Benn and Evans, 1998). Proglacial lakes have a lot in common with ice-dammed lakes in how they work and behave, where the main difference is that the barrier that keeps the water in check in a proglacial lake is not made of ice or snow. End moraines are good examples of barriers contributing to the formation of proglacial lakes. Not all scientists make this distinction however, some classify the proglacial lakes together with the ice-dammed lakes (Tweed and Russell, 1999). Most of the present day proglacial lakes have formed due to the glacier extent during the Little Ice Age (Evans and Clague, 1994). A good example of a proglacial lake can be seen in figure 1.

Figure 1. Proglacial lake in front of Skaftafellsjökull, Iceland (Bernhardson, 2010).

3. Hydrology

3.1. Jökulhlaup trigger mechanisms

There are three main ways in which a jökulhlaup can be initiated; by overspilling, by failure of the dam or by changes in the hydraulic pressure (Benn and Evans, 1998). It is especially the latter two that will cause the biggest floods since the conduits for the water can expand through thermal and mechanical enlargement. Tweed and Russell (1999) suggested a more detailed classification of the trigger mechanisms that may lead to the initiation of a jökulhlaup:

- Seismic activity
- Subglacial volcanic activity
- Subaerial breach-widening
- Subglacial cavity formation
- Syphoning
- Ice-dam flotation
- Overspill
- The Glen mechanism

3.1.1. Seismic activity

Seismic activity has been suggested by Tryggvason (1960) as a plausible trigger mechanism for jökulhlaups. It sounds quite likely that the forces released during an earthquake would be able to fracture glacier ice. However, Tweed and Russell (1999) highlight the fact that they were unable to find any published material that clearly proved that seismic activity has triggered a jökulhlaup, at least in the form of an earthquake.

3.1.2. Subglacial volcanic activity

As mentioned earlier in the thesis; subglacial volcanic activity can create huge amounts of melt water in a relatively short amount of time (Gudmundsson et al., 1997, Holden, 2008, Thordarson and Hoskuldsson, 2002). However, this might not have to lead to a jökulhlaup (Tweed and Russell, 1999). It is often secondary mechanisms that have been initiated by the volcanic activity that triggers a jökulhlaup. Powerful eruptions might cause such a big stress on the ice-dam that it might fail much in the same way as due to seismic activity. The large amounts of melt water due to volcanic activity can cause thermal enlargement of tunnels that will in turn trigger positive feedbacks by mechanical enlargement. Another common trigger mechanism due to volcanically melted water is flotation (see below).

3.1.3. Subaerial breach-widening

Earlier research has suggested that many glacial outburst floods drain their water through a single or a small number of channels once a certain threshold has been reached (Walder and Costa, 1996). Although this is often correct, it is far from every jökulhlaup that behave this way. Some may drain through subaerial (at the surface) breach-widening. This may be either due to breaching of the ice dam itself or breaching at the contact surface between a glacier and a rock wall. After examining outburst floods from all over the world, Walder and Costa (1996) noticed that most of the sudden break outburst floods were due to the failure of ice-dammed lakes that formed after a glacier had advanced into a main valley from a side valley, or from a side valley into an existing lake or fjord, cutting off the water's drainage paths. They therefore drew the conclusion that the lake drainage is affected by the processes that have formed the lake. Since the ice at the front of the glacier blocking the main valley is at the edge of the ablation zone it is usually also the thinnest. Also, the ice at the edge of the glacier can often get fractured during its advance. Those two characteristics make the zone between the main valley rock wall and the terminus of the glacier a probable area for drainage. The widening of the subaerial breach is most likely due to mechanical melting caused by ice and water interaction. Floods from subaerial breaches have on average higher peak discharges than floods from glaciers with an equal lake size that drain trough a subglacial channel (compare hydrograph a and b in figure 2, page 15).

3.1.4. Subglacial cavity formation

When a glacier moves over obstacles the pressure will increase and this can lead to melting of the ice at the glacier bed, a process called regelation, which facilitates the glacier's movement over the obstacle (Holden, 2008). If the velocity of the glacier is high enough it may prevent the water from refreezing and a subglacial cavity may form (Liestøl, 1956). Once a flow is present the cavities may expand in size. This may keep a subglacial drainage system active that could support the formation of a drainage tunnel that in turn could lead to drainage of an ice-dammed lake and a subsequent jökulhlaup (Knight and Tweed, 1991).

3.1.5. Syphoning

A glacier-impounded lake might drain into a glacier's internal drainage system (Tweed and Russell, 1999). This drainage is due to pressure differences between the water in the lake and the water in the glacier's drainage network. This often shows a seasonal pattern which is most likely due to the availability of water in the glacier's hydrological system during different parts of the year. This leakage of water through small cavities is known as syphoning. Even though syphoning does not necessarily cause jökulhlaups it is worth mentioning it since it can interoperate with other drainage mechanisms.

3.1.6. Ice-dam flotation

There are observations suggesting that when the water levels in the ice-dammed lakes at the outlet glaciers (parts of a larger glacier that extends into valleys) of Vatnajökull exceeds more than 90 per cent of the height of the barriers of the lakes the water can lift the barriers and drain underneath them (Thorarinsson, 1953). This drainage process is usually termed flotation and is due to the density differences between water and ice (Knight and Russell, 1993, Walder and Costa, 1996). This drainage process has been observed as early as 1929, when the ice-dam at Leynifoss near Langjökull, Iceland, lifted and water drained underneath the dam (Ahlmann and Thorarinsson, 1939). Adhesion between the ice and the surface bed is thought to inhibit this trigger mechanism. Knight and Russell (1993) suggested that if the lake level is constant and the ice dam is thinning due to ablation, flotation will occur when the ice dam has decreased to a thickness equivalent to 111 per cent of the lake's depth. The reason for this does not seem to be fully understood. However, this percentage based relationships do not always apply to all outburst events, suggesting that other processes might be at work (Walder and Costa, 1996). According to Nye (1976) flotation is mostly an ice-dammed and subglacial trigger mechanism for jökulhlaups. Knight and Russell (1993) suggested that flotation might cease to be the initiating drainage mechanism if there are oscillations in the glacier extent. This indicates that the jökulhlaup trigger mechanism for a particular ice-dammed lake might change with time.

3.1.7. Overspill

The trigger mechanism for outburst floods that is the easiest to grasp is that of overspilling (Tweed and Russell, 1999). When the lake gets so full that it rises above the height of the barrier keeping it in place it will drain, like when you pour too much water into a glass. Glacial outburst floods caused by overspilling are thought to be mainly polar glacier phenomena. Lakes dammed by polar glacier ice are thought to be more robust than the ones dammed by temperate glaciers and are therefore less likely to drain by other mechanisms. Overspilling has however been observed at temperate glaciers as well (Howarth, 1968).

3.1.8. The Glen mechanism

The theory of the Glen mechanism suggests that when an ice-dammed lake is 150 to 200 m deep the horizontal stress component then exceeds the vertical compressive stress component and the water starts to cut a hole through the ice in the dam (Glen, 1954). According to Tweed and Russell (1999) there is research that questions the Glen mechanism theory, both when it comes to the minimum threshold of water depth as well as if you can assume that this process is always at work if the criteria has been fulfilled.

Even if it might sound like all glaciers and ice-dammed lakes are severe hazards for humans, this is not the case. Not all ice-dammed lakes need to be drained catastrophically. Clement (1984) made a case study of an ice-dammed lake situated at the outlet glacier of Nordbogletscher, Greenland that suggests that this lake usually drains slowly and jökulhlaup events are rare. In fact, these kinds of lakes can be good sources for electricity through hydropower. Of course it is important to map the drainage pattern of these kinds of lakes before any construction projects are initiated. Non-catastrophic drained ice-dammed lakes have not been as thoroughly described as the jökulhlaup-prone ones, maybe explaining their more anonymous nature in research papers.

3.2. Glacial drainage routes

Waller et al. (2001) commented that earlier research, i.e. (Nye, 1976), made the assumption that water drains through single, subglacial conduits during jökulhlaup events. This has however been challenged by later research that describes observations of both supraglacial and englacial drainage routes as well (Roberts et al., 2001, Roberts et al., 2000, Russell et al., 2006, Waller et al., 2001). Supraglacial drainage can in many cases be due to the inability of the existing subglacial and englacial conduits to drain the water during the jökulhlaup (Waller et al., 2001). This will increase the water pressure to such an extent that it may actually fracture the ice and allow supraglacial and englacial drainage. Stereo-paired aerial photographs taken during the 1996 eruption at Grímsvötn suggest a vertical displacement of the glacier surface of a magnitude of 2-5 m (Björnsson, 1997).

Roberts et al. (2000) noticed after examining jökulhlaups from Skeiðarárjökull and Sólheimajökull, Iceland, that most of the supraglacial drainage routes were only active during a short timescale, minutes to hours, indicating that they may react to large, short-term increases in pressure differences. This indicates that other drainage routes probably are more dominant during a jökulhlaup event. They also suggested that when the ice fractured at shallow thicknesses there usually was a noticeable vertical displacement of the surface ice while this vertical displacement was not as evident if the fracture had a source deeper down in the ice.

Studies of the 1996 jökulhlaup at Skeiðarársandur suggest that the supraglacial drainage was only active in the beginning of the jökulhlaup, probably due to that the subglacial drainage after a while had its conduits expanded by thermal and mechanical enlargement (Waller et al., 2001). It is therefore not uncommon for jökulhlaups to change their drainage routes during a single jökulhlaup event (Tweed and Russell, 1999).

Roberts et al. (2001) claimed to have evidence of englacial and supraglacial deposition of sediments after the 1996 jökulhlaup. This suggests that sediment-rich water was transported from the base of the glacier upwards into the glacier and even reached the surface. They found fine-grained sediments as well as boulders deposited together; indicating that the englacial melt water had the ability to transport sediments of varying sizes. They also found frozen englacial flood deposits, suggesting that the englacial water flow might have been supercooled. The supercooling was probably due to an increase in floodwater elevation which in turn lead to a drop in water pressure as well as an increase in pressure melting point. Roberts et al. (2001) pointed out that little research has been carried out to describe these phenomena.

After the stored water has been more or less drained the pressure from the ice or till of the barrier seals the conduit and water can start to accumulate again (Tweed and Russell, 1999). In some cases the dam has decreased in thickness and size to such an extent that it will be permanently open and thus prohibit the accumulation of water that may cause a new jökulhlaup. The threshold for ice-dam thickness for which a conduit will remain open is thought to be around 50 m, if it is smaller than that it will not close (Liestøl, 1956).

Jóhannesson (2002), after studying the 1996 jökulhlaup at Skeiðarársandur, claimed that jökulhlaups that have an almost linear rise in their hydrographs cannot easily be explained by earlier theories, i.e. Nye (1976). Jóhannesson (2002) proposed that the main flow of the jökulhlaup was preceded by a subglacial pressure wave that formed a drainage path along the bed of the glacier that facilitated the rest of the drainage and allowed it to reach its peak discharge earlier than expected, as can be seen in figure 2 (b).

The frequency of surging events may influence the magnitude of jökulhlaups at a specific glacier (Björnsson, 1998). During a surge the water from the glacier is drained through a network of passageways of shifting sizes. A drainage system of this kind requires a high pressure to drain water through the system. This pressure facilitates sliding over large areas due to the lubricating effect of increased pressure at the glacier bed. During a non-surging event the water is transported through a series of tunnels that tend to grow by thermal and mechanical enlargement. Due to the differences in drainage systems a surging phase inhibits to some degree catastrophic drainage, at least for the studied site at Skeiðarársandur.

3.3. Temporal variability

Jökulhlaups show both a regular and irregular pattern. Many jökulhlaup-prone areas have a seasonal variation in jökulhlaup frequency; where the late summer season is the most active one because of the high amount of melt water during that time whereas winter is the least active one (Summerfield, 1991). However, this does not mean that jökulhlaups cannot occur during winter (Thordarson and Hoskuldsson, 2002). Off season jökulhlaups may be due to seismic, geothermal or volcanic activity which may either destroy existing dams by fracturing them or produce large amounts of melt water in a very short time. There is usually a very short prior warning to jökulhlaups from these sources. Sometimes it is possible to measure seismic activity that reflects the inflation of magma in a volcano a couple of days before an eruption, making it possible to warn people that a jökuhlaup might be imminent if enough melt water is produced.

Many jökulhlaups are strongly linked to the oscillations of glacier extent (Evans and Clague, 1994). During a glacier advance new ice-dammed lakes may form. When the glacier then retreats the dams will be weakened by the retreat as well as downwasting (thinning of a glacier by melting) to such an extent that jökulhlaups will be more frequent until the glacier has retreated so far that it no longer impounds the water and the ice-dammed lakes will disappear or the glacier will once again advance and strengthen the dams.

The average hydrograph from a jökulhlaup is quite different from other stream flow hydrographs (Benn and Evans, 1998). During an intense rainfall event an ordinary subaerial stream flow hydrograph shows a rapid increase in runoff which will diminish progressively after the peak discharge has been reached. Jökulhlaups on the other hand show a rapid increase in runoff from the initiation of the outburst to the peak discharge, after that the runoff will decrease rapidly as well. This is due to the fact that the water reservoir, the glacial lake, has emptied most of or all of its content. This might also be due to the fact that the main conduits have closed due to the pressure from the ice when the discharge is too weak to keep the conduit open (Tweed and Russell, 1999). The explanation for the rapid increase in runoff from jökulhlaups is thought to be mostly due to the thermal and mechanical enlargement of drainage routes. However, even jökulhlaups show differences in their hydrograph pattern (Jóhannesson, 2002, Walder and Costa, 1996). The jökulhlaup hydrographs can mainly be divided into two different groups; the ones with primarily tunnel drainage, and the ones with breach drainage. The hydrograph for the tunnel drained jökulhlaups look like the ones already described (see figure 2 a) with a slightly exponential rise. The breach drained ones however, have an even steeper increase of their runoff to the peak discharge point, almost linearly, like the hydrograph (b) in figure 2.

Hydrographs from both kinds of jökulhlaups may display an irregular pattern (Maizels, 1997). During a jökulhlaup the conduits from the ice-dammed lake can be blocked by ice and sediments that will temporarily decrease the discharge until the pressure rises to a sufficient level to remove the material that is plugging the conduit.

There are indications that due to the global warming during the last centuries the majority of the unstable proglacial lakes in the world have already drained and will not refill again (Evans and Clague, 1994). This means that failures of proglacial lakes will continue to decrease in a future with a warmer climate. This pattern is not as clear for ice-dammed lake jökulhlaups since they are more sensitive to short-term climate fluctuations. Ice-dammed lakes have an easier time

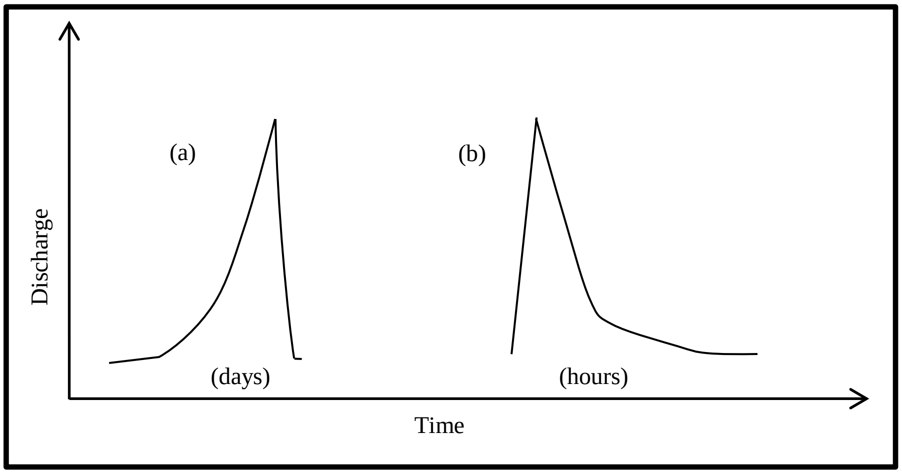

Figure 2. Hydrograph of an exponential rising jökulhlaup (a) and a linear rising jökulhlaup (b). Modified from Roberts (2005).

to reform in new areas with a warmer or colder climate than proglacial lakes, thus suggesting that jökulhlaup hazards from ice-dammed lakes will not decrease as quickly with a warmer climate as the ones from proglacial lakes.

As mentioned earlier in the text the magnitudes of the present jökulhlaups are nothing compared to the ones from earlier geological periods (Summerfield, 1991). Which is not so surprising since the amount of glacially stored and glacially dammed water is far less today than during a glaciation.

3.4. Prediction of jökulhlaups

Jökulhlaups can be divided into two main groups when you try to find warning signals that an outburst flood is imminent, namely volcanically induced jökulhlaups and non-volcanically induced jökulhlaups (Tweed and Russell, 1999). Since many jökulhlaups on Iceland are due to volcanic activity they are often preceded by seismic activity due to the movement of magma (Gudmundsson et al., 1997). Also, during movement of a glacier so called ice-quakes may be registered by a seismograph (Björnsson, 2003). In other words, seismographic measurements may act as a short-term indicator of jökulhlaups.

The smell of sulphur has been noticed in the rivers from Skeiðarárjökull prior to a jökulhlaup event (Ahlmann and Thorarinsson, 1939). This suggests that changes to the chemical composition of the melt water from jökulhlaup-prone glaciers might be a warning signal of volcanically induced jökulhlaups. This is further supported by Lawler et al. (1996) who examined the relationship between chemical composition of melt water from Jökulsá á Sólheimasandi, southern Iceland, and subglacial volcanic activity. They found that seismic activity and subsequent changes in electrical conductivity of the water in Jökulsá á Sólheimasandi could precede a flooding event.

Some glacial rivers in Iceland have experienced increased concentrations of sediments just before a jökulhlaup (Ahlmann and Thorarinsson, 1939). After examining jökulhlaups from Strandline Lake, Alaska, U.S.A, Sturm and Benson (1985) found that some supraglacial pools of water that were situated in front of the ice dam that barricades Strandline Lake had a tendency to fill up prior to a jökulhlaup event. They also found that the ice dam calved when a jökulhlaup was imminent and highlighted that these were phenomena that were easily identified through aerial and satellite images. Even though these were good short-term indicators for jökulhlaups from Strandline Lake, Sturm and Benson (1985) stressed that to be able to make long-term predictions an understanding of the processes that controls the refilling of Strandline Lake is required. This is something that can be applied to other jökulhlaup-prone lakes as well.

As can be noticed in the text above different lakes may be controlled by different processes and it is therefore hard to make a universal model of the lakes’ refilling and drainage.

To be able to predict jökulhlaups some scholars have tried to compare different jökulhlaups models with actual or hypothetical jökulhlaup events. Alho and Aaltonen (2008) compared a 1D hydraulic model to a 2D hydraulic model to see how well the 1D hydraulic model would follow the 2D one for a hypothetical hydrograph for a jökulhlaup at the

Möðrudalur floodplain, north-eastern Iceland. The 2D model is thought to be superior to the 1D one, however it is also more time consuming. The computing time for the 1D model took only a couple of minutes, while the 2D model took a little bit more than one day in general. They found that the 1D model deviated from the 2D one, but was thought to be accurate enough to simulate jökulhlaups with a not too advanced drainage pattern.

Werder and Funk (2009) had the opportunity in 2006 to monitor the water drainage during a jökulhlaup from the lake Gornersee at the Gornergletscher glacier, Switzerland, with the help of dye tracing and equipment to measure proglacial and lake discharge, lake temperature etc. Their aim was to compare the observational data to a jökulhlaup model to validate the accuracy of the model. They found that the model had difficulties with modelling accurate values for the flow speeds during different stages of the jökulhlaup, indicating that it lacked the ability to simulate the full complexity of the glacier’s drainage system.

4. Landforms in jökulhlaup-prone areas

It is quite hard to draw a strict line between what should be classified as only jökulhlaup induced landforms and what should not. Since most glaciers have retreated relatively large distances the last centuries jökulhlaups are now affecting areas that have been formed by glaciers (Evans and Clague, 1994). The outburst floods are now reforming previously glacier induced landforms, like terminal moraines. This review will therefore mention some of the landforms that might be affected by jökulhlaups, but not necessarily created by them. There is however one landform that is mentioned together with jökulhlaups more than any other, and that is the sandur (plur. sandar), or glacial outwash plain (Benn and Evans, 1998, Gomez et al., 2000, Magilligan et al., 2002, Russell et al., 2006, Summerfield, 1991, Thordarson and Hoskuldsson, 2002).

4.1. Sandur

Sandur is an Icelandic word that is used to describe glacial outwash plains consisting of glaciofluvial deposits created by braided rivers (Thordarson and Hoskuldsson, 2002). However, Gomez et al. (2000) suggested that glacial outwash plains mainly owe their stratigraphy (in this case the sequence of sediment layers) to jökulhlaup events. It hardly comes as a surprise that Iceland has a lot of sandar where the largest one is Skeiðarársandur, situated south of Vatnajökull.

The presence of fossil sandar in now deglaciated areas is a valuable tool to map the movement of the inland ice during the last glaciation (Krigström, 1962). One of the countries where you can see remnants of old sandar is Sweden, where there exist fossil glaciofluvial deposits mainly in the form of valley sandar. Benn and Evans (1998) claim that even though many sandar are prone to experience jökulhlaups this is not necessarily always the case and they can instead form by non-catastrophic river discharges.

4.1.1. Plain sandar and valley sandar

The sandar can be divided into two main groups depending on their spatial distribution, namely plain sandur and valley sandur (Krigström, 1962). The plain sandar are usually situated closer to the coast than the valley sandar, in many cases they actually make up the coastline. This is particularly visible in the south of Iceland where large areas consist of plain sandar (Thordarson and Hoskuldsson, 2002). The plain sandar usually have a few large melt water streams that form more and more braided patterns further away from the glacier terminus (Krigström, 1962). A good example of a plain sandur can be seen in figure 3. The valley sandar on the other hand usually have one main channel that divides into smaller, secondary channels further away from the glacier terminus. Fossil sandar of the plain type can be found in western Jutland, Denmark.

4.1.2. Sandur types

Maizels (1993) divides sandar into three different types, namely non-jökulhlaup sandar, limno-glacial jökulhlaup sandar and volcano-glacial jökulhlaup sandar. Since the non-jökuhlaup sandar do not experience jökulhlaups they are similar to braided river systems in their appearance and stratigraphy. The different types of sandar have different stratigraphies due to the different fluvial processes that affect them.

Maizels (1993, 1997) suggested that jökulhlaup-prone areas can be distinguished by their soil profile and grain size distribution from other areas affected by fluvial processes.

4.1.3. Sandur zones

Krigström (1962) suggested that a sandur can be divided into three main zones, he did however only give the zone closest to the glacier terminus a proper term, namely the proximal zone. Benn and Evans (1998) called the two remaining zones the intermediate zone and the distal zone and these are the terms that this thesis will use.

The proximal zone is characterized by deeply incised channels that often have a gently oscillating pattern (Krigström, 1962). These channels might be the continuation of the N-channels (channels cut into the bedrock underlying the glacier) from under the glacier. The

Figure 3. Plain sandur field with braided river. South Iceland (Bernhardson, 2010).

largest of the zones is the intermediate zone. The channels now become wider and shallower and start to show a more braided pattern to such an extent that it can be hard to separate the channels from one another. The channels in this zone show a fluctuating pattern with dry inactive channels that can be reactivated quite easily if there are changes in the river runoff. The distal zone is characterized by ill-defined, shallow channels that merge into a shallow bay capable of forming sheet flow during high river runoff, like a jökulhlaup (Benn and Evans, 1998, Krigström, 1962).

4.1.4. Soil properties

The distribution of grain size in sandar follow the normal fluvial pattern of coarser material close to the source of the river with decreasing grain sizes the further from the source the river is (Holden, 2008). However, sandar do not always have this well sorted pattern (Benn and Evans, 1998). This is thought to be because of the large fluctuations in the magnitude of the river discharge in the proglacial zones. There are big differences between the discharges in late autumn to those of early summer. Of course the presence of volcanic activity causes even larger fluctuations in the discharge rates (Thordarson and Hoskuldsson, 2002).

Because of the absence of cohesive sediments in large parts of a sandur and other factors contributing to the stability of the soil, like the absence of vegetation, the river banks are quite prone to erosion (Benn and Evans, 1998). The shifting landscape of the sandar is also noticeable in the formation and removal of bars in the rivers as well as the changing waterways of the channels (Krigström, 1962).

4.1.5. Water flow in sandar

Water channels in sandar are prone to make abrupt changes in their flow direction (Krigström, 1962). One explanation for this is the fact that there are a lot of dry inactive channels in a sandur field. When a channel overflows it may flow into a dry channel. Since the glaciofluvial deposits in a sandur usually have a low cohesion it is easily eroded and the water may cut its way through the barrier dividing the wet channel and the dry channel. This makes the water flow turn in its path and get a more curved appearance.

Water streams in sandar are usually similar to the ones that exist in other fluvial-influenced landscapes. Krigström (1962) suggested that one kind of bar formation in sandur areas is so common that it must be considered as something quite typical for these areas, although he never claimed that it is something unique for the sandar. The kind of bar formation in this case is the one that forms when two water channels join together. In the beginning the bar forms just in the junction between the two water channels (fig 4.1). With time, more and more material is deposited on the bar which grows out into the main water flow (fig. 4.2). The bar then channels the water towards the channel wall on the opposite side, causing erosion. The bar has a convex shape, causing the water flow from the affluent channel to divide into concentrated streams that cut through the bar in some places. This may actually cause the channel level to sink on a local scale and some parts of the bar may rise above the water surface. After this the

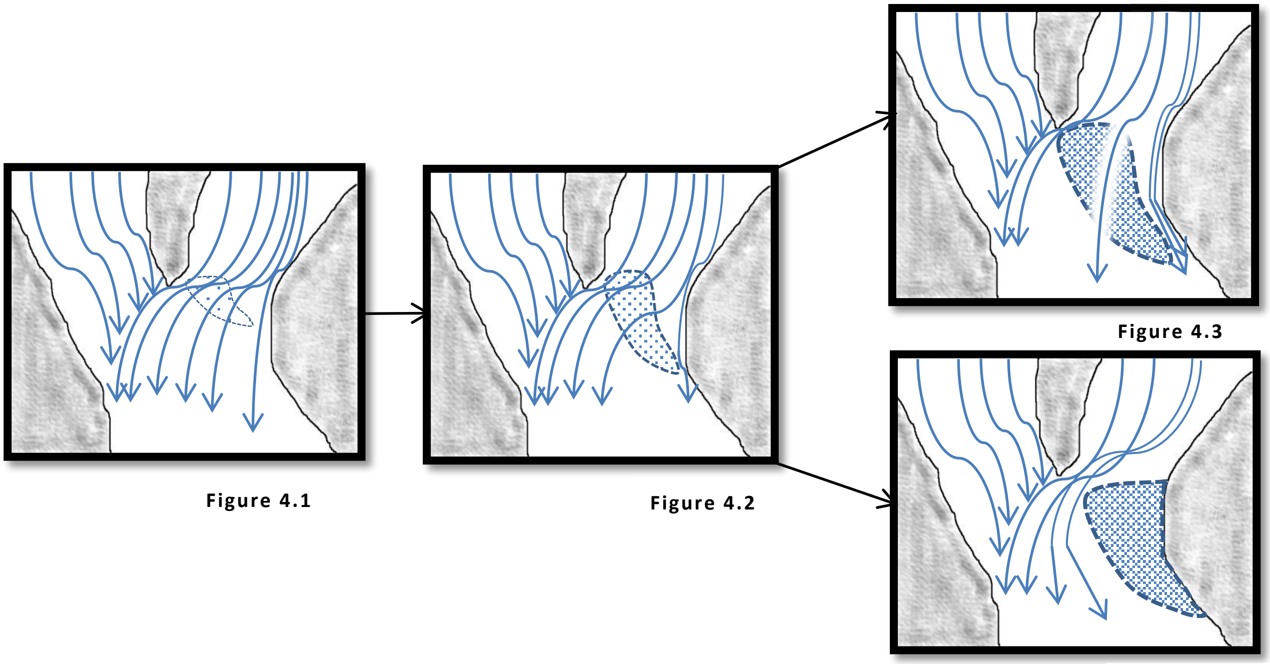

Figure 4.1

Figure 4.2

Figure 4.3

Figure 4.4

Figure 4. The different stages of the development of a river junction bar. Modified from Krigström (1962)

appearance of the river can take two main routes. If the water level stays the same the bar forms an island as can be seen in figure 4.3. If the water level does decrease the side of the bar that is leaning towards the channel bank of the affluent channel will grow slowly in size until it has completely grown together with the channel bank (fig. 4.4).

Because of the glaciofluvial and aeolian processes, most sandar are rather coarse-grained and there are usually only limited patches of vegetation, which makes the sandar even more vulnerable to erosion as stated earlier in the text. (Robinson et al., 2008).

4.1.6. Terrace formations

Sandar, just like any other landform affected by fluvial processes may form terraces (Allaby, 2008). Terrace levels often reflect different temporal stages of sandur development (Magilligan et al., 2002). It is not uncommon that old sandar may more or less be completely made up of terraces (Benn and Evans, 1998). Because of the discontinuous pattern of river discharge as well as sediment transport for aggradation (increase in land elevation due to deposition of sediments) the sandur rivers can fluctuate between a depositional and an erosional phase. After examining a four- mile tract of the Donjek River, Yukon, Canada, Williams and Rust (1969) divided the outwash plain into four different topographic levels. Even though Williams and Rust (1969) never used the terms sandur or glacial outwash plain in their paper, their description of their examined area shows a lot a similarities with the description by other authors concerning sandar (Gomez et al., 2000, Krigström, 1962, Magilligan et al., 2002).

Level 1: Is the level with the highest fluvial activity and can be viewed as the main channel level. Vegetation is sparse at this level and sedimentary processes are very sensitive to changes in river runoff, it is not uncommon with bar migration.

Level 2: Has a higher elevation than level 1 and is usually only affected by fluvial processes during flood events. Some channels might be active even during non-flood stages, with a lower runoff than the level 1 channels. Vegetation is also more common at this level due to that the glaciofluvial sediments are less prone to erosion at this level.

Level 3: The main difference between level 3 and the previously mentioned levels is usually the presence of an abundant vegetation cover. The channels at level 3 are mostly inactive except during flooding events, where the discharge at this level often is quite low.

Level 4: Have inactive channels even during most flooding events. The vegetation cover, if present, is usually abundant and the soil is dry compared to the other levels. Not surprisingly level 4 has the highest elevation of all the levels.

Of course not all four levels need to be present at all sandar, and in some cases a sandur can be divided into even more levels (Benn and Evans, 1998). Figure 5 shows terrace formations in the proglacial zone of Skaftafellsjökull, Iceland. Like mentioned earlier in the thesis sandar usually cover areas that have been glaciated as recently as the Little Ice Age (Evans and Clague, 1994). Different moraine formations will affect the paths of the glacial rivers as well as the paths of jökulhlaups, and of course the moraine formations will be affected and reworked by the jökulhlaups and rivers as well.

Figure 5. Proglacial zone in front of Skaftafellsjökull, Iceland. Notice the kettle holes and terrace formations as well as the river bars (Bernhardson, 2010).

4.2. Kettle holes and dead-ice topography

The forces released during jökulhlaups are capable of transporting ice masses from a few millimeters to several meters in diameter (Roberts, 2005, Robinson et al., 2008). The jökulhlaups deposit the large masses of ice unto the sandur and a so called dead-ice topography or hummocky terrain may form (Summerfield, 1991), as can be seen in figure 7. This is not something unique for sandur fields, and can be seen in many formerly glaciated areas, for example Wales, UK (Holden, 2008).

Evans (2003) suggested that sandur areas with dead-ice topography should be called pitted or kettled sandur. A kettle hole is formed when a big block of stagnant ice deposited out on a plain slowly melts (Holden, 2008). The weight of the ice subsides the land and a hole is formed in the ground (fig. 6). The hole is filled with water in the beginning, but it might be drained with time if it is not recharged with water. Quite often the dead-ice is covered by a sediment cover, insulating it and causing it to melt more slowly than would otherwise be the case (Benn and Evans, 1998). Robinson et al. (2008) suggested that the low turbidity of these kettle lakes fulfil the right conditions to allow microbial photosynthesis.

After examining ring-formed structures created after the 1918 jökulhlaup on Mýrdalssandur, Iceland, Maizels (1992) suggested that they actually were formed by in situ melting of ice blocks rich in sediments. She categorized the kettle holes into four different types depending on their depths and the height of their rim structures. Type 1 is the normal rim-free kettle holes described earlier in the text. Types 2 are the rimmed kettles that are relatively deep

Figure 6. Kettle holes in front of Skaftafellsjökull, Iceland (Bernhardson, 2010).

with a thin and incomplete rim. Type 3, called crater kettles, are a bit like the opposite of type 2, with a shallow depth and a high rim. Type 4 are the kettle mounds, also called till-fill kettles, and are as the name implies kettle holes that have been formed by ice blocks so rich in debris that they actually have created a mound covering the underlying hole. Since the rims had a diameter of ca. 30 m to over 40 m and could be several meters high this is a good indication of the size and debris content of the ice blocks. The ice blocks that created the rim structures on Mýrdalssandur should have had a mean debris content of 10 to 40 per cent, while the size of some rims implies that the maximum debris content might have been well over 70 per cent.

There exist more modern observations of the relationship between kettle holes and jökulhlaups, i.e. Fay (2002). During the jökulhlaup at Skeiðarársandur in 1996 a large amount of ice blocks were deposited on the sandur. Some of the ice blocks were deposited on a line transverse or parallel to the flow direction of the jökulhlaup, forming so called kettle chains. The reason for this pattern is thought to be due to the fact that the velocities at the leeside of already deposited ice blocks are lower than in the rest of the river. The decrease in velocity facilitates deposition of ice blocks that would otherwise be light enough to be carried further downstream. The chains are in some areas as long as 270 m and the ice blocks forming them are thought to have had a diameter of up to 45 m. The ice block initiating the formation of a kettle chain is hardly surprising larger in size than the rest since it must have been large enough to be deposited despite the discharge velocity. This has the consequence that the largest kettle holes in the kettle

Figure 7. Hummocky terrain in a proglacial area, South Iceland. Notice the people in the picture for scale (Bernhardson, 2010).

chains is situated at one of the ends.

It might seem strange that the transverse kettle chains have been deposited more perpendicular than parallel to the water flow. Fay (2002) suggested that these kettle chains were formed during the rising stage of the flood when the direction of the water flow was different from the main flow direction of the jökulhlaup.

4.3. Other landforms

It is not only ice blocks that can be transported by jökulhlaups, this is also true for large boulders (Maizels, 1997). It is therefore not uncommon with boulder erratics (rocks removed from their place of origin and are therefore different from the surrounding rocks when it comes to size and/or composition) and/or boulder pavements (boulders so closely packed that they resemble a pavement) in areas that have experienced jökulhlaups.

Like mentioned earlier in the text; jökulhlaup-prone areas exhibit a lot of glacier related landforms, like moraines and eskers. According to Russell et al. (2006) there are cases when eskers have formed during a jökulhlaup event. These eskers may form in supraglacial, englacial or subglacial environments, although the supraglacial and englacial eskers tend to erode faster than the subglacial ones.

Since jökulhlaups usually have high magnitude discharges they can create landforms that are not as common in other fluvial affected areas (Maizels, 1997). One of these landforms is the large-scale dune. These kinds of dunes have many different names, like mega-ripples and whaleback dunes but they describe more or less the same landform. Dunes of this kind have been identified with elevations of 15 m and wavelengths as long as 200 m. The controlling factors for the formation of large-scale dunes are many times the supply of material that will make up the dunes as well as the depth of the water flow. Since glaciers have the ability to release high amounts of both sediments and water they have the ability to create these large-scale landforms.

5. The 1996 jökulhlaup at Grímsvötn and its effect on Skeiðarársandur

5.1. Setting

Skeiðarársandur (see fig. 10) is situated in the central south of Iceland (Thordarson and Hoskuldsson, 2002), covering an estimated area of 1000-1350 km^2 and is the largest sandur in Iceland (Gomez et al., 2000, Magilligan et al., 2002, Thordarson and Hoskuldsson, 2002). There are also claims that Skeiðarársandur is actually the largest active sandur in the world (Robinson et al., 2008, Smith et al., 2006). It extends from the glacier terminus of Skeiðarárjökull all the way to the coast, a distance of approximately 20 km (Robinson et al., 2008).

Skeiðarárjökull is the largest of the southern outlet glaciers extending from Vatnajökull, the largest glacier in Europe (Thordarson and Hoskuldsson, 2002). Skeiðarárjökull has a total area of 1370 km^2 (Björnsson, 1998), a terminus that is 23 km wide (Robinson et al., 2008) and has an ablation zone of 1200 km^2 (Thordarson and Hoskuldsson, 2002). The glacier has shifted extensively in historical time, and good observations of the changes exist for the last 350 years (Magilligan et al., 2002). One of the more recent changes was a surge in 1991 where the eastern part of the glacier advanced up to 450 m and the western part advanced up to 1000 m (Björnsson, 1998). Despite sporadic surging events, Skeiðarárjökull has, just like most of the world's glaciers, retreated since the Little Ice Age (Evans and Clague, 1994, Magilligan et al., 2002). Skeiðarárjökull's maximum extent during the Little Ice Age is still visible in Skeiðarársandur because of the remaining moraine and esker formations deposited at this time. However, jökulhlaup events since then have fractured a lot of these landforms and they are not always easily identified. A good example of fluvial processes affecting glacier related landforms can be seen in figure 8.

Since Skeiðarársandur is a glacial outwash plain it is built up of glaciofluvial sediments (Magilligan et al., 2002). Guðmundsson et al. (2002) made seismic soundings of Skeiðarársandur in 1997 and 1999 and their results suggest that the sediment layer at the glacier terminus of Skeiðarárjökull has a thickness of 80-100 m with an increasing thickness towards the coast, reaching a maximum of 250 m. The sandur is thought to consist of 100-200 km^3 of sediments. Skeiðarársandur is created mainly by glaciofluvial processes during the Holocene and has experienced large fluctuations in extent as well as topography over time (Magilligan et al., 2002). The statement that Skeiðarársandur is a Holocene phenomenon is supported by Guðmundsson et al. (2002) that claim that the majority of the material on Skeiðarársandur has not been exposed to compaction which would be the case if it was covered by glacier ice during the Weichselian glaciation. If these sediments have been deposited mostly during the Holocene this would mean that approximately 1 km^3 has been deposited per century. They also suggest that the deposition of material most likely have fluctuated a lot since the last glacial period because of shifting availability of glacier ice and fluctuations in volcanic activity.

The melt water that triggers the jökulhlaups at Skeiðarársandur has its origin either from Lake Grænalón or from the caldera lake Grímsvötn (Thordarson and Hoskuldsson, 2002). Grímsvötn is the largest subglacial lake in Iceland (Björnsson, 2003), occupies the caldera of the central volcano with the same name and is situated in the western part of Vatnajökull (Thordarson and Hoskuldsson, 2002). Grímsvötn is part of the so called Fire Districts in Iceland which is the volcanically most active area in Iceland. Grímsvötn has the capacity to produce large volumes of melt water due to its geothermal activity. The average energy output is estimated to be somewhere between 4000 and 5000 megawatts, making it one of Iceland's most potent geothermal systems. During high magnitude jökulhlaups it is not uncommon that the whole sandur is flooded. Grímsvötn caldera lake is thought to have an average depth of 600 m (Thordarson and Hoskuldsson, 2002) and will drain when the water level has risen 80-110 m over the equilibrium level (Björnsson, 2003), something it does every five to ten years (Thordarson and Hoskuldsson, 2002).

When a jökulhlaup finally is initiated it drains from Grímsvötn all the way under Skeiðarárjökull to finally emerge at the terminus of the glacier and unto Skeiðarársandur, a distance of approximately 50 km (Thordarson and Hoskuldsson, 2002). An ordinary jökulhlaup is thought to move with a speed of 5 m s^{-1} between Grímsvötn and the glacier terminus of Skeiðarárjökull, while extraordinary jökulhlaups may move more than twice that speed, ca. 12 m s^{-1} (Björnsson, 1998). Jökulhlaups from Grímsvötn usually burst unto Skeiðarársandur from the outlet of Skeiðará river, situated at the eastern part of the Skeiðarárjökull terminus (Thordarson and Hoskuldsson, 2002). Jökulhlaups from Grímsvötn tend to have an exponential rise to their peak discharge and an abrupt fall afterwards (Björnsson, 2003). Floods of a low magnitude often have a longer duration than high magnitude floods.

Figure 9. River in a proglacial area that has cut through dead-ice topography, South Iceland (Bernhardson, 2010). Notice the ice core and the mix of sediment grain size in the cross section of the river bank.

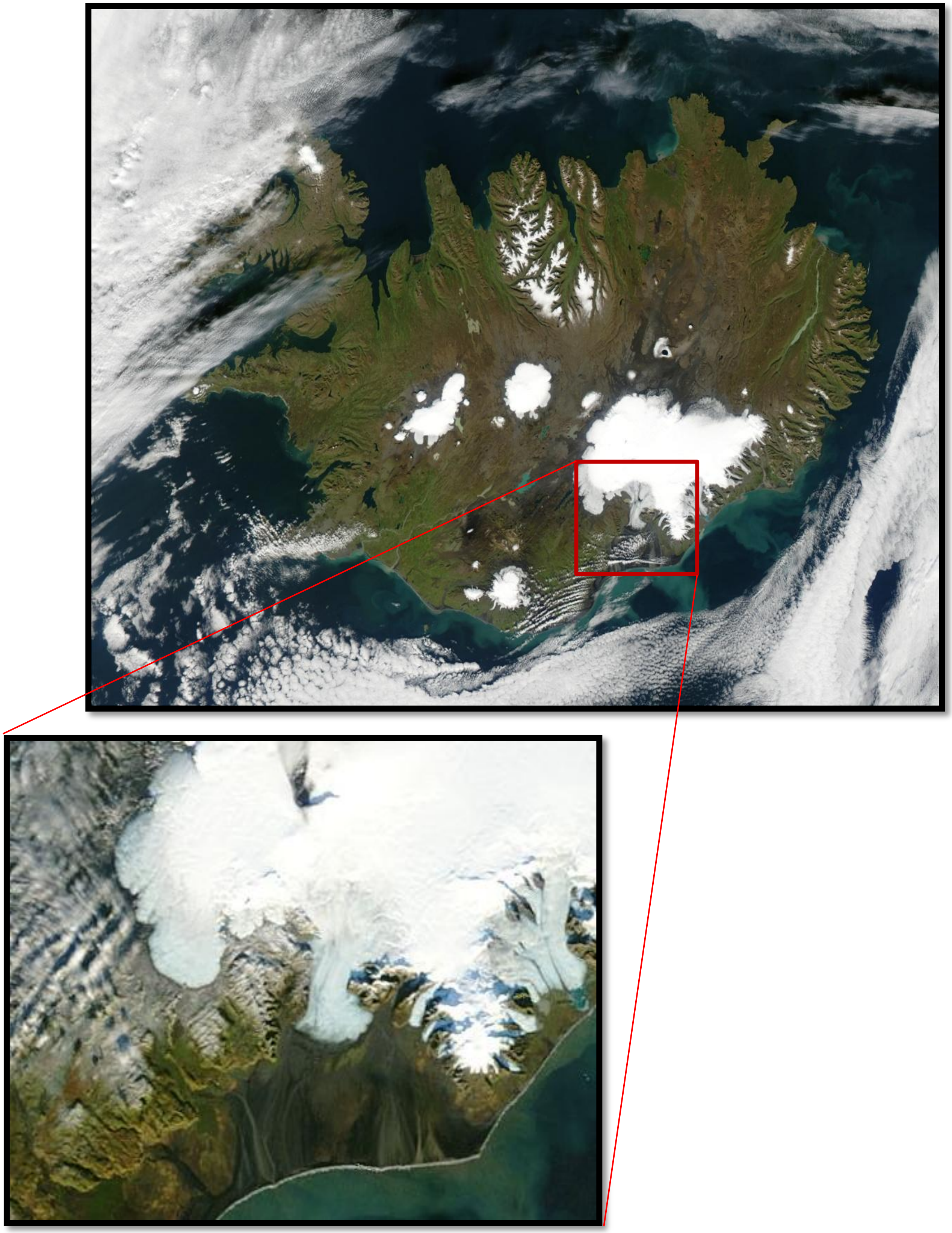

Figure 10. Satellite image of Iceland taken in September 2002. The magnified area (image from 2004) shows the southern part of Vatnajökull with Skeiðarárjökull in the center of the picture. The dark area south of Skeiðarárjökull is Skeiðarársandur (Image courtesy of NASA, 2011 (modis.gsfc.nasa.gov)).

As mentioned earlier in the text, sometimes it is even possible to smell sulphur at the river outlets prior to a jökulhlaup as solutes from the caldera lake reaches the glacier terminus.

Lake Grænalón is situated in a tributary valley on the western side of Skeiðarárjökull (Thordarson and Hoskuldsson, 2002). It is an ice-dammed lake and it is fed by the mountains surrounding it. Lake Grænalón usually drains when it reaches its critical threshold to initiate flotation and drains quite often, once every 1-2 years. Jökulhlaups from Lake Grænalón emerges from the western rivers of Skeiðarárjökull, i.e. Gýgjukvísl, Núpsvötn and Súla.

5.2. The 1996 jökulhlaup

In the evening on the 30th of September 1996 seismic activity was registered at Vatnajökull (Gudmundsson et al., 1997). This would later be identified as the onset of the Gjálp fissure eruption between Grímsvötn in the south and Bárðarbunga (a volcano situated underneath Vatnajökull) in the north. After 30 hours since the beginning of the eruption the glacier roof was breached (Björnsson, 2003) and an eruption column consisting of tephra reached an approximal altitude of 4-5 km (Gudmundsson et al., 1997). This eruption is thought to be the 4th largest during the 20th century in Iceland. During the eruption approximately 3 km^3 of ice melted until the eruption ended on the 13th of October. The water kept accumulating at the caldera lake of Grímsvötn and on the morning the 5th of November floodwater was registered to have started to emerge from the eastern part of Skeiðarársandur at the Skeiðará river (Snorrason et al., 1997). One particularly thing with this jökulhlaup in contrast to older ones is that the caldera lake reached the water level when drainage usually commences already four days after the eruption (Einarsson et al., 1997). Despite this, as mentioned earlier in the text, it took almost two weeks before the jökulhlaup was initiated. Ice-quakes signalled on the 4th of November that the lake had reached a sufficient depth to be able to initiate flotation of the ice dam, something quite unusual for jökulhlaups emerging from Skeiðarárjökull that tend to drain through conduits. The jökulhlaup's discharge rate increased linearly (Björnsson, 2003) and is thought to have reached a discharge with a volume of 40 000 m^{3}s^{-1} in less than 14 hours (Björnsson, 1998, Snorrason et al., 1997). This makes it the steepest hydrograph ever recorded at Skeiðarársandur. Jónsson et al. (1998) suggested that the peak discharge was at high as 52 000 m^{3}s^{-1} and Sigurdsson et al. (1998) estimated the total peak discharge of the jökulhlaup to 53 000 m^{3}s^{-1}. Not even an hour after that the floodwater started to emerge from Skeiðarársandur did the ice fracture and water started to drain supraglacially as well (Roberts et al., 2000). No historical observations prior to the 1996 jökulhlaup exist that Skeiðarárjökull has drained supraglacially (Thórarinsson, 1974). After about an hour floodwater outlets started to form from the east towards the west along the ice-margin (Roberts et al., 2000). In the afternoon, supraglacial and ice-marginal outlets had developed along the whole glacier terminus of Skeiðarárjökull. This westward migration of the drainage routes was probably an indication that the existing conduits did not have the capacity to deal with the discharge. This is hardly surprising since the hydrograph of the 1996 jökulhlaup was as steep as it was (Björnsson, 1997). Björnsson (2003) suggested that this westward drainage migration will initiate when the river discharge exceeds approximately 3000 m^3 s^{-1}.

During the jökulhlaup large blocks of ice broke loose from Skeiðarárjökull and were deposited unto the sandur (Björnsson, 2003, Fay, 2002). On the short time interval of 4-7th of November 1996, the jökulhlaup had its most intense phase (Björnsson, 2003). All in all, Skeiðarárjökull is thought to have had released 3.2 km^3 of melt water during the 1996 jökulhlaup. The damage to Icelandic bridges, roads and power lines is estimated to have reached nearly 15 million U.S. dollars due to the 1996 jökulhlaup at Skeiðarársandur (Jónsson et al., 1998).

Despite the magnitude of the jökulhlaup there were relatively small or no elevation changes of the high-elevation areas in Skeiðarársandur's interior (Smith et al., 2006). However, the jökulhlaup created a number of new channels at Gígjukvísl approximately 1-2 m deep and 200-600 m across. Bars several hundred meters wide and more than 1 m thick were deposited between the new channels. The eastern part of the sandur at Skeiðará also experienced deposition of sediment. In the following four years the landscape was evened out and resembled more and more its pre-jökulhlaup appearance in the western part of the sandur while the eastern part experienced less post-jökulhlaup erosion. All in all, 22 cm of glaciofluvial sediments were deposited over the whole of Skeiðarársandur during the jökulhlaup. Five years later, in 2001, only 11 cm of the jökulhlaup deposited sediments remained. This would indicate that the impacts on a sandur by jökulhlaup events are short-term, however after a seismic sounding of Skeiðarársandur, Guðmundsson et al. (2002) suggested that sediments deposited in subsurface incisions on Skeiðarársandur may have a jökulhlaup origin, and therefore indicate that the effects of jökulhlaups on sandar not necessary need to be short-term.

6. Discussion

There has been a lot of research regarding jökulhlaups and other outburst floods. Regrettably from this author's point of view it looks like the golden age of glaciofluvial geomorphology has passed. This is unfortunate indeed since there are a lot of processes regarding jökulhlaups that are still not fully understood.

There seems to be two main classes of hydrographs for jökulhlaups, but as stated in the text not all scientists have the same explanation for their appearance. Jóhannesson (2002) proposed a subglacial pressure wave that preceded the main flow of a jökulhlaup which should have facilitated the formation of drainage tunnels and thus explain a linear rising jökulhlaup. Jóhannesson stressed the fact that the existing theories of jökulhlaup drainage are unable to explain this phenomenon. This is in contrast to Walder and Costa (1996) who explained a linear rising jökulhlaup hydrograph with subaerial breach widening instead of drainage through a main tunnel as is usually thought to be the case. However, there is nothing that says that either of them is wrong. It might simply be that jökulhlaup hydrographs can be categorized into two main groups based on their appearance even if the processes controlling the discharge rates might have different origins. In any case it is evident that more research is necessary to be able to fully understand these processes.

Like mentioned earlier in the thesis the process of flotation does not seem to be fully understood. Why flotation would initiate when the lake water depth exceeds 90 per cent of the ice-dam's height, or when the ice-dam reaches a thickness 111 per cent of the lake depth, is often not explained in detail. The fact that many glaciers have behaved in a way that deviates from this makes it even clearer that our current understanding of the controlling processes are lacking. This is also true for the Glen mechanism.

As is evident of this thesis, it is not an easy task to create a single model that can simulate the drainage and refilling of jökulhlaup-prone lakes, whether it is a subglacial, proglacial or any other kind of lake with water of glacial origin. The vast combination of storage types as well as trigger mechanisms make jökulhlaups hard to simulate on a general scale. That some jökulhlaup-prone areas show a regular drainage while others do not is also aggravating simulation attempts. One could assume that the only models that would be successful are those adapted to specific lakes. However, these would probably be full of errors as well, especially when you highlight the fact that jökulhlaups from a specific lake or glacier can change their drainage routes between different jökulhlaup events, and even during a single jökulhlaup event. For example, there can be supraglacial drainage in the beginning of a jökulhlaup because the pre-existing conduits cannot handle the initial discharge. A deeper understanding of the interaction of the different trigger mechanisms with the lake water storage types is necessary to improve these models.

The reason why the 1996 jökulhlaup was an unusually large event seems to be because of a number of factors. The melt water continued to accumulate in the Grímsvötn caldera even after it had reached the threshold when it usually starts to drain, having the consequence that more water flowed from the caldera lake than normal when it finally did drain. The theory of a subglacial pressure wave preceding the main jökulhlaup flow that facilitated the drainage of the melt water, in combination with the abnormally large water volume sounds like a logical explanation for the magnitude of this jökulhlaup. Not to mention that the volcanic eruption itself was one of the largest in Iceland during the last century, indicating that there was abundant energy to produce large volumes of melt water to create this unusually large jökulhlaup.

The complexity of jökulhlaups makes it hard to give a definite answer to the questions that this thesis had the intention to answer. Jökulhlaup is a term for an outburst flood with glacial origin and does not take into account what processes that are involved, i.e. it is a descriptive term, not an explanatory one. That different scientists have different definitions of the word does not in any way facilitate this problem. This is also true for the different landforms. Not only do some of them have different definitions but also a lot of terms describe the exact same phenomena, due to the fact that many landforms have their own unique names in different languages.

The aim of an increased understanding of jökulhlaups is in the end to diminish damages to communities and the loss of human lives. The author himself got the impression during his stay in Iceland that there seems to be cooperation between the Faculty of Earth Sciences at the University of Iceland and the emergency service in Iceland. The University´s monitoring of seismic activity linked to ice-quakes and inflation of magma in the volcanoes helps to forewarn the citizens that a jökulhlaup might be imminent. With further understanding of jökulhlaup related processes these forewarnings can improve even further in their accuracy.

7. Conclusions

- The trigger mechanisms controlling the initiation of jökulhlaups are diverse. It can therefore be hard to simulate the behaviour of jökulhlaups, at least with a general model.
- The impacts of jökulhlaups show both a long-term as well as a short-term pattern and can occur regularly as well as irregularly.
- There is no clear evidence of landforms only created by jökulhlaups. There are however some landforms that are present at jökulhlaup-prone areas so often that they can be considered as something quite typical for these areas. Among these landforms the sandur is the most common.
- Water flow from jökulhlaups tends to drain through pre-existing waterways, although the flow may form new waterways if the discharge exceeds the capacity of the pre-existing drainage routes.
- An abnormally large eruption in conjunction with storage of melt water that exceeded the usual threshold for drainage from Grímsvötn made the 1996 jökulhlaup at Skeiðarársandur to an unusually large event.
- An increased understanding of jökulhlaup-controlling processes is needed to be able to mitigate damage to infrastructure as well as the loss of human lives.

8. Acknowledgements

The author would first and foremost like to thank his supervisor Jonas Åkerman for his interest in and valuable comments regarding this thesis. A special thanks to MODIS Web, NASA, for letting their pictures be used in this thesis. Other thanks go to students at the Department of Earth and Ecosystem Sciences who even though they themselves were writing about vastly different topics always expressed encouragement. Lastly, special thanks go to friends and family for support and encouragement.

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