Densification of Firn on Langjökull Glacier, Iceland

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Faculty of Earth Science
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2015

DENSIFICATION OF FIRN ON LANGJÖKULL GLACIER, ICELAND

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10 ECTS thesis submitted in partial fulfillment of a
Baccalaureus Scientiarum degree in Geophysics

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Reykjavik, May 2015

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Density Measurements in the Ice Tunnel
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Bibliographic information:
Hulda Rós Helgadóttir, 2015, Densification of Firn on Langjökull Glacier, Iceland, B.Sc. thesis, Faculty of Earth Science, University of Iceland.

Printing: Háskólaprent, Fálkagata 2, 107 Reykjavík
Reykjavik, Iceland, May 2015

Hereby I certify that I have written this Bachelor's Thesis independently and that I have used no other aid than the specified resources and tools. Furthermore, this thesis was not handed in or published in this or a similar form before.

Hulda Rós Helgadóttir

Abstract

Langjökull is the second largest glacier in Iceland, around 925 km^2 (Björnsson, 2009), and lies in the western higlands of the island. It is a temperate glacier like other glaciers in Iceland, which means that the temperature in the ice is at pressure melting point except for the uppermost meters where seasonal temperature changes from the surface are detectable. The ice tunnel is situated in the south-west part of Langjökull, north-east to Geitlandsjökull, and is placed close to the equilibrium line altitude at around 1270 m a.s.l. The tunnel gives a unique opportunity to explore the physical properties of glaciers in general, and the properties of Langjökull glacier. Density measurements were made along the tunnel to find out at what depth the firn becomes ice. Temperature measurements were made as well. All measurements were made on March 11th and April 12th 2015.

Útdráttur

Langjökull er næststærsti jökull landsins, um 925 km^2 (Björnsson, 2009) og liggur á vesturhálendi Íslands. Hann er þíðjökull eins og aðrir jöklar Íslands, en það merkir að hitastig í jöklinum er við þrýstingsbræðslumark nema í efstu metrunum þar sem veðurfarsbreytingar við yfirborð koma fram. Ísgöngin eru staðsett á suðvestur hluta Langjökls, rétt norðaustan Geitlandsjökuls. Göngin eru við jafnvægislínu í u.þ.b. 1270 hæð og gefa einstakt tækifæri til könnunar á eðliseiginleikum jökla almennt og Langjökuls. Mælingar voru gerðar á eðlismassa inn eftir göngunum til að komast að því á hvaða dýpi hjarn verður að jökulís. Einnig var hitastig hjarnsins mælt inn eftir göngunum. Mælingar á voru gerðar þann 11. mars og 12. apríl 2015.

Preface

The engineering office Efla started the ice tunnel project in the year 2010. After consulting with scientists and people well-acquainted with the area, constructions started in April 2014 and will finish in June 2015. To make the tunnel happen, collaboration has been required; scientists, engineers, artists, farmers and workers from the vicinity have been working hard to make this idea a reality. This ice tunnel requires a lot of work for maintenance but it gives a unique opportunity to explore the physical characteristics of Langjökull glacier. Being interested in glaciers, I did not hesitate to seize the opportunity to have a project in the tunnel when my teachers proposed this idea. This has been a long but fun and a very informative process.

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Abbreviations and Symbols

ELA: Equilibrium line altitude
ρ: density
$\rho(z)$: density at depth z
ρ_i: density of ice
ρ_s: density of surface snow
z_ρ: a constant that corresponds to a characteristic depth of the firn
k_T: thermal conductivity
k_T^i: thermal conductivity of pure ice
α_T: thermal diffusivity
c: specific heat capacity
T: temperature
q: heat flux
$\frac{\partial T}{\partial z}$: temperature gradient
t: time
A_T: amplitude of the temperature variations
ω: the frequency of cyclic variation

Acknowledgments

I want to thank my advisers, Alexander Helmut Jarosch and Guðfinna Aðalgeirsdóttir, for good guidance from the beginning. I also want to thank Finnur Pálsson for guidance and information. Thanks to Reynir Sævarsson, my contact at Efla consulting engineers, who also deserve great thanks for allowing me to work in the ice tunnel along with Into the Glacier (Ice Cave Iceland). Thanks to Fríða Björk Gunnarsdóttir for the measuring cylinders, thanks to my family, Svanhildur Edda Þórðardóttir, Helgi Bjarnason and Finnur Þór Helgason, and greatest thanks to Kristinn Magnússon for assistance and support.

1 Introduction

1.1 Langjökull

Langjökull glacier is situated on the western part of the highlands of Iceland. It is the second largest glacier of the island with an area of approximately 925 km^2 and volume of 207 km^3 (Björnsson, 2009). Langjökull is on the most northern part of a volcanically active zone which has been active for 6-7 million years. The glacier connects the central volcanoes Prestahnúkur, Kálfstindar and Hengill. Langjökull formed when climate was colder than it is now (Björnsson, 2009) and the accumulation area was big enough to maintain its size. Langjökull is an important water source. It has a few drainage areas that lead to Hvítá in Borgarfjörður, Þingvallavatn and Hvítá in Árnessýsla, among others (Pálsson, F., Gunnarsson, Jónsson, Steinþórsson & Pálsson. H.S. 2014).

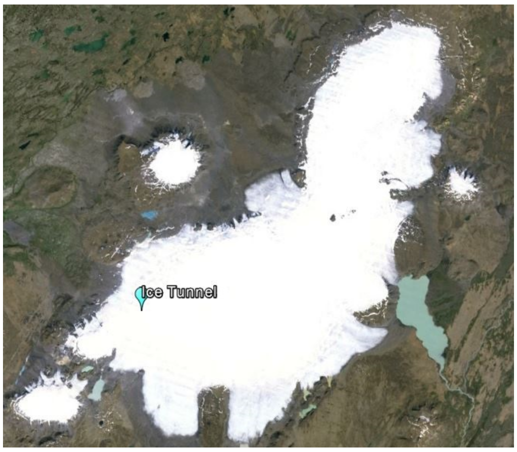

Figure 1.1: Langjökull glacier and position of the ice tunnel (Google, 2013)

As the result of warmer climate in the 20th century, Langjökull has lost a lot of its ice. From 1900 to 1970 it lost 16% of its present volume (Björnsson, 2009). Annual accumulation measurements on Langjökull began in 1996. From 1996 to 2004, the glacier lost 5,3% of its volume, and its accumulation area has been between 10 to 40% of the glacier. From newly predictions, it is estimated that Langjökull will shrink but keep a similar form until 2050. Around 2075, it will split in two and in 2115 it will be dead ice without an accumulation area, which could disappear the next 15 to 20 years (Björnsson, 2009).

1.2 ELA and Density Measurements

Equilibrium Line Altitude (ELA) is the altitude where the equilibrium line is. Above the equilibrium line, more snow accumulates than melts over the year and below it more snow melts than accumulates. Thus, at the line itself, the amount of snow that melts is just the amount which accumulated. The ELA is not necessarily in the same place from year to year, depending on the conditions on the glacier. Figure 1.2 shows how the glacier ice flows around the equilibrium line.

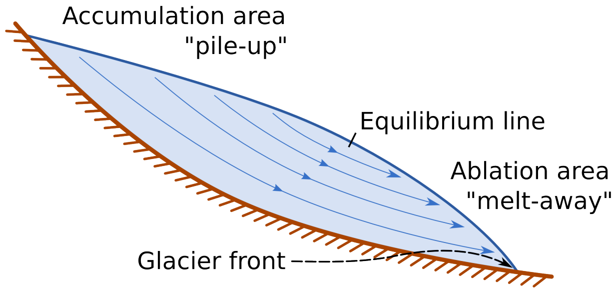

Figure 1.2: The flow of a glacier around the ELA. Snow that falls on top of a glacier moves down as new snow layers accumulate on top. It flows along the bottom of the glacier and finally reaches the glacier front in the ablation area. Thus, the oldest ice is at the bottom of the glaciers at the glacier fronts. (Spensberger, 2013)

The ice tunnel is situated close to the ELA of Langjökull and reaches more than 140 m inside the glacier. It gives a unique opportunity to explore the glacier and it was decided to measure the density and temperature of the firn at different places along the tunnel. Density measurements have been made on glaciers before, but they are usually made in pits at the surface or by examining ice cores. Glacier temperature measurements are made, for example, by drilling down a thermistor, whose resistance differs by temperature. Unfortunately, the ice tunnel lacks the chance of making measurements in a straight profile, but it gives the chance to see the glacier alive in perspective. The goal of these measurements was to find out at what depth glacier ice can be found in the tunnel and to see how deep the seasonal temperature changes from the surface are detectable.

2 Theoretical background

2.1 From Snow to Ice

The process of glacier ice formation can be long and complex. It starts, of course, by snow falling on a glacier. As time passes, more snow falls on top of previous layers with the result of packing and densification of older layers. The term *firn* refers to matter that is in the intermediate stages of transformation; not new or settled snow and not yet glacier ice (Cuffey & Paterson, 2010). This is a broad definition which lacks the clear division between snow and firn but has to be accepted for now. There is however a clear distinction between firn and glacier ice: firn becomes glacier ice when the interconnecting air- or water- filled passages between the grains are sealed off. That process is called pore close-off.

Table 2.1: Typical densities from snow to ice [kg/m^3] (Cuffey & Paterson, 2010)

New snow	50-70
Damp new snow	100-200
Settled snow	200-300
Wind packed snow	350-400
Firn	400-830
Very wet snow and firn	700-800
Glacier ice	830-923

2.1.1 From Snow to Ice When Meltwater Is Present

Icelandic glaciers are temperate glaciers. That means that they are at melting point throughout, except for a surface layer in which the temperature falls below 0°C for part of the year. Temperate glaciers only have wet-snow zones (all the snow since the previous summer has warmed to 0°C) and ablation zones where the glacier loses mass by the end of each year (Cuffey & Paterson, 2010).
The time it takes for the transformation from snow to ice to occur varies greatly

but the main driving factor of the transformation in temperate glaciers is meltwater. The snowflakes turn to grains which become rounded and melting increases the rate of that process. Grains can join together in clusters by refreezing after melting and they join most rapidly in the surface layers because the surface layers undergo the cycle of freezing and thawing. Meltwater accelerates packing by lubricating the grains and permits very close packing. Packing can thus achieve a higher maximum density in a meltwater area than in a dry-snow zone. Refreezing of meltwater also speeds up the later stages of transformation because air spaces are filled in that way. If refreezing of large amounts of meltwater occurs, it forms ice layers and ice lenses, a rapid transition from snow to ice. Formation of ice layers accounts for the large variability of densities with depth in the firn on temperate glaciers.

2.1.2 Density Changes

The progress of transformation from snow to ice varies between places. If no melting occurs, even in summer, it slows down the transformation so both ages and depths of glacier ice tend to be greater at cold places than warmer ones.

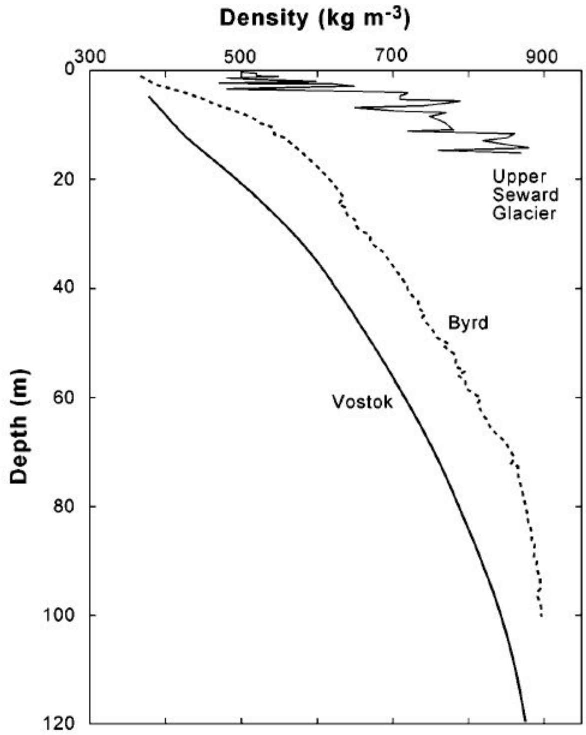

Figure 2.1: Density variation with depth in a temperate glacier (Upper Seward - Alaska) and in cold glaciers (Vostok and Byrd - Antarctica) (Cuffey & Paterson, 2010)

As figure 2.1 shows, the transformation occurs rapidly in the wet-snow zone, compared to cold glaciers. It shows how different conditions can affect the rate of transformation from snow to ice. The density also varies a lot in the Upper Seward Glacier, which indicates existence of ice layers. The transformation from snow to ice at the Upper Seward Glacier takes only 3 to 5 years while it takes 280 years at Byrd and 2500 years at Vostok. Upper Seward Glacier shows an unusually rapid transformation though. The firn becomes ice in the Upper Seward glacier at a depth of 13 m.

To describe the density-depth relation, this empirical equation can be used (Schytt, 1958):

$$\rho(z) = \rho_i - [\rho_i - \rho_s]exp(-z/z_\rho) \tag{2.1}$$

Where $\rho(z)$ is the density at depth z, ρ_i is the density of ice (917 kg/m^3) and ρ_s is the density of surface snow. The letter z_ρ is a constant for each location and corresponds to a characteristic depth of the firn. That means that below z_ρ, most of the ice has gone through pore close-off.

2.2 Temperature in Ice

Temperature distribution in ice is affected by many factors. Climate determines the surface temperature through energy balance, the base is melted or warmed by geothermal heat and frictional heating, and ice deformation and refreezing of meltwater warm the interior. Heat is transferred within the glacier by conduction, ice movement and in some cases water flow. Different types of temperature distributions may be found in different parts of the same glacier.

2.2.1 Thermal Parameters

Thermal conductivity, k_T, is the property of a material to conduct heat. For dry snow, firn and ice it can be expressed by the following formulae:

$$k_T = 2.1 * 10^{-2} + 4.2 * 10^{-4}\rho + 2.2 * 10^{-9}\rho^3 \tag{2.2}$$

$$k_T = \frac{2k_T^i\rho}{3\rho_i - \rho} \tag{2.3}$$

Equation (2.2) shows the Van Dusen (1929) formula which, in most cases, gives a lower limit. One has to remember though that low-density hoar layers can be less conductive. Equation (2.3) is the Schwerdtfeger (1963) formula and it gives an

upper limit. Here, k_T is the thermal conductivity, k_T^i is the thermal conductivity of pure ice, 2.1 $W/(m * K)$, ρ is the firn's density and ρ_i is the density of ice.
Thermal diffusivity, α_T, is a materials ability to conduct thermal energy relative to its ability to store thermal energy. It can be calculated for any density and temperature using (Cuffey & Paterson, 2010)

$$\alpha_T = \frac{k_T}{\rho c} \tag{2.4}$$

Where c is the specific heat capacity, which can be expressed with the empirical formula (Cuffey & Paterson, 2010)

$$c = 152.5 + 7.122T \tag{2.5}$$

Where T is the temperature in Kelvin.

2.2.2 Temperature of Surface Layers

The penetration of seasonal and long-period changes in surface temperature can be described with the heat conduction theory. Fourier's law of heat conduction states that

$$q = -k_T \frac{\partial T}{\partial z} \tag{2.6}$$

Here, q is heat flux, the amount of heat energy flowing across a unit area in unit time, k_T is thermal conductivity and $\frac{\partial T}{\partial z}$ is the temperature gradient. The minus sign indicates that the heat flows in the direction of lower temperatures. Thus, Fourier's law states that the heat flux, q, at a point in a medium is proportional to the temperature gradient (z is measured in the direction of the temperature variation).

Consider an element of unit cross-section and thickness δz in a material. The heat flowing in one side is q and the heat flowing out of the other side is $q + [\partial q/\partial z]\delta z$. If $\partial q/\partial z$ is positive, more heat flows out than in so the element cools. The change in heat in unit time equals $-\rho c[\partial T/\partial t]\delta z$, where ρ is the density, c is the specific heat capacity, T the temperature in Kelvin and t the time. For constant k_T (Cuffey & Paterson, 2010):

$$-\rho c \frac{\partial T}{\partial t} = \frac{\partial q}{\partial z} = -k_T \frac{\partial^2 T}{\partial z^2}$$

or

$$\frac{\partial T}{\partial t} = \alpha_T \frac{\partial^2 T}{\partial z^2} \tag{2.7}$$

according to (2.4)

Now, consider a cyclic variation of temperature at the surface (z=0) with fluctuations about mean value following

$$T(0,t) = A_T sin(2\pi\omega t) \tag{2.8}$$

Here, A_T is the amplitude and ω: the frequency (cycles per time) of the variation. The solution of of (2.7) gives the temperature variation in the subsurface at depth z as

$$T(z,t) = A_T exp(-z\sqrt{\pi\omega/\alpha_T}) sin(2\pi\omega t - z\sqrt{\pi\omega/\alpha_T}) \tag{2.9}$$

which shows two things:
a) The amplitude of the wave decreases as $exp(-z\sqrt{\pi\omega/\alpha_T})$. The higher the frequency, the more rapid is the attenuation with depth. Surface temperature variations can be expressed as harmonic series; the higher harmonics attenuate most rapidly and the temperature perturbation at depth approximates a wave of the fundamental frequency.
b) Temperature maxima and minima propagate at velocity $2\sqrt{\pi\omega\alpha_T}$

Field observations confirm that seasonal variations are undetectable below a depth of about 15 to 20 m, like figure 2.2 shows.

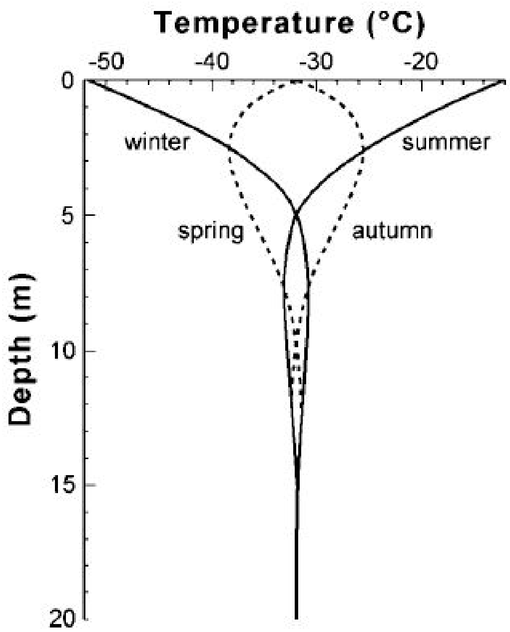

Figure 2.2: A theoretical seasonal cycle of firn temperatures. This applies to central Greenland. Seasonal temperature changes of the ice are only in the uppermost 15 to 20 m (Cuffey & Paterson, 2010)

2.2.3 Temperate Glaciers

Temperate ice is a complex material which consists of ice, water, air, salts, carbon dioxide and, in volcanically active places like Iceland, particles of ash. Impurities in the ice depress the melting point in proportion to the solute concentration in the liquid inclusions (Cuffey & Paterson, 2010). They also increase the effective specific heat capacity of ice near the melting point.
For a glacier to be temperate, it must contain heat sources and sinks. They are provided by the freezing of small amounts of water and melting of small amounts of ice. Refreezing of 1 g of water produces enough heat to raise the temperature of 160 g of snow or firn by 1°C. The water in a temperate glacier comprises about 1% of the glaciers volume and has various sources (Cuffey & Paterson, 2010):

- Percolation and conduit flow from the surface
- Ice melted by deformational heating
- Melting induced by pressure changes
- Pockets of water trapped when the ice formed

3 Methods and Measurements

3.1 Density Measurements

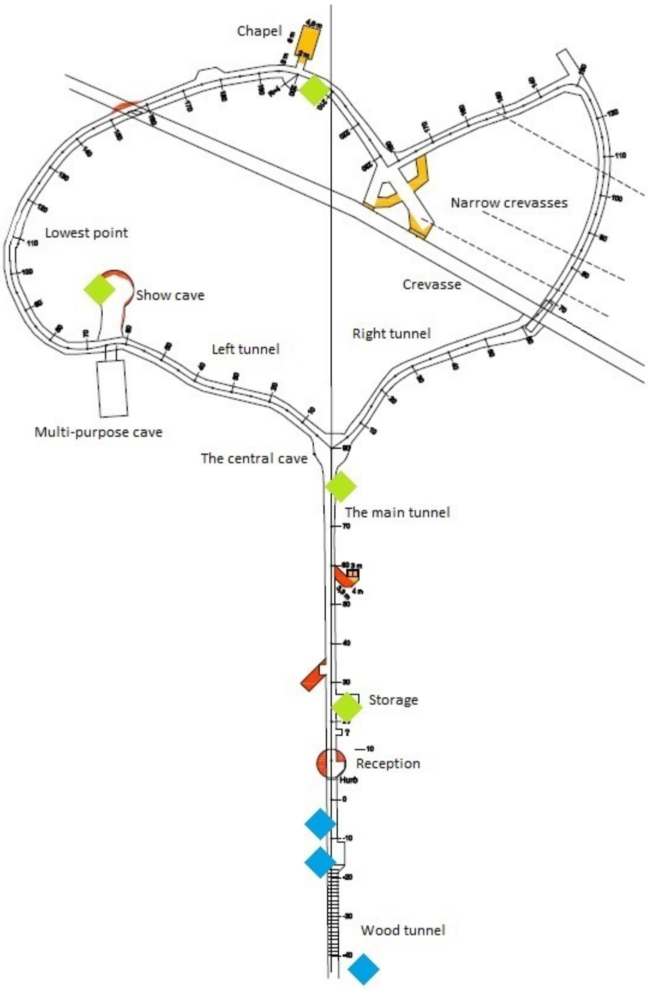

Figure 3.1: Density measurements in the ice tunnel. The diamonds indicate the places samples were made. Green diamonds show location of measurements made on March 11th and the blue diamonds indicate location of measurements made on April 12th. Two to four pieces of firn/ice were sampled in a vertical profile in every spot. The map is used by courtesy of Efla

Figure 3.1 shows a drawing of the ice tunnel, made the 7th of April by Efla. The trips to Langjökull glacier were on the 11th of March and on the 12th of April 2015. In both cases, a "base camp" was put up in the multi-purpose cave where the measurements were made. The first step of the density measurements in the tunnel was to chop small pieces of ice from the glacier wall. A vertical profile of two to four pieces was made in every spot to at least get a glimpse of a straight profile down the glacier. Conditions differ in every spot and since it was not possible to get a continuous profile from top to bottom, this was considered the best way. It was also kept in mind that the outermost ice in the walls might have changed or transformed due to exposure to soot and warmth from the machines, or expanded due to the pressure difference the tunnel produces. The pieces used in these measurements were thus all taken a few centimeters inside the wall.

After chopping, the pieces were brought to the multi-purpose cave. The next step was to saw the pieces so they would fit in the measuring cylinder. After that, a piece was weighed and put into a thin plastic bag. Each piece was dipped into the measuring cylinder, which contained water, and the water displacement registered. The water displacement shows the volume of the piece according to the fact that the volume of water displaced is equal to the volume of the submerged body. From these information, the weight and the volume, the density can be calculated. The following list contains the equipment used for these measurements:

- Pick
- Saw
- Scale (Salter Brecknell, C3225)
- Plastic bags
- Measuring cylinders
- Water
- Knife

(a) The ice was dipped into water to find its volume

(b) Kristinn Magnússon working hard on chopping the ice

Figure 3.2: Density measurements and ice sampling

On April 12th, measurements were made outside the tunnel to obtain the density in the snow in the surface. In that case the measurement was made by pounding a hollow cylinder into the snow and weighing the cylinder full of snow. The weight of the empty cylinder was then subtracted. The following list contains the equipment used for that:

- Cylinder
- Hammer
- Scale (Salter Brecknell, C3225)

(a) Pounding the cylinder in the snow

(b) Releasing the cylinder

(c) The cylinder full of snow

Figure 3.3: Density measurements at the surface

Three samples were taken at the surface and an average density registered.

3.2 Temperature Measurements

The temperature measurements were mainly made on the 12th of April. For these measurements, a thermometer (KI&BNT, WT-1) was inserted into the firn/ice and the temperature read. It was not easy to make the thermometer stay put in the firn because the firn was very hard, so an electric drill was used to drill a hole for the thermometer. The drill reached 10 cm in the firn/ice.

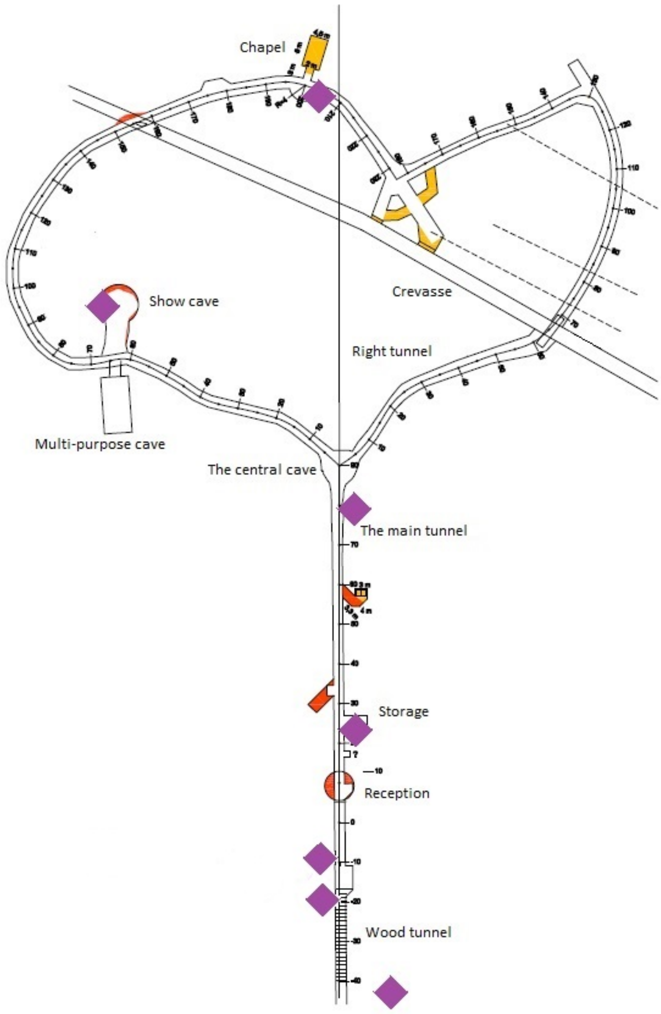

Figure 3.4: Temperature measurements in the ice tunnel. The diamonds indicate the places where temperature was measured. The map is used by courtesy of Efla

Figure 3.4 shows where measurements were made. One measurement was made in the snow in the surface, four measurements were made in the main tunnel, two in the show cave and one close to the chapel.

4 Results and Discussions

4.1 Density Measurements

Figure 4.1 shows the graph of density with depth.

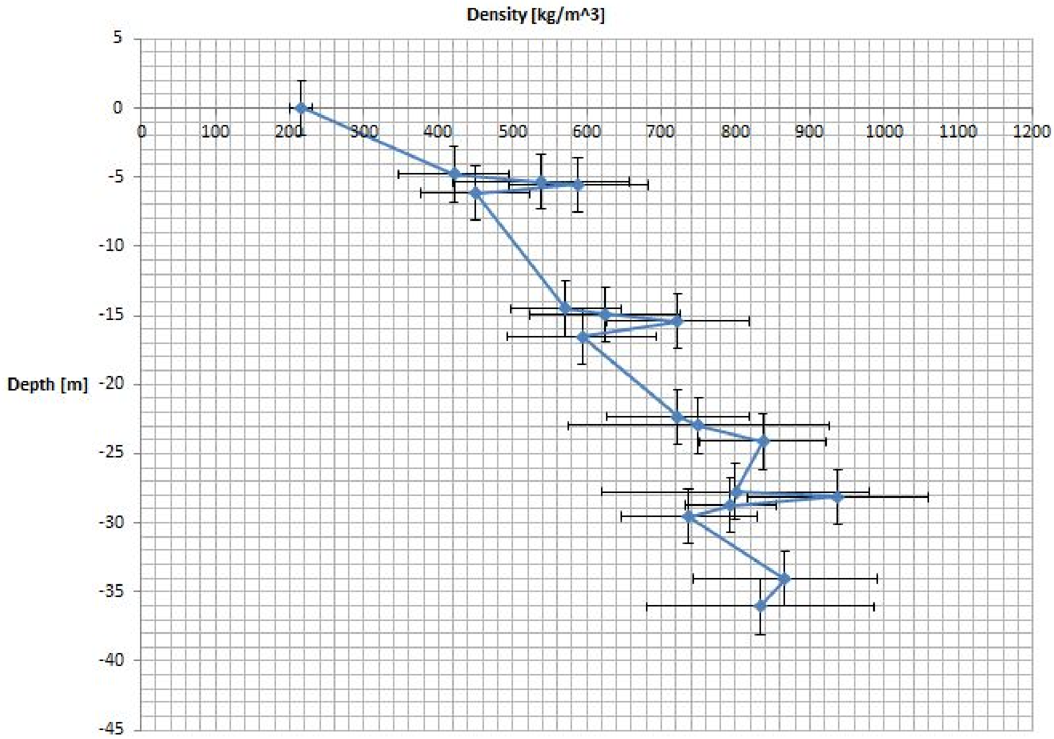

Figure 4.1: The result of density measurements in the ice tunnel

The depth is the depth below the surface and was estimated from the following information:

- The inclination of the glacier is 1/8 (Reynir Sævarsson, e-mail, February 20th 2015)
- The contour lines lie perpendicular to the tunnel

- The headroom in the tunnel was estimated to have an average of 3 m
- The height of the floor compared to the central cave was given in certain places (Reynir Sævarsson, e-mail, February 20th 2015)
- The floor of the main tunnel had a negligible inclination
- Snowfall from this winter had condensed to a 5.8 m layer on top of previous layers (Finnur Pálsson, e-mail, May 19th 2015)

To estimate the depth, the longitudinal distance from the front of the tunnel to the measuring point was measured using a map from Efla. That number was divided by 8 to get the distance from the surface. Winter snowfall and the headroom were added to that number to get the distance to the floor. If the height of the floor was higher or lower than the central cave, the difference was added or subtracted. The height of each measurement sample was measured from the floor. To find the depth of each sample point, the distance from the floor to the point was subtracted. When plotted, the depth was defined negative.

The error of the density was calculated with the standard method for multiplication and division:

$$\Delta\rho = \rho(\frac{\Delta m}{m} + \frac{\Delta V}{V}) \tag{4.1}$$

Where, ρ is the density like before, m is the weight and V the volume. The scale had an error of 2 g according to the manufacturer, so Δm is 2 g. The measuring cylinders had a scale of 2 ml, which was estimated to be the reading error so ΔV is $2 * 10^{-6}$ m^3.
The error of the depth is estimated to be 2 m, to include a possible deviation in headroom height and the inclination of the floor. It was also estimated that the volume a plastic bag takes is so small that it does not require an extra error. Expansion of the ice in the tunnel is evaluated to be negligible.

4.2 Density Discussions

The density profile shows a similar profile as the Upper Seward glacier in 2.1. The spikes in the profile represent denser ice/firn lenses that occur regularly in the glacier walls like figure 3.2(b) shows. The first time the density of ice (830 kg/m^3) occurs is at around -24 m depth. That might be a lens, or at least a bit denser than its surroundings, but at -34 m there seems to be permanent glacier ice. These numbers include the 2015 winter snow. The density increases with depth as it reaches the density of glacier ice. In this case, the depth does not seem to be quite enough for the ice to reach a constant density but it is likely that it will do so at greater depths, perhaps in the next 20 m.

From these results, one can estimate the coefficient z_ρ from equation (2.1). That is done by using a method of least-squares fitting in Matlab. That gives an estimation like figure 4.2 shows.

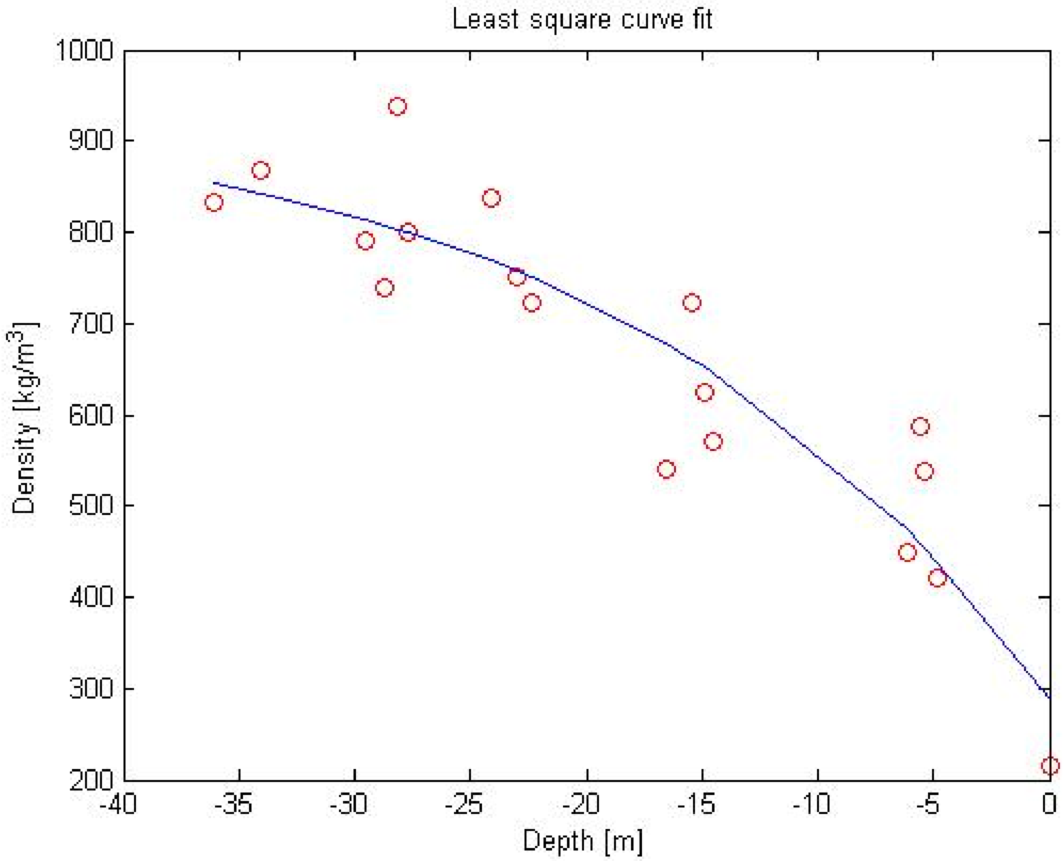

Figure 4.2: The approximation of z_ρ from equation (2.1) *with the least square method*

From this, the characteristic depth of the firn is:

$$z_\rho = -18.56m$$

It tells us that the depth to z_ρ is mainly firn but below that depth, the main part of the ice has gone through pore close off and has become glacier ice. One has to keep in mind though that equation (3.1) deviates most strongly from measured densities in the uppermost 20 meters (Cuffey & Paterson, 2010). It is difficult to explain the difference between the measured depth of glacier ice and the value of z_ρ. It could be that the density of glacier ice occurs above -24 m in ice lenses, and the difference could lie in the fact that the errors of the density or the depth were not taken in account.

It is also possible to plot the thermal conductivity from the density measurements, from equations (2.2) and (2.3).

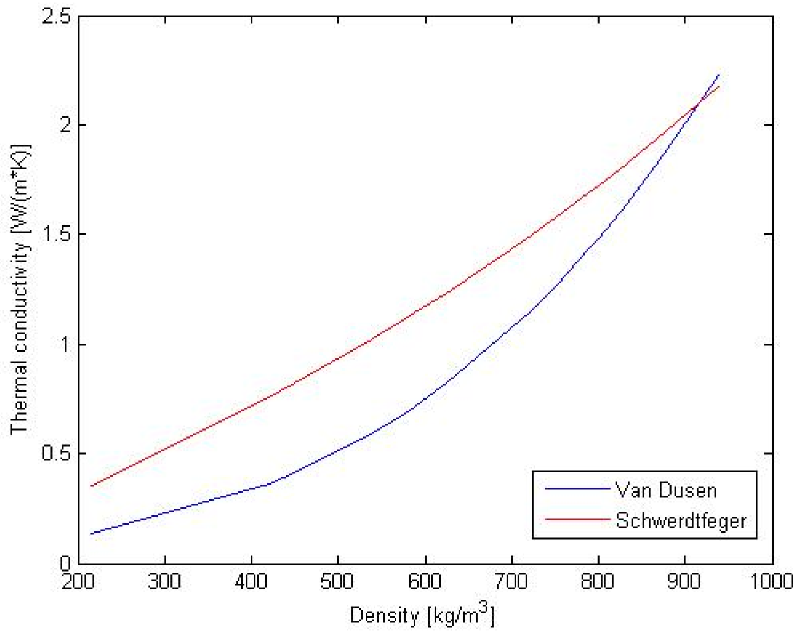

Figure 4.3: A plot of thermal conductivity vs. the density from the Van Dusen formula and the Schwerdtfeger formula

The Van Dusen formula, eqation (2.2), gives the lower limit and the Schwerdtfeger formula, equation (2.3) gives the upper limit. They both show that when the density of the ice is low, its ability to conduct heat is less, that is, the ice isolates better when the density is lower. The Van Dusen part rises linearly but the Schwerdtfeger one rises as a third order polynomial; slower than the Van Dusen line at first but rises up and cuts the line at a value of the density of ice and $k_T = 2.1$ W/(m*K).

It is difficult to estimate the age of the ice at this depth. When explosive volcano eruptions occur in Iceland, like Eyjafjallajökull in 2010, ash layers can cover big areas. When ash layers cover glaciers, they can increase the melting if the ash layer is thin enough. If the ash layer is very thick it can actually isolate the glacier and decrease melting. After the eruption in Eyjafjallajökull, melting increased on Langjökull (Pálsson, F. et al., 2014) and all the glacier became an ablation area. Estimating the age of the ice is therefore a bigger project. It is possible to make other measurements in the tunnel that can be linked to these measurements. Sif Pétursdóttir measured the deformation of the ice in the tunnel and used the density measurements presented here when necessary (Pétursdóttir, 2015). By investigating the accumulation rate in the area, it would be possible to evaluate the densification rate of the firn in this area, or the subduction rate.

4.3 Temperature Measurements

Figure 4.4 shows the temperature with depth in the ice tunnel.

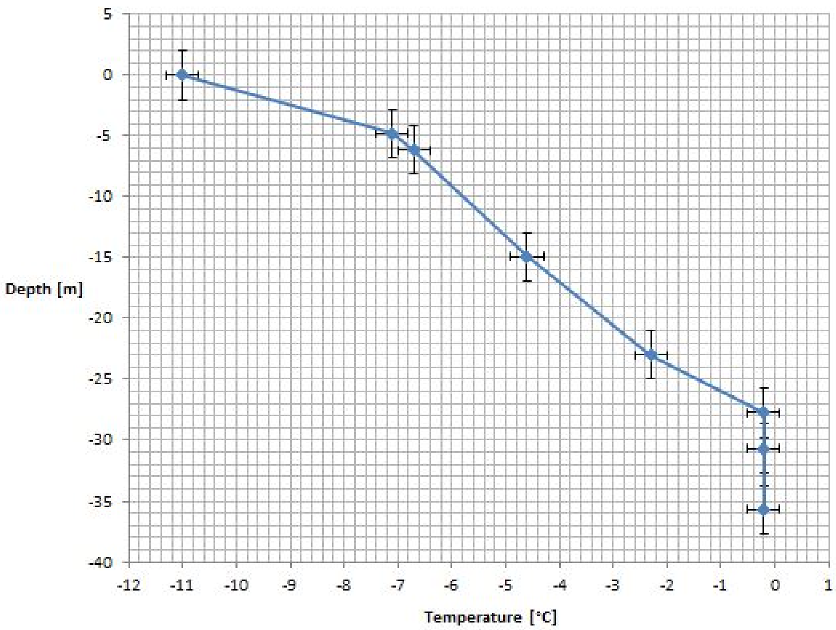

Figure 4.4: The result of temperature measurements in the ice tunnel. Temperature variations are detected in the uppermost 23 to 27 m

The error of the depth is estimated to be 2 meters. To measure the offset of the thermometer, ice cubes were put in a bowl where they melted. While melting, the thermometer was put in the meltwater. According to physics laws, this water should be 0°C. However, the thermometer measured it to be 1.2 °C. All temperature measurements were thus decreased by 1.2°C and the error estimated 0.3°C. The precision of the thermometer is 0.1°C and an extra 0.2° were added due to the offset measurement.

4.4 Temperature Discussions

To shift the temperature down by 1.2°C was a logic decision. The temperature in the deeper layers was measured to be 1°C in the frozen ice. It was encouraging to measure the offset in the thermometer.
Figure 4.4 shows that the temperature increases gradually with depth until it reaches -0.2°C between 23 m and 27 m depth. The theoretical background states that temperature fluctuations are detectable town to 15 to 20 m depth, like figure 2.2 shows, so these results have a bit higher value. The ice tunnel might increase the fluctuation because changes in weather do likely influence the ice further inside the tunnel. The workers also work on big machines in the tunnel that might affect the temperature in the ice. There was probably around 10°C difference in the air temperature in the tunnel when the measurements were made and it would have been interesting to measure the air temperature in the tunnel to see when it got stable.

From figure 4.4, the best line from the top to the depth of a fixed temperature gave a $\frac{\partial T}{\partial z}$ of -0.36. Using Fourier's law of heat conduction, equation (2.6), it is possible to plot the heat flux in the glacier.

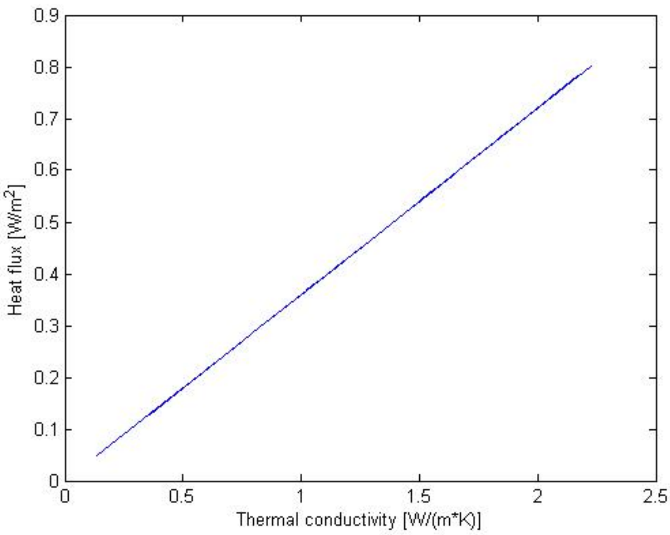

Figure 4.5: A plot of the heat flux vs. the thermal conductivity. This includes both the Van Dusen formula and the Schwerdtfeger formula

Since the temperature increases with depth, the heat flux in the glacier is upwards, from the depths of the glacier to the surface. The plot also shows that the heat flux is lower when the thermal conductivity - and density - is lower, and increases as the other factors increase.

5 Conclusions

From the density measurements, the density of glacier ice was found, first at 24 m depth but probably as an ice lens, and from 34 m to 36 m depth so one can assume that glacier ice can be found below that depth. The density measurements gave a chance to calculate z_ρ, a characteristic depth of firn, and was found to be -18.56 m, but the difference between the characteristic depth of firn and the measured depth of glacier ice is difficult to explain. The temperature profile shows a profile where the temperature from the surface has an influence on the uppermost 23 to 27 m, which is a bit higher than the theoretical background confirms. That might be because the air can easily flow in the tunnel so the influence from the outside temperature might therefore reach deeper. These measurements show interesting results and open a door to other measurements, such as deformation measurements and subduction- and/or densification rate measurements. It will be interesting to watch how the tunnel develops in the coming years.

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Appendix

A

Density Measurements

The table shows the data from the density measurements, along with the calculated depth.

Weight [kg]	Volume [ml]	Depth [m]
0.02	24	-36.06
0.026	30	-34.06
0.028	38	-29.54
0.046	58	-28.74
0.03	32	-28.14
0.016	20	-27.74
0.036	43	-24.125
0.015	20	-22.075
0.026	36	-22.325
0.019	32	-16.525
0.026	36	-15.425
0.02	32	-14.925
0.024	42	-14.525
0.018	40	-6.15
0.02	34	-5.55
0.014	26	-5.35
0.016	38	-4.8
0.217	0.001 m^3	0

Temperature Measurements

This temperature is the temperature after shifting the measurements by 1.2°C, as the calibration of the thermometer suggests, and the calculated depth.

Temperature [°C]	Depth [m]
-11°C	0
-7.1	-4.8
-6.7	-6.15
-4.6	-14.925
-2.3	-22.975
-0.2	-27.74
-0.2	-29.54
-0.2	-30.67
-0.2	-35.7

B

Matlab function

This is the Matlab function used to estimate z_{rho}, using the least square method.

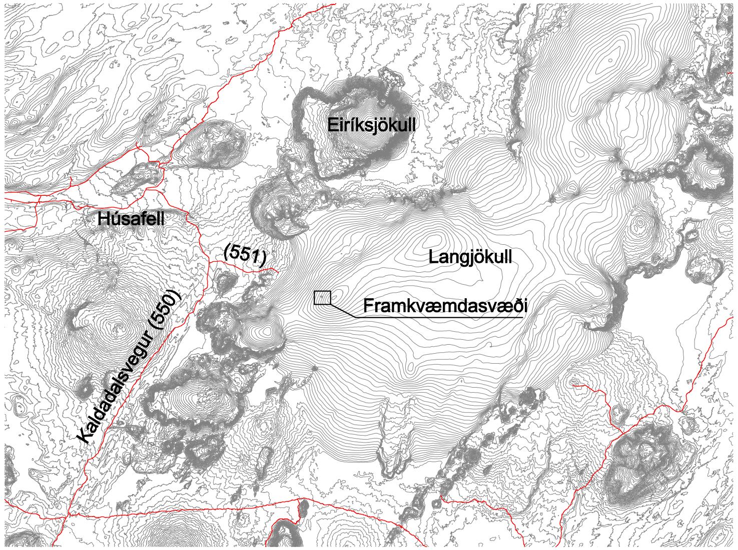
```
z = [0 -4.8 -5.35 -5.55 -6.15 -14.525 -14.925 -15.425 -16.525 -22.325...
    -22.975 -24.125 -27.74 -28.14 -28.74 -29.54 -34.06 -36.06];

rho_z = [215.7 421.1 538.5 588.2 450 571.4 625 722.2 539.8 722.2 750.0 ...
    837.2 800 937.5 739.1 789.5 866.7 833.3];

plot(z, rho_z, 'ro')
title('Least square curve fit')

fjor = @(p,xdata) p(1)+p(2)*exp(-xdata/p(3));

pgisk = [917 -701.3 -1];

[p, fminres] = lsqcurvefit(fjor, pgisk, z, rho_z)

hold on
plot(z, fjor(p,z))
xlabel('Depth [m]')
ylabel('Density [kg/m^3]')
hold off
```

C

Maps and figures

These are maps and figures regarding the ice tunnel from Efla.

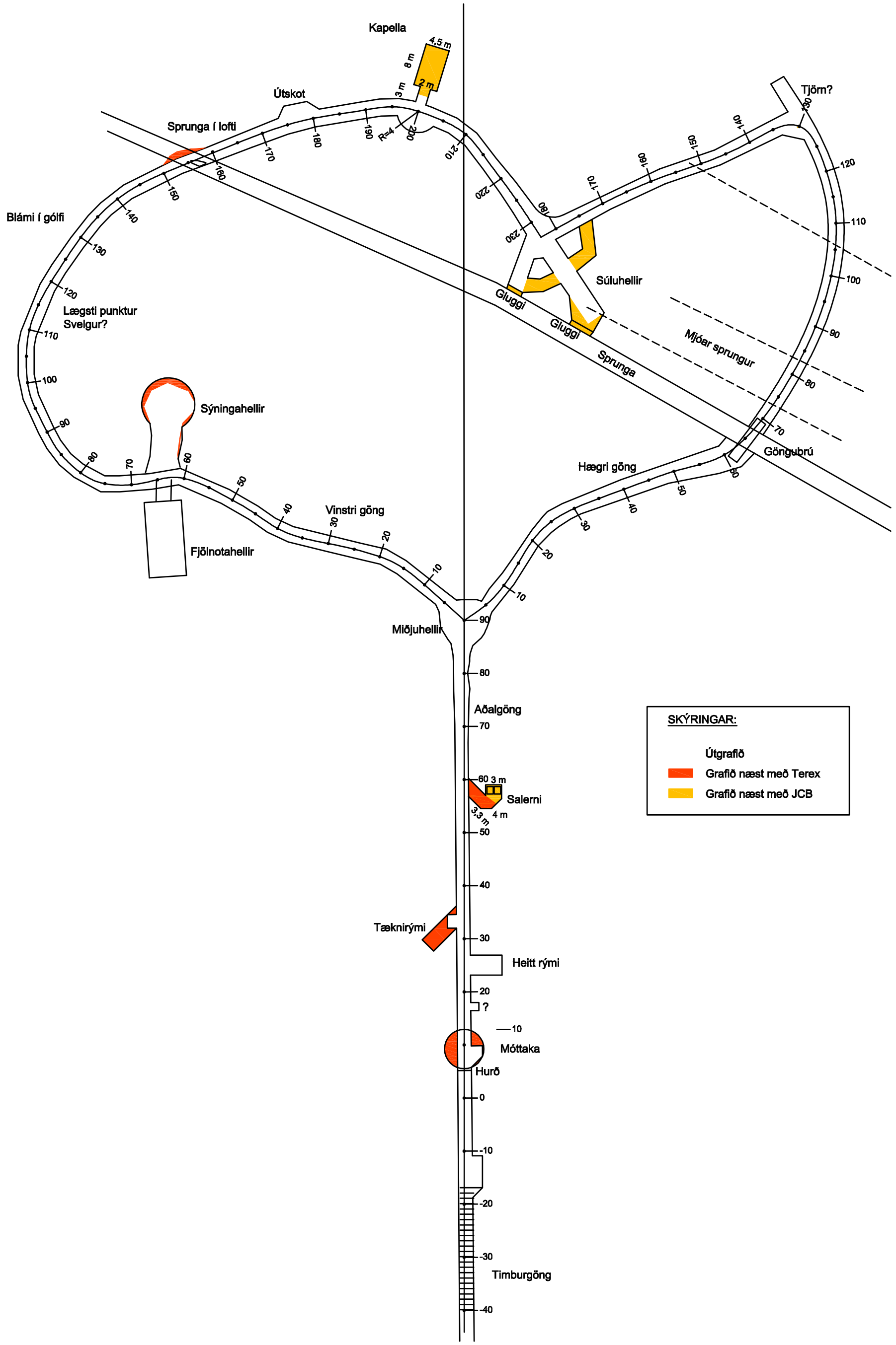
Yfirlitsmynd
M 1:500.000



Yfirlitsmynd
M 1:10.000

O:\I\Ísgöng ehf_5036\001_Ísgöng í Langjökli\08_Teikningar\Ísgöng - 02-04-2015.dwg

Planmynd
M 1:1.500



AÐALHÖNNUÐUR

ÚTG.	DAGS.	ÚTGÁFUFERILL	HANNAÐ	TEIKN.	YFIRF.

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Ísgöng í Langjökli
Vinnuteikningar

Yfirlitsmyndir

TEIKNINÚMER	BLAÐSTÆRÐ			
5036-001	A3	HANNAÐ:	RS	des 2014
01		TEIKNAÐ:	RS	des 2014
		YFIRFARIÐ:		
DAGS.	MÆLIKVARÐI			ÚTGÁFA
7.4.2015				

SAMÞYKKT:
Kennitala:

Ísgöng - Mælingar 17. febrúar