



# **Morphology and Development of the Longyearbreen Ice Cave, Central Spitsbergen, Svalbard**

Anna Stella Guðmundsdóttir



**Jarðvísindadeild  
Háskóli Íslands  
2011**

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10 eininga ritgerð sem er hluti af Baccalaureus Scientiarum gráðu í  
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Leiðbeinandi  
Ólafur Ingólfsson

Jarðvísindadeild  
Verkfræð- og náttúruvísindasvið  
Háskóli Íslands  
Longyearbyen, Ágúst 2011

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## Yfirlýsing höfundar

Hér með lýsi ég því yfir að ritgerð þessi er byggð á mínum eigin athugunum, er samin af mér og að hún hefur hvorki að hluta til né í heild verið lögð fram áður til hærri prófgráðu.

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Ágúst 2011

# Abstract

Monitoring of the Longyearbreen ice cave, the western drainage system of Longyearbreen glacier, central west Spitsbergen in Svalbard, for two field seasons reveals considerable changes between years in the morphology of the cave. Meltwater and internal deformation of the glacier ice are most important causes of changes in the cave channel. Meandering cut offs, Moulin, ice shelves, lakes and sediments are among the most important features that I studied by mapping the passage. Each of these features contribute to the development of the cave, reveal changes between the two field seasons and give indications for how the cave will evolve from this day on. My data and observations shows that the channel is of cut and closure origin, starting as a supraglacial stream that has cut into the glacier with incision rate higher than ablation rate. The annual changes of the morphology from April 2009 to April 2010 are addressed in details showing that above average temperatures in the melting season of 2009 and unusually high precipitation rate in January 2010 have had a high impact of the otherwise slower evolution of the channel. Going into details with the morphology over this period of time as well as the speculations about the initial formation of the cave can perhaps give an idea of the caves future development; it is highly likely that during the melting seasons over the next years the blockage in the end of the channel might not open up which would lead to the closing of the cave.

## Útdráttur

Kortlagning á íshelli í vestari bræðsluvatnsrás Longyearbreen jökuls á Svalbarða, yfir tvö tímabil í vettvangsvinnu sýnir töluverða breytingu milli ára í lögun hellisins. Bræðsluvatn, úrkoma og innri aflögun jökulíssins eru mestu áhrifavaldarnir við þróun hellisins. Mikilvægt er að skoða hin ýmsu kennileiti í hellinum þar sem hvert og eitt þeirra hjálpar til við að segja þróunarsögu hellisins til þessa dags, sjá breytingar milli tveggja vettvangsvinnutímabila og afla vísbendinga um hvernig hellirinn muni þróast áfram næstu árin. Athuganir úr þessari rannsókn voru bornar saman við hugtaka líkan fyrir þróun svokallaðra cut and closure rása gefa til kynna að bræðsluvatnsrás þessi sé slík rás þar sem hún byrjar sem bræðsluvatnsflæði ofan á jökli en sker sig smátt og smátt niður í jökulinn og við tekur aflögun jökulsins sem lokar rásinni að ofan. Í ritgerðinni er farið ýtarlega í breytingar á lögun hellisins frá apríl 2009 til apríl 2010 en hitastig var yfir meðaltali á leysingartímanum 2009 og óvenju mikil úrkoma átti sér staði í Janúar 2010 sem leiddi til þess að þróun hellisins, bæði formfræðileg og út frá setflutningi gekk hraðar fyrir sig en gera má ráð fyrir að gerist vanalega. Þegar litið er til smáatriða í lögun hellisins yfir þetta tímabil auk hugleiðinga um hvernig hellirinn myndaðist upphaflega má gefa sér hugmyndir um framtíð hellisins en mjög líklega mun stífla sem liggur í neðsta hluta rásarinnar ekki rofna að vori einhvers næsta árs sem leitt getur til þess að bræðsluvatn fylli að hluta til eða alveg upp rásina og þar með lokað hellinum.

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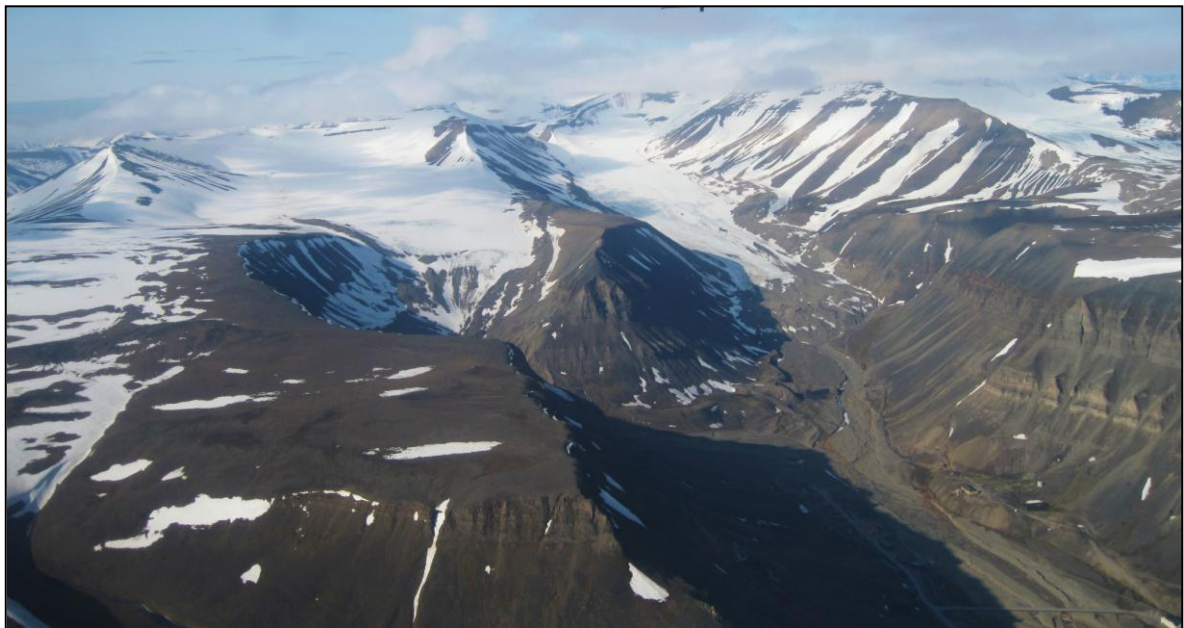
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# 1 Introduction

During March and April 2009 and 2010 I mapped the lowermost part of Longyearbreen ice cave, central western Spitsbergen, Svalbard (see figure 1.1). First I mapped the cave as a Term project in 2009 for a Physical Geography course in the University centre in Svalbard, where I documented sediment and ice features present in the cave. A year later I returned to the ice cave with the purpose of detailed mapping of it for this thesis. The purpose of mapping the cave so thoroughly over two field seasons is to reveal the considerable changes that can occur over the course of one year in the cave morphology and sediment transportation due to meltwater erosion and -transportation and movements within the ice body. I also use the maps and cross sections to support the idea of a cut and closure origin of the channel and compare how the evolution of the cave fits with a conceptual model of conduit development by cut and closure from Gulley et al. (2009). The cave was mapped in both plain and profile view for the most accurate comparison of both the ice and sediment features of the cave, which then are drawn in on the maps and the most important ones described more thoroughly with emphasis on the changes that have occurred.



*Figure 1.1 The two glaciers that flow towards the Longyeardalen valley. Longyearbreen is to the right on the photo and Larsbreen is to the left. Photo: A.S. Guðmundsdóttir, 2009.*

## 2 Geological settings

The Longyearbreen glacier is situated in the central west part of Spitsbergen, the largest island in the Svalbard archipelago. Svalbard lies in the Arctic Ocean and comprises islands between 74°-81° North and 10-35° east. The climate is generally mild for its latitude with an annual mean temperature of -6°C and mean annual precipitation of 400 mm in Longyearbyen. More than 60% of Svalbard is covered by glaciers and with such a low precipitation they are maintained because of the low temperatures. The mass balance turnover is low and the glaciers move slowly, also due to the temperature regime (Liestøl and Hagen 1993).



Figure 2.1. An overview map of Svalbard.

Map source: Map Sharing.org

Longyearbreen occupies a cirque accumulation basin above Longyearbyen, a Norwegian settlement in Svalbard, at 78°11'N, 15°31'E (fig. 2.3). The glacier is ca 5 Km long (Gulley et al, 2009) and it flows northward down in the direction of Longyearbyen valley.

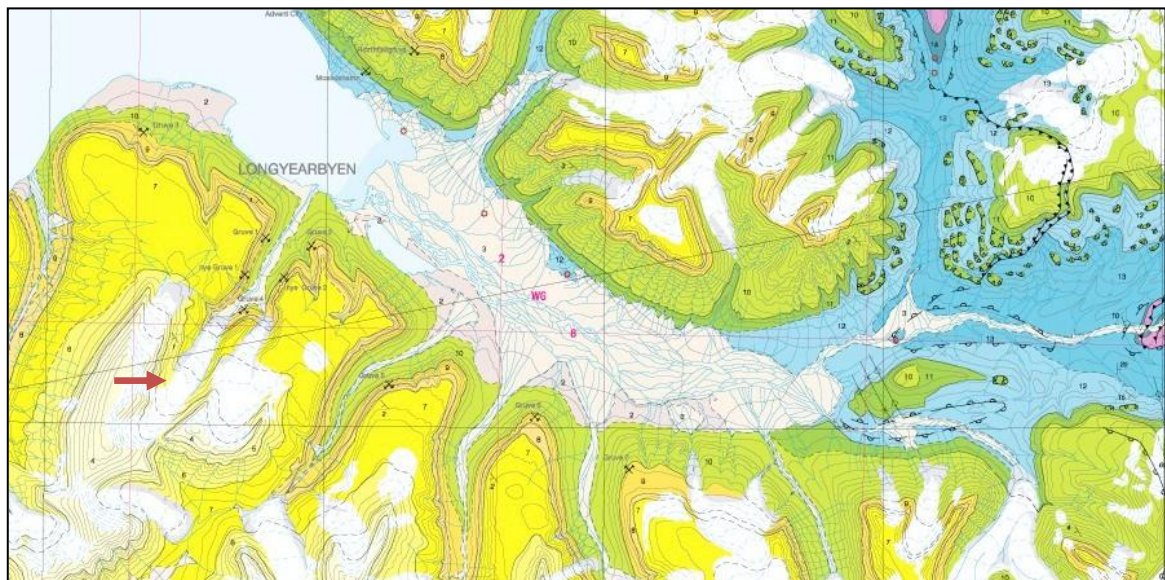


Figure 2.2 Geological map of Adventdalen. Longyeardalen lies in the Longyearvalley and Longyearbreen glacier is situated above the town of Longyearbyen. The arrow on the the map points to the approximate opening of the cave. Map: Geonetnpolar.no

Direct temperature measurements and radio echo soundings show that Longyearbreen glacier is predominantly below pressure melting point with the exception of a temperate surface layer in the upper reaches of it which is associated with refreezing of summer meltwater within the snowpack. (Etzemüller et al, 2000; Gulley et al, 2009). According to Blatter and Hutter (1991) Longyearbreen is therefore a polythermal glacier of type B. It seems to be frozen to its bed everywhere and moves entirely by ice creep with observed ice-flow velocities of 1-4 m a<sup>-1</sup> (Etzemüller et al, 2000; Gulley et al, 2009). The glacier surface is not very crevassed and it is mostly debris free apart from rather big ice cored terminal moraines and side moraines. Numerous meltwater channels develop on the glacier surface in the ablation season with lateral drainage systems on both sides having supraglacial and englacial reaches (Gulley et al, 2009).



*Figure 2.3. A view over Longyearbyen valley towards Longyearbreen which is marked with a red arrow. Photo: A.S. Guðmundsdóttir, 2009.*

According to Humlum 2002 (Humlum, 2005), Longyearbreen glacier is a typical central Spitsbergen glacier with respect to topographical setting. As there is no morphological or structural evidence that suggest surges in the past and findings of subglacial in situ vegetation it is possible to exclude a surge for at least the last 1104 cal. yr BP. Therefore it is most likely that the growth of Longyearbreen glacier represents a normal dynamic response to changes in precipitation, air temperature and changes in the amount of drifting snow and prevailing wind.

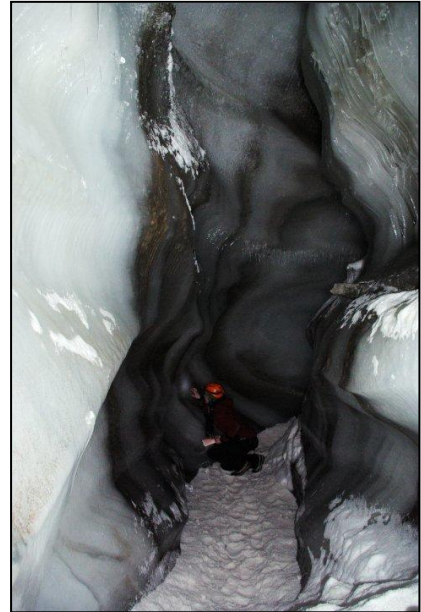
Crevasses are narrow and few below the equilibrium line of Longyearbreen glacier. Supraglacial meandering meltwater channels constantly erode into the glacier every

melting season and when these channels reach the depth of 8-12 m the channel slowly closes up in the upper part of it due to ice deformation. Therefore these channels are gradually transformed into englacial meandering tunnels and number of these channels can reach 20-50 m down to the bed. The glacier ice deformation rate is low in Svalbard due to low ice temperatures so in the winter, when the meltwater discharge has ceased these channels provide an access into the glacier and to its bed (Vatne 2001; Humlum, 2005).

### 3 Methods

Using distance measurer, inclinometer, compass and SAP (Shetland Attack Pony) instrument (electronic compass and inclinometer) I accurately mapped the shape of the cave with the help from various field assistants. To carry out the measurements we marked stations in the cave wall (Fig. 3.1) or on rocks in the cave with an ice axe where one could see well from one station to the next one. The stations were usually situated at meandering turns or on rocks in the cave. The stations made in 2009 are marked from A1 to A20 and the stations from 2010 are marked from -B7 to B16 with station A1 and B1 being the same starting station both of the years.

The distance measurer was used to measure the distance between stations both the years and in 2009 we used a compass to measure the bearing between stations and an inclinometer to measure the angle between each station. In 2010 I used an SAP instead of a compass and an inclinometer. SAP is the first combined electronic compass and clino and therefore measures both the inclination and the bearing with better than 1% accuracy. This instrument is much easier in use than the compass and inclinometer, especially in the dark cave, and therefore the work goes much faster.



*Figure 3.1. Locating stations and drawing the cave shape.  
Photo: E.Ólafsdóttir, 2010.*

After visiting the cave few times and finishing all the measurements between the stations the next step was to draw up a framework of the cave both in plan and profile view and a few cross sections. After drawing up the cave framework we went back in to the cave (Fig. 3.2) to draw the walls, floor, ceiling, sediment and ice features. When needed, we measured certain well chosen stations more thoroughly to be able make better cross sections.

The last step of the map making was to scan the hand drawn copy of the cave map and then draw it up properly in Adobe Illustrator, along with a legend and the cross sections.

One of the problems I encountered was that the cave shape did not allow exact height measurements from all angles. Often there were ice shelves in the way and sometimes it was just the curved ceiling ending up really narrow or in old passages, preventing a proper view from the station. This would be possible with proper climbing equipment and more training but for now I focused on measuring the best way possible for this situation.

Another problem was that when mapping the cave in 2010 the plan was to map it from the end of the channel and upwards like in 2009, but coming to the end of the channel, a new room had opened up that was not there in 2009. This room is higher up than the channel end from 2009. The room split up in two parts by the opening of it and I mapped one part of that channel but the other one was going almost completely parallel to the ceiling of

station -2 B and onwards up glacier. I could not see to the end of it and could not follow it since the floor was only a thin snow and ice layer making a roof over the former end of the cave.

For the measuring of the cave ceiling at station 8 in 2009 (which is the same spot both the years), I used a second station number since the ideal station to be able to see perfectly between next stations was in the outer meander but the ceiling was too low there. This can be better understood by looking at the cross sections from this point. For the profile maps I used the higher number since that one is more accurate for the area.

At the end of the mapping in 2010 it was impossible to measure properly further than B16 due to heavy snow in the cave which had to be crawled through to get around in the meandering cut off. The measurements there were just lightly made to be able to draw up the meandering cut off and numbers from last year from stations A17-A19 were used again to give the idea of how it looks but minimum changes were at that area.

B14 is just to use as a criterion as it is situated in a meandering and to be able to draw up the most accurate form of the meandering from all directions. Because of the snow cover from station 16 and onwards and the helping station B14 the end of the profile map should not be looked at literally but only to look at the direction of superimposed ice and approximate distances between stations.



*Figure 3.2 Going down the cave entrance. Photo: M. Sigurðardóttir, 2010.*

# 4 Data

## 4.1 Tables

Table 4.1 . Results of 2009 measurements.

Main stations	Bearing	Dip	Distance (m)	Up (m)	Down (m)	Right (m)	Left (m)	extra station	From A (m)	Up (m)
<b>A1</b>				0,7	1	0	1,56	<b>1</b>	1,56	3,75
A1-A2	140°	12°	8,5							
<b>A2</b>				0,3	0,9	1,42	1,1			
A2-A3	150°	0°	5,47							
<b>A3</b>				0,59	0,62	1,8	0	<b>3</b>	1,8	2
A3-A4	268°	8°	11,83							
<b>A4</b>				1,6	0,6	0	1,13			
A4-A5	232°	2°	14,11							
<b>A5</b>				1,28	0,51	0	1,69			
A5-A6	116°	2°	6,97							
<b>A6</b>				1,92	0,77	1,57	0			
A6-A7	164°	4°	6,93							
<b>A7</b>				0,5	0,91	0	1,36	<b>7</b>	1,36	4,46
A7-A8	78°	4°	7,18							
<b>A8</b>				0,6	1	3,87	0	<b>8</b>	1,9	5,3
A8-A9	197°	2°	7,71							
<b>A9</b>				5,72	1,1	0,6	1,19			
A9-A10	118°	10°	3,08							
<b>A10</b>				2,95	1,58	0,79	0			
A10-A11	220°	14°	6,65							
<b>A11</b>				1,6	1,17	1,8	0,2			
A11-A12	288°	15°	3,98							
<b>A12</b>				3,7	1,51	0,84	0,3			
A12-A13	352°	4°	6,2							
<b>A13</b>				1,5	1,4	0,84	0,8			
A13-A14	325°	0°	2,4							
<b>A14</b>				3	1,25	0,5	0,75			
A14-A15	290°	6°	5,78							
<b>A15</b>				1,6	1,38	0,9	0,38			
A15-A16	310°	1°	3							
<b>A16</b>				2,6	1,47	0	1,3.			
A16-A17	230°	6°	4,6							
<b>A17</b>				1	1,33	0	1,72			
A17-A18	120°	6°	4,69							
<b>A18</b>				0,83	1,52	0,64	0,7			
A18-A19	58°	15°	3,77							
<b>A19</b>				1,39	1,25	1,1	0,57			
A19-A20	160°	15°	4,5							

*Table 4.2. Results from the 2010 measurements. The numbers are from the same area that was measured in 2009.*

Main stations	Bearing	Dip	Distance (m)	Up (m)	Down (m)	Right (m)	Left (m)	Extra station	From B (m)	Up (m)
<b>B1</b>				1,86	0	1,31	0,77			
B1-B2	125°	12°	7,77							
<b>B2</b>				1,7	1,1	0,2	1,46			
B2-B3	131°	8°	5,56							
<b>B3</b>				1,42	0,42	1,8	0			
B3-B4	227°	9°	6,05							
<b>B4</b>				1,09	1,15	1,42	1,36			
B4-B5	218°	0°	19,2							
<b>B5</b>				1,54	0,7	0	1,87			
B5-B6	153°	1°	7,65							
<b>B6</b>				1,43	0,92	1,35	0,43			
B6-B7	150°	3°	4,83							
<b>B7</b>				1,35	0,48	0	1,71			
B7-B8	56°	4°	10,11							
<b>B8</b>				5,63	1,21	4,02	0,45	<b>8</b>	2,4	0,43
B8-B9	169°	1°	5,44							
<b>B9</b>				5,8	0,88	2,07	1,76			
B9-B10	159°	4°	6,1							
<b>B10</b>				4,43	0,28	1,7	0,68			
B10-B11	223°	5°	6,93							
<b>B11</b>				3,4	0,5	1,37	0			
B11-B12	301°	6°	4,66							
<b>B12</b>				3,48	1,09	1,06	0			
B12-B13	339°	4°	6,05							
<b>B13</b>				1,51	0,84	0	1,46			
B13-B14	296°	4°	8,04							
<b>B14</b>				2,11	1,1	X	X			
B13-B15	290°	4°	6,03							
<b>B15</b>				3,07	0,84	1,36	0			
B15-B16	160	9°	10,9							
<b>B16</b>				1,62	0,98	0,25	1,32			

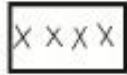
*Table 4.3. Results from the 2010 measurements on the newly opened area in the inner most part of the cave.*

Main Stations	Bearing	Dip	Distance (m)	Up (m)	Down (m)	Right (m)	Left (m)	Extra stations	From B (m)	Up (m)
<b>B1</b>				1,86	0	1,31	0,77			
B1-B-2	81°	0°	11,03							
<b>B-2</b>				1,69	0,24	1,33	1,24			
B-2 - B-3	336°	10°	8,97							
<b>B-3</b>				4,11	0	0,48	0,23			
B-3 - B-4	312°	37°	6,82							
<b>B-4</b>				0,76	0,83	1,42	0,51			
B-4 - B-5	327°	0,8°	6,92							
<b>B-5</b>				0,65	0,24	0,78	0,73			
B-5 - B-6	323°	0,5°	7,98							
<b>B-6</b>				0,56	0,93	0,43	2,18			
B-6 - B-7	301°	10°	4,97							

## 4.2 Legend



Sediment of various sizes.



Snow roof



Lake



Superimposed ice layers in the channel walls



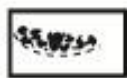
Superimposed ice filled with sediment of various grain sizes



Ice shelves



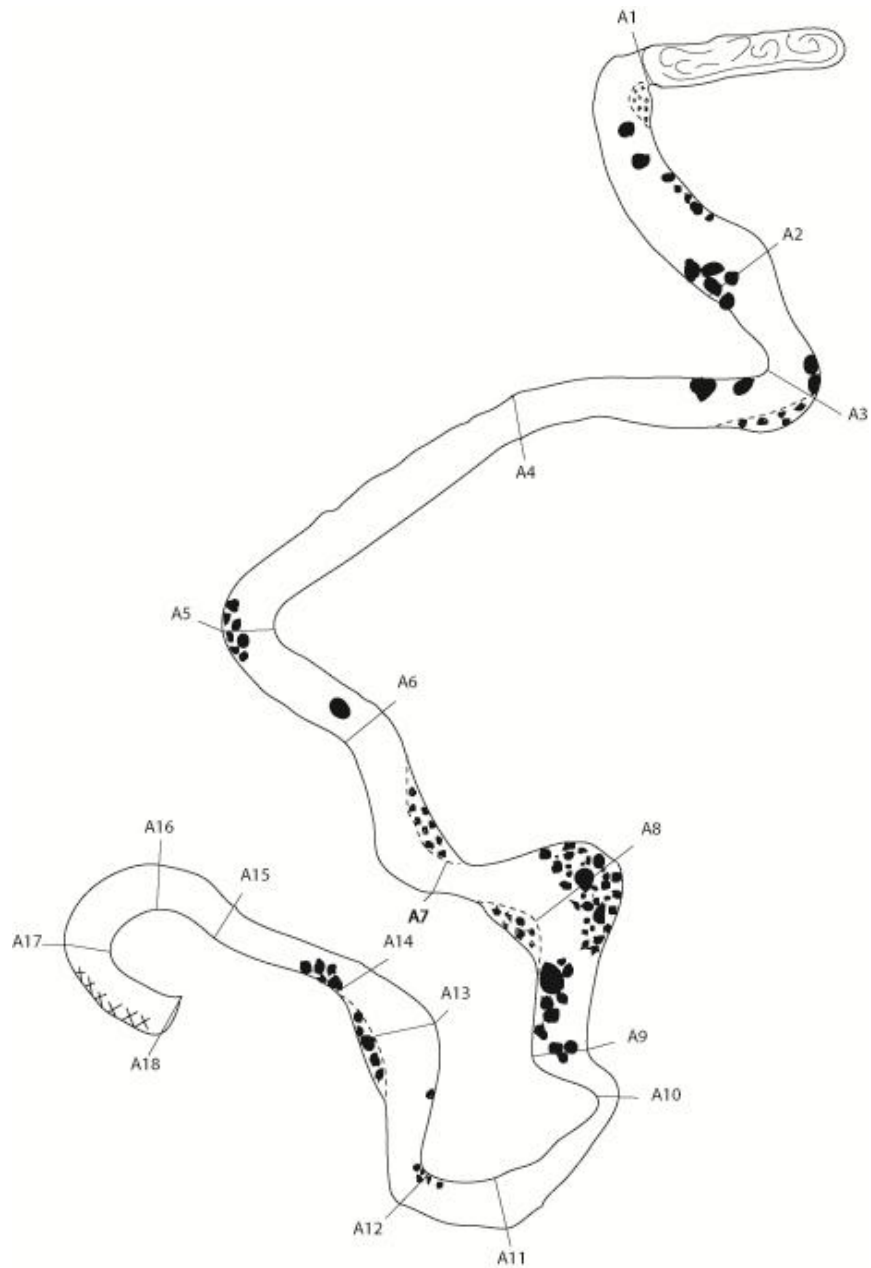
Irregular ceiling height



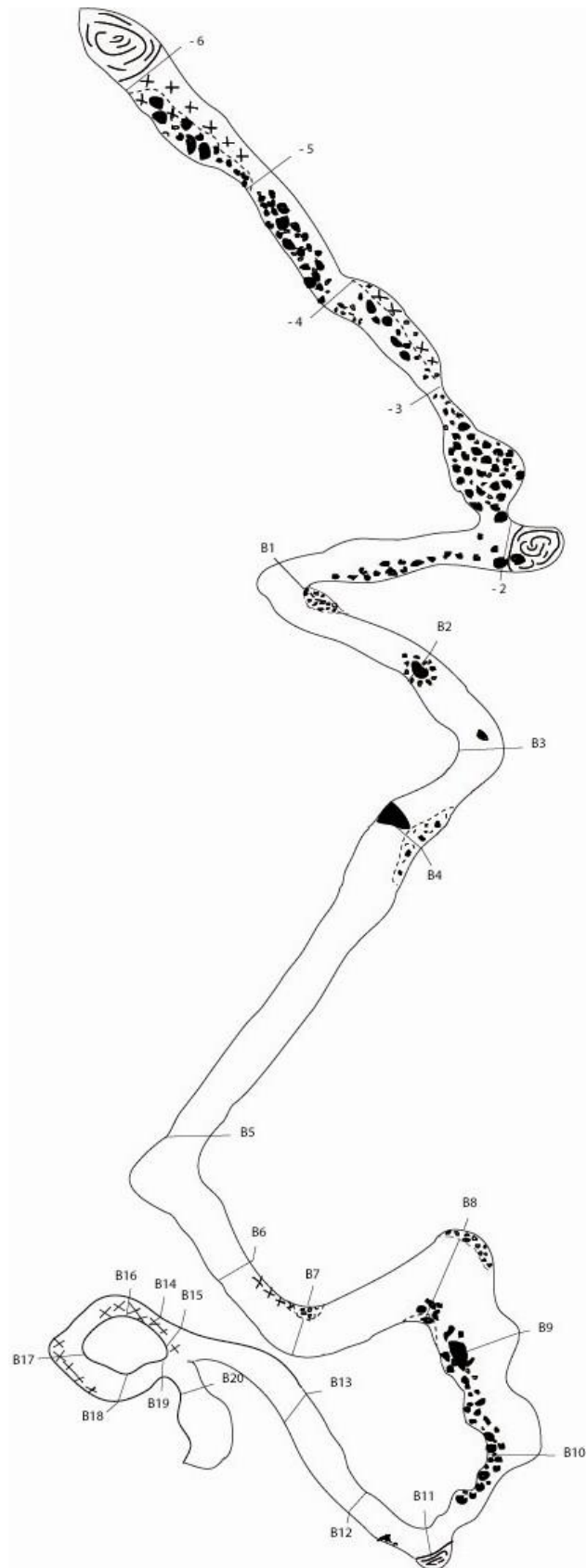
Sediment covered ice shelves

## 4.3 Maps

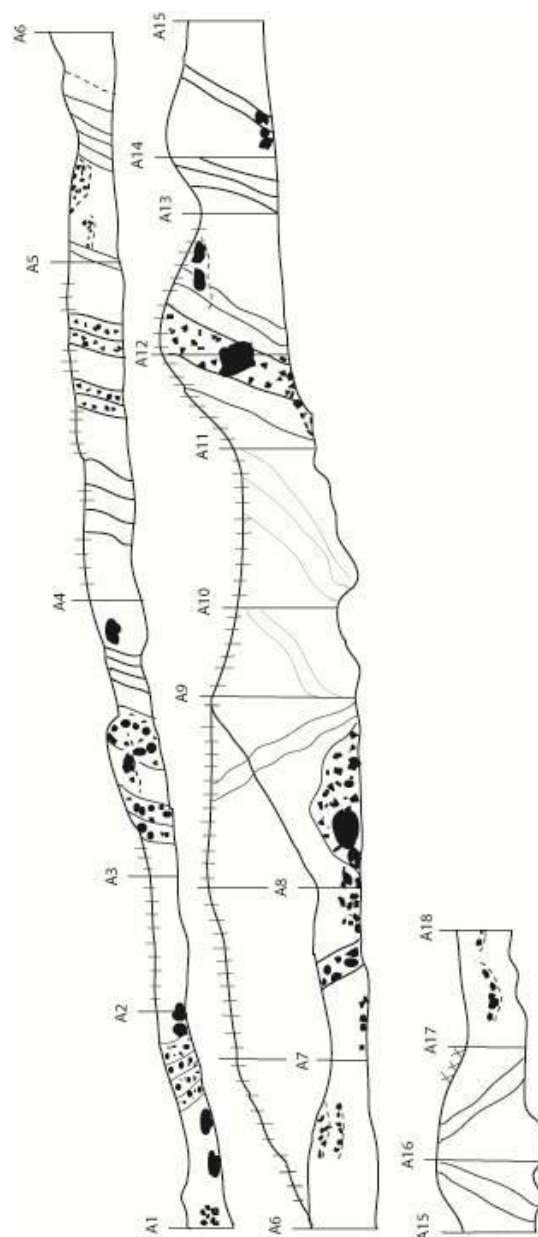
### 4.3.1. Plain view map from 2009



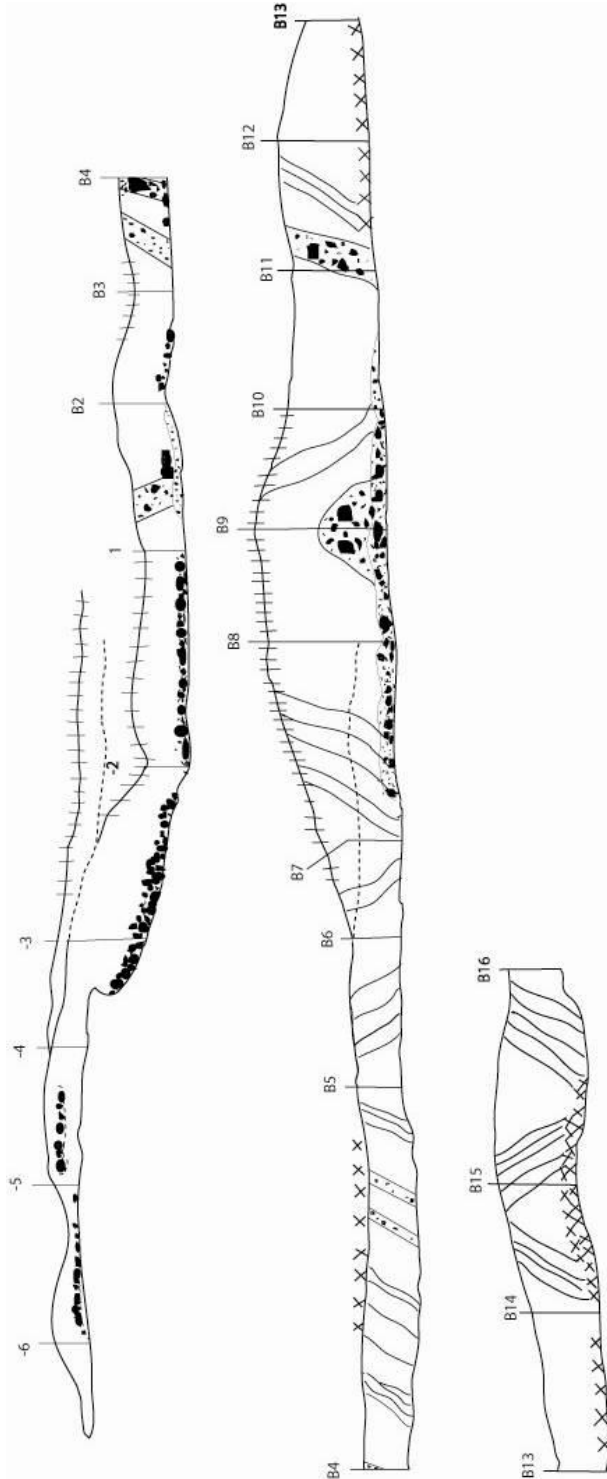
#### 4.3.2. Plain view map from 2010



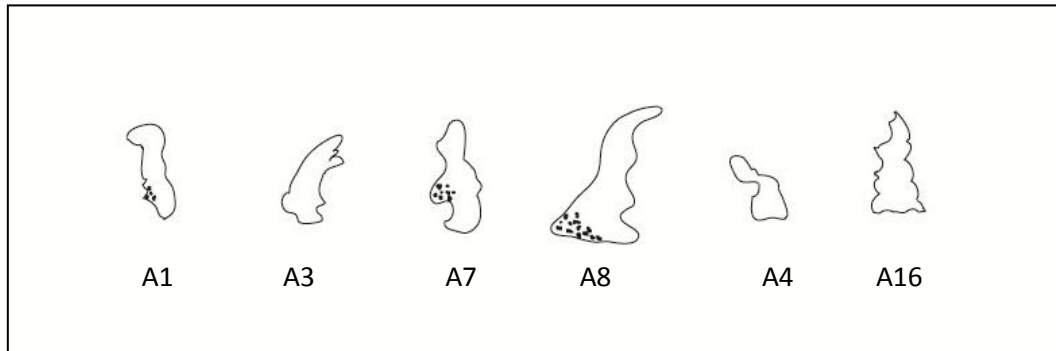
### 4.3.3 Profile map from 2009



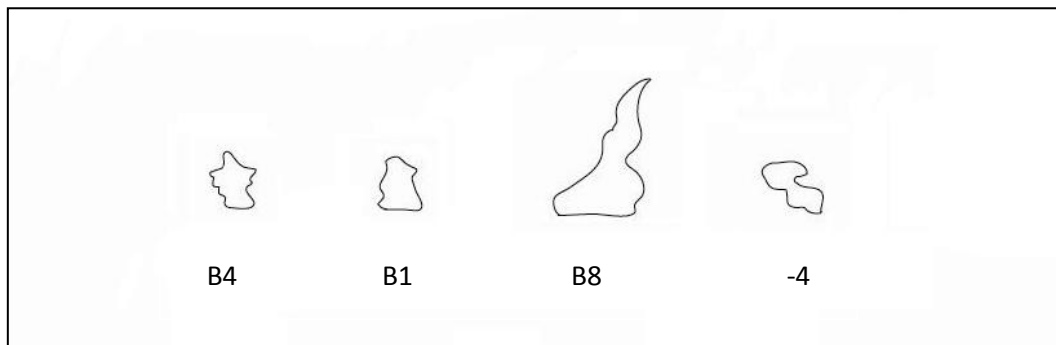
4.3.4 Profile map from 2010



## 4.4 Cross sections



*Cross sections from the 2009 measurements showing the station numbers.*



*Cross sections from the 2010 measurements showing the station numbers.*

# 5 Morphology

## 5.1 Ponds

The cave is gradually sloping down glacier with few steeper steps along passages where small waterfalls have formed during the melt season. Beneath these the cave floor is bulging up (Fig.5.1). This is the result of water collecting in erosional basins during melt that freezes and bulges up in the winter when meltwater production stops. These bulges were much more noticeable in 2009 than in 2010.

At various places along the cave passage it is possible to see well rounded sediment filling in the ceiling or in the walls (Fig. 5.2, 5.3) This I have interpret to be former cave floors where ponds have formed and with time have partly filled up with sediment when the stream runs down the cave carrying a lot of sediments which gets trapped in the ponds deep depressions. One of the biggest ones seen in 2009 was between station A17 and A18 but it in 2010 it was not to be seen due to snow cover.



*Figure 5.1 A waterfall and a bulged up pond beneath it.  
Photo: A.S. Guðmundsdóttir.*



*Figure 5.2 A former pond or a sediment trap. Photo: A.S. Guðmundsdóttir.*



*Figure 5.3 A cross section of an old pond high up in the ceiling. Photo: A.S. Guðmundsdóttir.*

## 5.2 Ice shelves

The cave is meandering considerably and in most of the meanders there are ice shelves, often with sediments sitting on top of them, in some places it is in the inner side of the meandering and in other places the sediment is on the outer side of the meandering. Station 8 (which is the same station both the years) has both sediment covered shelves in the inner meander and the outer meander. The shelf in the inner meander of station 8 is older and considerably higher up than the one in the outer meander.

In 2009 the outer shelf at station 8 was noticeably wide and had a lot of sediments on top. Coming back in the cave in 2010 there was only a small part of the shelf left; the rest had been eroded away with all its sediment (Fig. 5.4).



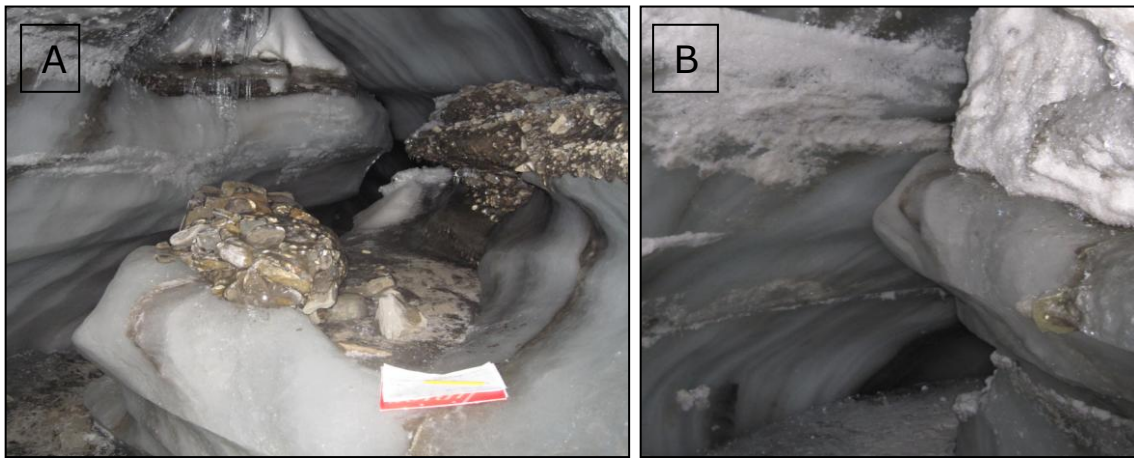
*Figure 5.4 The still forming ice shelf at station 8 in 2010. The dotted lines show where the shelf was reaching in 2009. Photo: A.S. Guðmundsdóttir.*

The inner shelves are likely formed in places where the slope of the channel floor is steep or when the water flow rate is high, like in the summer during intense melting period or high precipitation. The water therefore passes the inner meander with less force and erodes more of the outer meander with the result that a part of the ice is left out in the inner meander forming the shelves. When the flow is slowing down as it gets colder and the stream reduces again it might erode the lowest part of the shelf a bit, making the shelf stick out. This might be what happened at station 8 between the two field seasons.

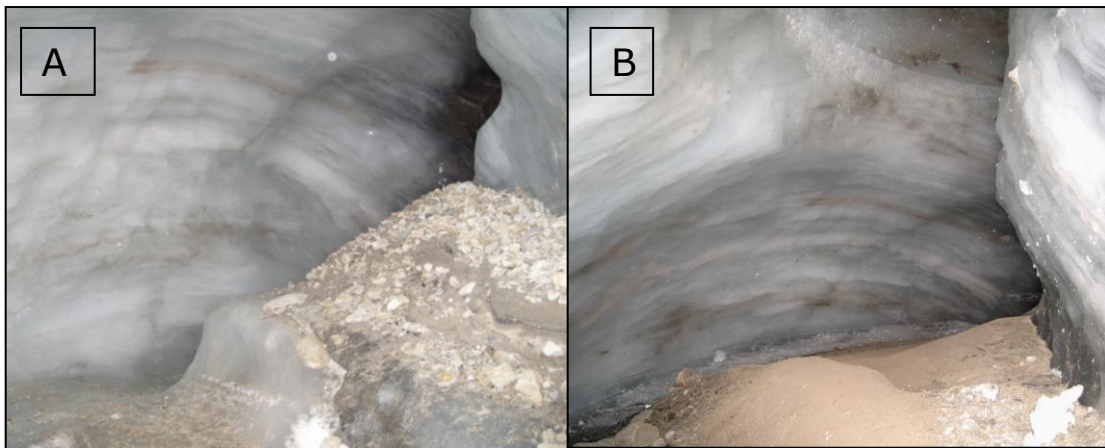
The outer shelves are more likely to form in places where the slope is not as steep or when the flow rate is less. The water drains the shortest way to get through the channel and skips the outer part of the channel, erodes more the inner meander and leaves a higher shelf in the outer part of the meandering. The sediment lying on top of the shelves might be from when the flow is decreasing and loses its power to carry on the sediment.

These ice shelves can be observed intermittently through the whole cave. They are evolving every year as big shelves in meanders and are not to be confused with smaller steps in the passage walls which are visible when looking upwards towards the ceiling. The bigger shelves can be forming for some years while smaller steps represent former height of the cave floor as they form annually and are seen on both sides of the passage.

At the inner most part of the cave, by station 1 there was a big inn meander ice shelf with considerable amount of sediment of different sizes (Fig. 5.6.A) but when coming back in 2010 the ice shelf had mostly eroded away and only very fine sediment was left on the small shelf (Fig.5.6. B). By station 7 the shelves only got higher as the floor had been eroded and a thick layer of snow and ice covered the shelf making it impossible to see if the sediment was intact (Figure 5.5.A and 5.5.B).



*Figure 5.5 A) Ice shelves with sediment on top of them by station 7 in 2009. B) The same lower ice shelf in 2010 but now snow covered and much higher and evolved. Photos: Guðmundsdóttir, A.S.*

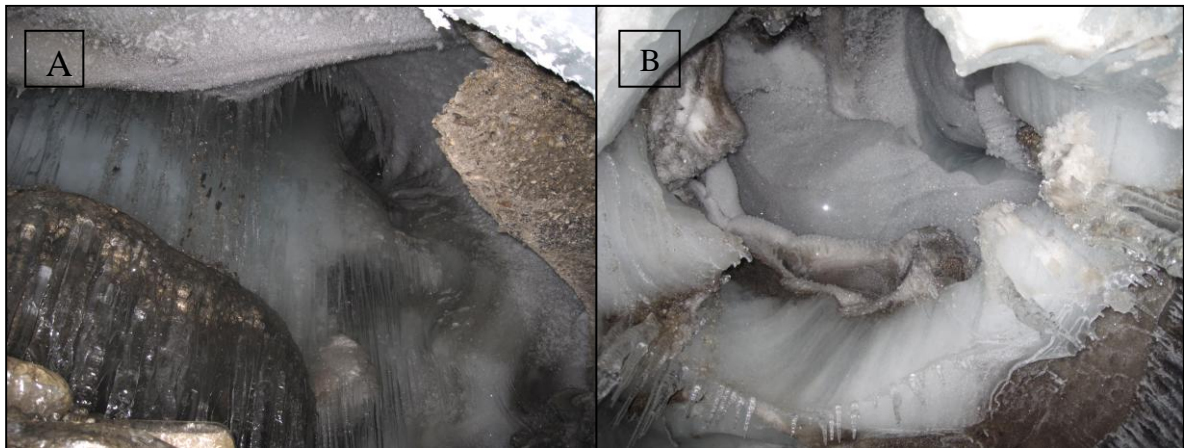


*Figure 5.6 A) An ice shelf covered with sediment of all sizes by station 1 in 2009. B) The shelf had eroded considerably in 2010 and the coarser sediments were mostly gone only leaving fine clay and silt particles. Photos: Guðmundsdóttir, A.S.*

## 5.3 Moulin

At approximately the middle section of the cave, the hallway of the cave starts to widen and easier to get through. This occurs right after passing a small rounded side step in the cave where ones suddenly sees clearly up to the ceiling and where there are extraordinary many icicles compared to elsewhere in the cave. This I interpret to be a Moulin, which is a narrow, tubular chute or crevasse which surface water uses to enter the glacier. When more water enters the channel, the channel walls get wider due to more erosion/melting of the streaming water.

Around stations 6 and 7 there are many stages of sediment filled shelves and former cave floor levels surrounding the area and almost forming a circular hollow instead of a long passage. At this area one can see properly to the ceiling where there seems to be a small tube or a passage at the top and unusually many and big icicles surround the area (Fig. 5.7). This makes it seem like something different than the normal down passage stream cut into the cave. This could be a Moulin as well but not as big and obvious as the one that is situated in the middle section of the cave. This is not shown on the maps as it is only possible to see and measure it if one gets higher up towards the ceiling.

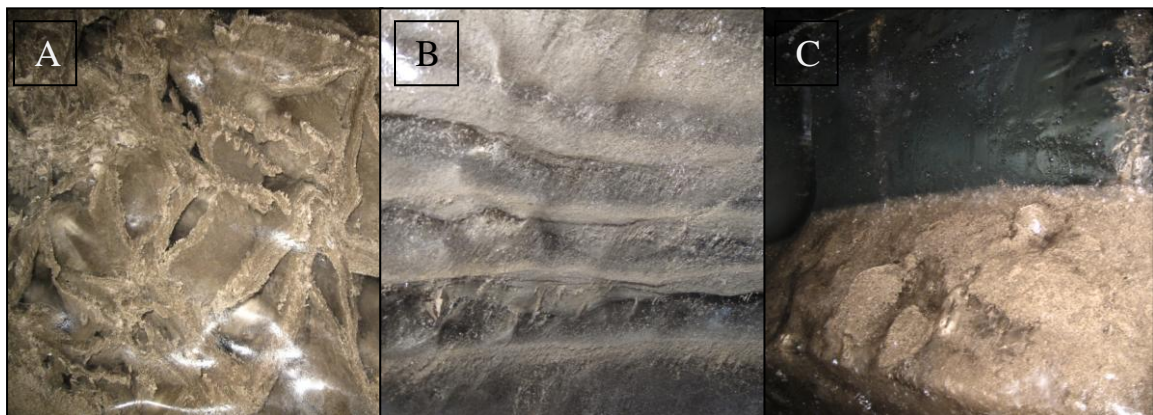


*Figure 5.7 A) Possible Moulin by stations 6-7. B) Seen up the Moulin that is situated at ca. The middle of the caves passage. Photos: Guðmundsdóttir, A.S.*

## 5.4 Superimposed ice

Pure superimposed ice layers (Fig.5.9.A) and superimposed ice layers with sediment (Fig.5.9.B), or sediment bands as I refer to it here, occur through the whole cave. The superimposed ice forms at firn line at shallow depth because of a surface melting during summer or due to heavy winter rainfall (Baird, 1952). When the melt refreezes it releases latent heat. This zone restricts any further percolation of melt water but can melt from radiative energy once overlying snowpack is < 20 cm. In early summer the superimposed ice can be bubbly and at late summer, the ice is bubble poor (Boggild, 2007). As the superimposed ice in Longyearbreen ice cave is bubble poor it was most likely formed during late summer.

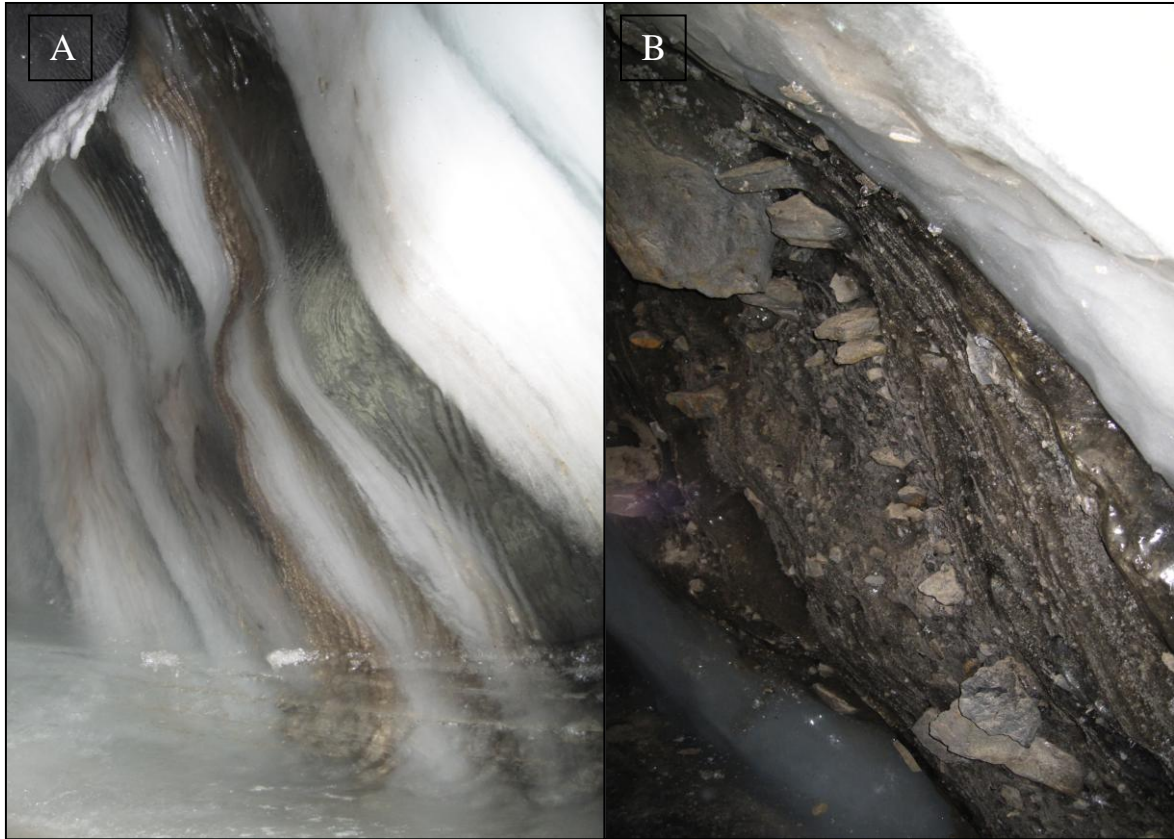
The sediment bands can contain sub-angular to angular pebbles, cobbles and boulders along with finer material such as sand, silt and clay particles. At few places along the passage there are sediment bands which only contain finer material of silt and clay. They can vary in thickness and shape but most of the sediment bands that are lying close together are parallel to each other and are forming almost a straight line. The largest exception to this is a thick layer of superimposed ice between stations 1 and 2 which contains clay sized sediment in it that is highly irregular and forms many small bands of sediment within the superimposed ice layer which are not parallel to the ice layer but point in many different directions. This layer can be seen on figure 5.8 A.



*Figure 5.8 A) Irregular fine sediment in superimposed ice. B) Fine layered silt and clay in superimposed ice. C) A thick layer of very clear superimposed ice above a thick layer of superimposed ice filled with fine sediment. Photos: Guðmundsdóttir, A.S.*

The fine sediment bands in the superimposed ice are likely the result of very fine sediment that has been transported by wind to Longyearbreen, and then has percolated through the snow and firn with rain and meltwater and deposited with the superimposed ice. The sediment bands that contain bigger grain sizes, up to boulder size, are likely the result of rock avalanches that have fallen down onto the glacier from the mountains surrounding the glacier at the top of the cirque.

The superimposed ice layers can show the flow lines of the glacier. The dipping direction of the superimposed ice is drawn up in the profile map and can be used to see the how it is at various places along the passage and see how they are parallel to each other at different stations along the passage. This can be seen by looking at both the maps in profile and plan view.



*Figure 5.9 A) Layers of superimposed ice, both clear ice and layers with fine sediment in it. B) Superimposed ice filled with sediment of all sizes. Photo: Guðmundsdóttir, A.S. 2009*

## 5.5 Cave Lakes

Bodies of water or lakes can be stored in various glacier environments wherever free drainage is prevented by some form of ice (Benn & Evans, 2010). Englacial lakes such as the ones we have in Longyearbreen ice cave are usually small and typically occupying blocked conduits or small Moulins (Benn & Evans, 2010; Gulley et al., 2009b). This can result in the closing of the caves passage for good if the dam cannot be broken and the water is allowed to fill up the passage while trying to find another way to drain through the glacier.

In the northern end of the map from 2009 one could see on the map that the cave ends in ca 8 m long, elongated lake after station A1. The lake must have formed when the ablation zone of the glacier froze in the autumn, causing a channel blockage in the deepest end of the cave so the water could not drain out through the end of the cave and filled up the lowermost part of it. Beneath the lake surface I suspect there is an englacial Moulin or waterfall. It is impossible to see the tunnel continue as the ceiling lowers down to the lake surface.

When mapping the cave again in 2010 the blocked channel had drained during the melting season allowing the cave still to reach as far down to the ablation zone. Another blockage must have formed again at the same area or close by after the cave had drained enough but now the lake was much smaller than the one in 2009. It was now not longer an elongated lake but a small rounded lake in the deepest part of channel which made it possible to walk further in the cave.

In the map of 2010 at the furthest end of the cave, a newly found passage can be detected. At the furthest end of that passage there is also a small rounded lake, similar to the one at station -2, where the water most likely had drained through to the end of the glacier at one point.

The lakes are not totally frozen, they have straight and even surfaces and are very distinct from the ice on the cave floor which is uneven and often has a thin bubbly layer on it which sometimes breaks when stepped on.



*Figure 5.10 A) The lake seen from station 1 in 2009. It was only frozen the first meters. B) The same passage in 2010 that the lake was at in 2009, view towards station 1. The area was completely dry and only fine sediment left on the floor. Photo: M.S. C) The lake in 2010. It was considerably smaller and not frozen. Photo: Sigurðardóttir, M.*

## 6 Development of the ice cave

### 6.1 The formation of the cave to this day

The Longyearbreen ice cave is an englacial meandering channel incision with a closed roof. It formed from supraglacial meltwater stream channel that evolved into an englacial conduit. For this to happen, the ablation rate must be slower than the incision rate of the meltwater and does that only happen where surface melting is inhibited by low air temperatures or debris cover on the glacier. When the water has incised the glacier ice significantly internal deformation will take over and push together the upper part of the conduit. Snow drifts or jams of rafted ice blocks can then initiate closure of the upper reaches of the conduit and at lower levels of the glacier snow, debris and aufeis can add to blockages where gaps persist in the conduits roof (Gulley et al. 2009). Looking at photo 6.2 and at the cross section from station 4 one can see a closure as a result of the glacier ice pushing in from one side closing up the roof as the water in the channel keeps melting and eroding the path and therefore avoiding closure of the channel itself. These processes are best made out by looking the conceptual model of conduit development by cut and closure from Gulley et al (2009). At this point the Longyearbreen ice cave seems to be mainly at stages b and c but at the uppermost reaches of the cave it seems to be at stage a when looking into the cross sections.

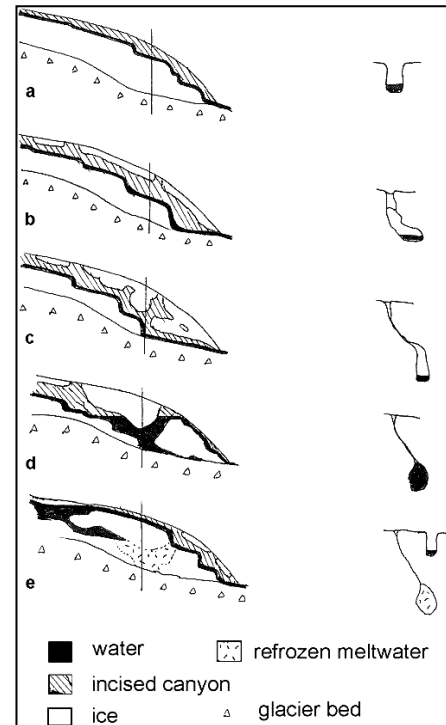


Figure 6.1 Generic model of cut-and-closure conduit evolution (Gulley et al. 2009a)

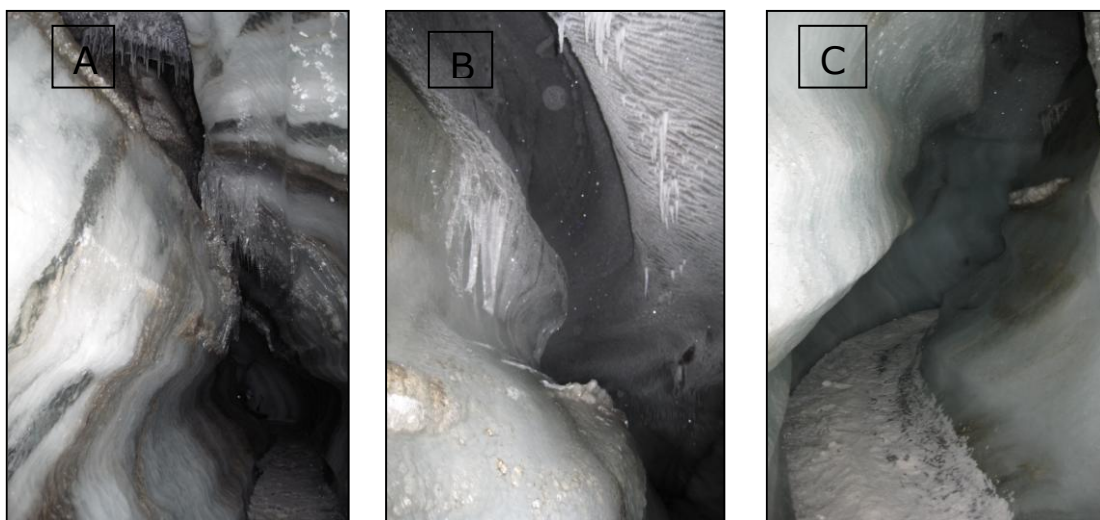
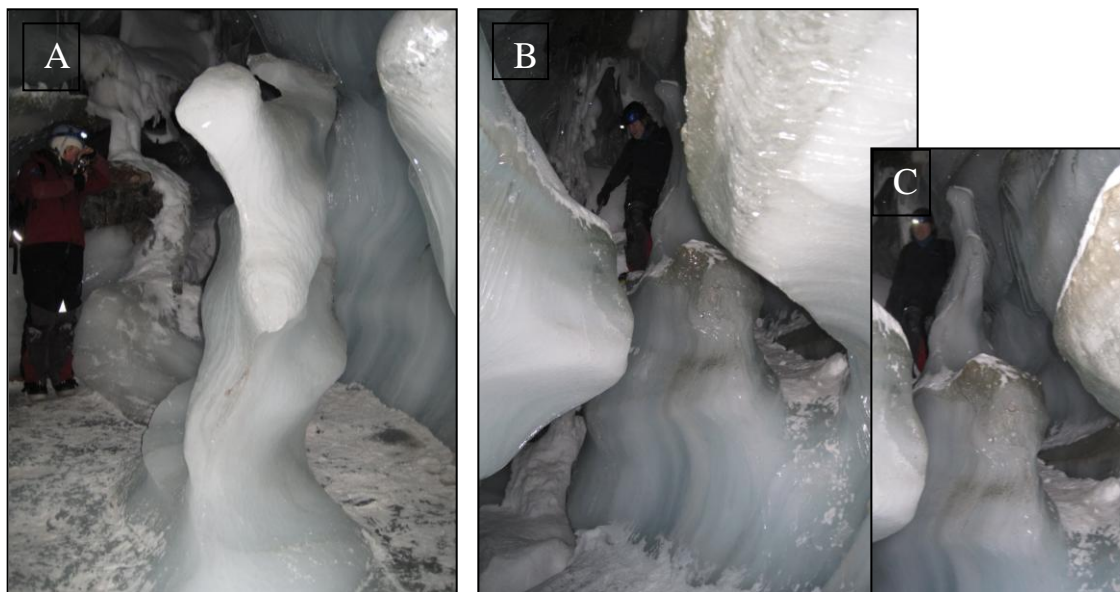


Figure 6.2 Various cross views of the channel. Showing stages b-c. Figure A shows a closure in process between stations 4 and 5. Photos: Guðmundsdótti, A.S.

## 6.2 The major changes and discoveries between the field seasons of 2009 to 2010

### 6.2.1 Lowering of cave floor

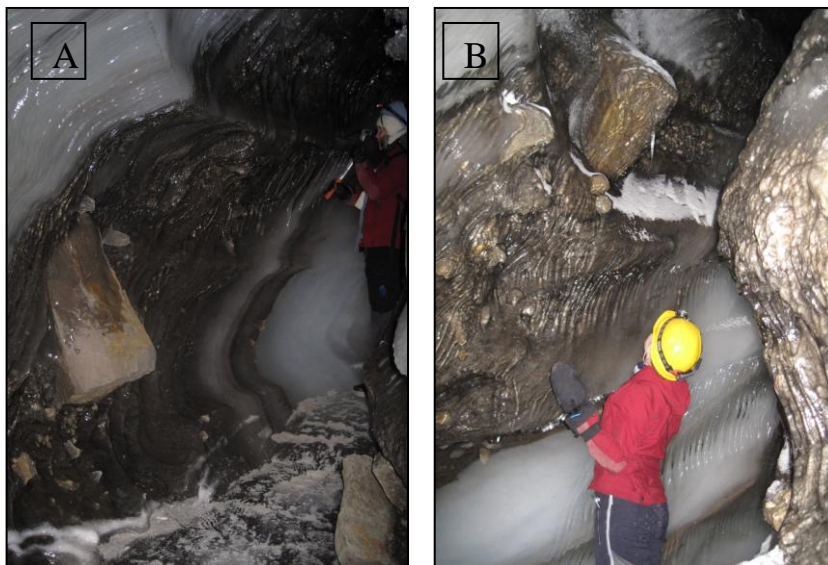
Coming back to the cave in 2010 the first changes noticeable was the lowering of the cave floor. In the uppermost reaches of the cave the channel had eroded down 1-2 metres which seems to be unusually large when looking up the walls of the cave where one can see former annual floor levels in the ice having only ca. 0.5-0.7 metres lowering per year. This can be seen clearly on pictures taken at the same spot in both field seasons (Fig. 6.3, 6.4, 6.5) where the meltwater has made a nice ice sculpture that in 2009 was standing ca 2 metres lower than in 2010. It can also be seen on photos of glacier table where it is at ca knees height in 2009 and above the head in 2010 and a big boulder in a sediment band around station A3 and B3 which was considerably higher up in the ceiling the latter year. The biggest change in the elevation of the cave between years is at the uppermost part of the channel, close to the caves entrance, further down the passage where the map starts the changes are not as great but they do vary a lot and can be from few cm to ca meter.



*Figure 6.3 A natural ice sculpture in the uppermost part of the channel. A) The ice sculpture in 2009. B) and C) The ice sculpture in 2010 was much higher up due to extreme erosion of the caves floor. Photos: Guðmundsdóttir, A.S.*



*Figure 6.4 A) Glacier table sticking out of the glacier ice in 2009. Photo: Benn, D. 2009. B) The same rock in 2010 high above the head. Photo: Sigurðardóttir, M.S. 2010.*



*Figure 6.5 A boulder sticking out in a sediment band close to station 3. A) Picture from 2009, note the person far to the right for scale. B) Picture from 2010, the boulder is considerably much higher up in the ceiling. Photos: Guðmundsdóttir, A.S.*

### 6.2.2 Meandering cut off

In the south end of the cave in 2009 the passage was meandering into a sharp loop. When returning in 2010 the loop had been cut off by the stream and a small waterfall had formed. The water must have been able to erode/melt the wall in the middle of the loop early in the melting season leaving the meander for good. The changes in the meandering cut off itself seemed to be very small if any at all but difficult was too see it because of a heavy snow layer. It was though very obvious that the floor level in the meander itself had only lowered few cm. The new little passage on the other hand was very steep and wide.



*Figure 6.6 The meandering cut off. View from station B20. The dashed line shows where the wall that was eroded was before. Photo: Guðmundsdóttir, A.S.*

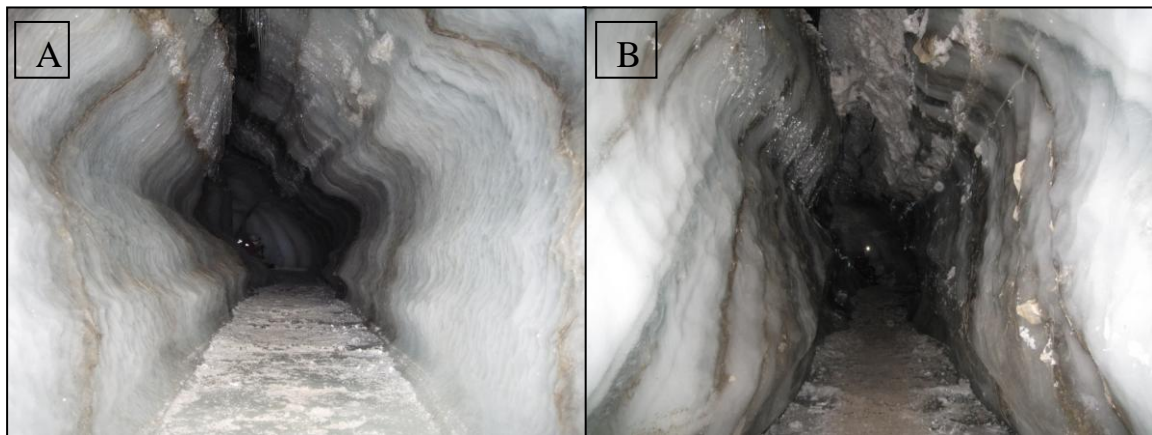


*Figure 6.7 The meandering cut off seen from where the wall was before towards station B20 where Minney is standing. The white arrows show where the water was flowing before the field season in 2009 and the orange arrows show the flow route before the field season in 2010. Photo: Guðmundsdóttir, A.S.*

### 6.2.3. Internal deformation

The internal deformation of the glacier ice can be seen clearly when looking at the plain view maps where the stations 13 and 17 are much closer together on the map in 2010 than on the 2009 map and the passage between station 3 and 5 has changed its form a bit and has narrowed.

Looking at photos from the passage between stations 4 and 5 it is possible to see the change that has happened during the year (Fig 6.8). The form of the wall has changed a bit and the walls are considerably closer together than in the year 2009. A big boulder that is sticking out of the wall is also a good referent as the tip of the boulder was almost touching the wall in 2010 on the other side but it was not close to do that in 2009 (Fig. 6.9).



*Figure 6.8 A) The passage between station 4 and 5 in 2009. B) The same passage between stations 4 and 5 taken from the same spot in 2010. The passage has narrowed considerably and changed shape. Photos: Guðmundsdóttir, A.S.*



*Figure 6.9 A) A big boulder is sticking out of the wall by station A4 in 2009. B) The same boulder in 2010 considerably closer to the opposite wall. Photos: Guðmundsdóttir, A.S.*

#### 6.2.4. A new passage

The draining of the lake revealed a whole new space in the cave in 2010. This cavity was situated by the start of the 2010 lake reaches at station -2, to the left of it looking down channel. The new cavity is at higher level than the lake and there is a relatively steep slope and a big step upwards to the room, which is basically another channel. The newly found channel then continues considerably straight to the end where there was a lake similar to the one at station -2.

This cavity also has another reaches which is going in opposite direction to the passage from the entrance of the cavity, which was along the passage of the main channel that I mapped. This I have interpreted to be an older channel at higher relieve from which the new channel has developed from and a snow-ice roof has closed up between. I did not map that area properly since the snow roof was not stable enough to walk on but a part of it is drawn up on the profile map.

The passage between stations -2 and -3 is full of sediment lying irregularly on the floor and covering it completely. Around and over the irregular lying sediment there is an ice layer indicating that a considerable amount of water was present there when the channel started to freeze over again. Icicles in the old passage were also of great amount so a opening in the ceiling in this area is very likely to be present but impossible to see because of the icicles themselves.



*Figure 6.10 A view from station -2 to the entrance of the new room. Photo: Guðmundsdóttir, A.S.*



*Figure 6.11 A view towards station -3. After the slope and the step the passage continues onwards and also in the direction of where the snow roof is up in the right corner of the picture. Photo: Guðmundsdóttir, A.S.*



*Figure 6.12 The green arrow shows main route of the passage up the step and forward towards station -4. Photo: Guðmundsdóttir, A.S*



*Figure 6.13 A lot of icicles sticking down from the ceiling in layers. The snow roof is by Christians feet. Photo: Guðmundsdóttir, A.S.*



*Figure 6.14 A close up on the snow roof over station -2 taken from above, in the new room. Photo: Guðmundsdóttir, A.S.*

### 6.2.5. Sediment and snow

As the meltwater flows through the cave in the melting season, sediment that is bound in superimposed ice erodes out of the walls and is transported by the water further down in the cave. At lower relieves the sediment starts to settle, leaving the bigger boulders distributed in clusters on the floor along the passage throughout the rest of the cave and finer sediment is deposited on ice shelves along the passage and on the floor in the lowermost part of it. At station 1 there is a big mound of very fine sediment, silt and clay size, sitting on an ice shelf in the inner meander of the channel. The area by station 1 is one of the lowest parts of the cave and therefore the rest of the fine sediment has gathered in this area.

In 2009 the sediment was distributed all through the passage but increased gradually the lower one went in the cave. In 2010 much of the courser sediment, like granules, pebbles, cobbles and smaller boulders that was there in 2009 were gone and then when coming to the caves lowest part, a lot of that sediment had been deposited on the floor there. The caves passage was though much dirtier in general in 2010. It had considerable amount of clay and silt distributed all over the floor and the walls. Extreme amount of sediment was in the new room of the cave but that part represents the lowermost part of the cave and therefore all the sediments that does not make it down through the lake passage end up there.

The only snow in the cave in 2009 was the snow in the uppermost reaches of it, close to the entrance, and old snow in former snow roofs in the lower part of the cave. When returning to the cave in 2010 the amount of snow inside was surprising. Snow was lying everywhere on the floor of the cave all through the passage, more on some places than others and often reaching high up in the walls. During the early winter of 2010 the channel probably reopened due to heavy rainfall and warmer period in January and February 2010 and snow managed to get into the channel.



*Figure 6.15 showing various places in the cave with considerable amount of snow or sediment cover. Photos: Guðmundsdóttir, A.S.*

## **6.3 The future of Longyearbreen ice cave.**

If the channel continues to behave like it has been doing the last years, the internal deformation and water force working together could result in another and even bigger meandering cut off by stations 13 and 17 as a passage could easily open up between them if the ice gets much thinner due to the concurrent of the internal deformation of the ice body and the erosional power of the water flow.

The future of the cave might though not be too bright as there are several factors that could lead to the closing of the cave.

Cut and closure internal deformation and the internal deformation of the glacier ice cave might close it up if the water flow is not efficient enough to continue to erode/melt the ice at the same or higher rates than it takes the ice to deform and close up the walls.

If the ice blockage in the ablation zone will not melt in the melting season, the meltwater will be unable to drain and therefore it will fill up the channel until it can find a weak point somewhere in the glacier to drain through. This weak point could for example be a crevasse. The rest of the channel at lower elevation than the point of this new drainage will likely become stagnant and if energy balance allows it, it will freeze. In 2009 it seemed that the channel was going to be filled up, mostly due to the blockage forming the big lake at the end of the cave, perhaps sometime during the next years, most likely the winter of 2010 but that did not happen.

If a blockage forms that will not be able to clear in the melting season and the flow does not find an alternative weak point to drain through, the water will fill the channel up completely and drain supraglacially until it finds a Moulin or a crevasse on the top of the glacier to drain into and with that start to form a new cave.

## 7 Discussion

The passage morphology has changed from year to year as a result of vertical incision and horizontal meander migration. Little by little the supraglacial meltwater stream cuts down into the glacier ice forming a meandering canyon that by time closes up by ice creep if the incision rate is faster than surface ablation. The upper reaches of the canyon can also be plugged by snow. When the lower levels of the channel become plugged by aufeis accumulation or by creep closure the water in it can back up to find another way to discharge (Gulley et al. 2009). The new route of the water depends on the balance between the gradients in hydraulic potential that drive the water flow and the resistance to flow (Benn & Evans, 2010). This is what might have happened in the lowest part of the cave where the new found room by the lake is.

The most likely explanation would be that the passage that I mapped was at one point much higher up in the ceiling and finally drained down where the lake is at station -2. At some point a blockage happened in the ablation zone, perhaps like the one that is now blocking the complete drainage of the channel causing the lakes presence today, but at that time the blockage did not melt in the melting season like it seems to do partly now so the water had to look for a different way out. The stream likely found a weakness in the wall next to the station -2 and found a way to drain through this second lake at the very end of the map in 2010 by station -6.

Later, perhaps during a warmer melting season, the old blockage of station -2 must have opened up and the channel continued to drain down there abandoning the old passage that leads to station -6. The lake at station -6 has most likely frozen completely and will therefore not be draining water again in the future. So if the lake at station -2 will not drain at one point, the water will have to find a completely new way out, a weak point, which may be a bit higher up in the channel.

Temporal and spatial patterns of surface meltwater production can vary a lot, depending on local climate at a given time. Most glaciers can experience short term variations associated with changing weather conditions in addition to the normal annual melting cycle (Benn and Evans, 2010). Due to heavy rain and considerably warm temperatures that was in the Longyearbyen area in January-February 2010 the cut-closure channel might have opened up and let water and fine sediment with it inside the cave. In the year 2010 there was considerable more of finer sediment such as silt and clay distributed along the caves floor and walls and much less was of coarse sediment in the cave. Before the incised channel closed up again with a snow roof, a considerable amount of snow managed to collect in the passage, making it a bit more difficult for accurate measurements at certain areas along the passage.

Looking at the weather data from Svalbard Airport it shows that the average temperatures from June 2009 to May 2010 are higher than normal. Therefore it might be that the water force in the melting season of 2009 was much more than in the melting season in 2008 and additional erosional period in January was added to the otherwise calm, minimum erosive winter months. Possible evidences of that might be; the meandering cut off, the more extreme sediment transport, erosion and down cutting and the fact that the cave had opened up in the winter letting water, sediment and then snow inside the cave.

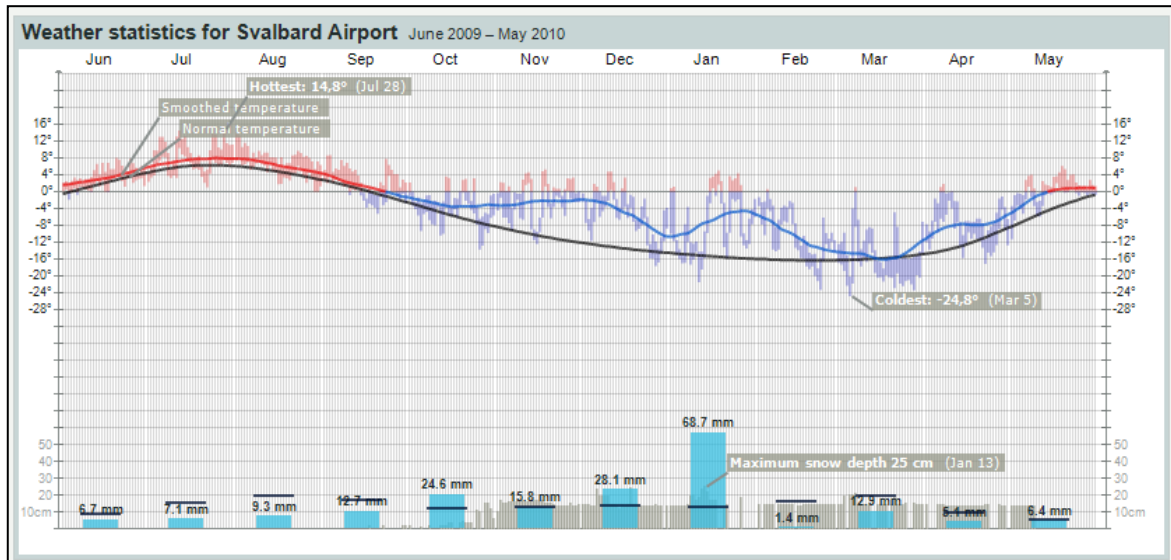


Figure 7.1 The black lines show the temperature and precipitation normal, red/blue line shows mean daily temperature which is smoothed over 20 days so its comparable to the normal temperature, red/blue fields show observed maximum and minimum temperatures, light blue columns show the total precipitation for the month and the black lines crossing them are the precipitation normals and the maximum snow depth is marked by the dark gray columns behind the precipitation columns ( www.yr.no, 2010).

It does not seem to be many changes inside the loop of the meandering cut off since the lowering of the floor was only few cm at the most and there were no visible changes of the walls apart from their new snow cover. This indicates that the cutting of the wall in the meander must have happened early in the melting season leaving the meander almost untouched and therefore it was at a much higher level than the new floor of 2010.

The big ice shelf from 2009 at station 8 seems to have eroded away instead of getting bigger and higher like I had expected it too. This is most likely the result of the heavy water flow that ran through the cave either in the melting season or in the heavy January precipitation. If the water force would have been less, the water would have gone easier on the turn at station 8, cutting down the channel at the inner part of it as it seem to have done the year before when it formed this wide pebble and cobble covered shelf.

Ice deformation occurs in response to spatial variations in pressure so a passage inside a glacier will contract or enlarge if there is a pressure difference between the passage and the surrounding ice. This is known as effective pressure,  $N$ :  $N = P_i - P_w$ .  $P_i$  is a simple function of the weight of overlying ice,  $P_i = \rho_i g (h_i - z)$  where  $h_i$  is the elevation of ice surface and  $z$  is

the elevation of the point in question. If the passage is not water filled the  $P_w$  will be zero if the passage is water filled,  $P_w$  can then be less than, equal to or in excess of the ice pressure (Benn & Evans 2010). Longyearbreen glacier is a cold based glacier and moves therefore only by internal deformation. A direct proof of the internal ice deformation can be seen both when comparing the same places or areas on the plan view maps and on photographs from both years. The main difference is to be seen between stations 4 and 5 and also between stations 11 to 16. The passage is considerable thinner in 2010 than 2009 at these areas; the walls have been pushed closer together on a higher rate than the water erosion is taking place. Another evidence is a big angular boulder that stood out from the glacier wall a bit more than half way across the passage between station 4 and 5 in 2009 was in 2010 touching the ice shelf by the wall on opposite side.

## 8 Conclusion

Water production, -storage and transport exert a profound influence on glacier behaviour as it substantially contributes to the glaciers erosion, debris transportation and deposition. When looking for evidences of changes between years mapping the cave, which seems to be of cut and closure origin, as thoroughly as possible is important to be able to see the changes in the shape of the cave, both vertical and horizontal, and changes in sediment distribution and transportation. These changes can be very small so using photographs can be useful for second references. Mapping a single cave thoroughly annually over several field seasons might give a very thorough description of every small and detailed step in the formation and evolution of it and perhaps a better understanding of the englacial hydrology and -sediment transport inside a glacier meltwater channel. Using meteorological data the smallest changes in temperatures and precipitation can be compared to any changes in the caves morphology and sediment distribution to see how influential these smaller scale changes can be on the channel and the whole hydrological system of the glacier.

# References

- J.D. Gulley, D. I. Benn., D. Müller, A. Luckman (2009). *A cut-and-closure origin for englacial conduits in uncrevassed regions of polythermal glaciers*. Journal of Glaciology 55(189): 66-80.
- Liestøl, O. and J. O. Hagen (1993). *Glacier atlas of Svalbard and Jan Mayen*. Oslo, Norsk polarinstitutt.
- Baird, P. D. (1952). *The glaciological studies of the Baffin Island Expedition, 1950. Part I: Method of nourishment of the Barnes Ice Cap*. Journal of Glaciology 2: 2-9; 17-19.
- Boggild, C. E. (2007). *Simulation and parameterization of superimposed ice formation*. Hydrological Processes 21(12): 1561-1566.
- Benn, D.I. and Evans, D.J.A (2010). *Glaciers and Glaciation*. Printed in India for Hodder Education, Hachette UK Company.
- Humlum, O., Elberling, B., Hormes, A., Fjordheim, K., Hansen, O.H. and Heinemeier, J. (2005). *Late Holocene glacier growth in Svalbard , documented by subglacial relict vegetation and living soil microbes*. The Holocene, 15 (3), 396-407.
- Yr.no (2010). *Weather statistics from Longyearbyen (Svalbard). Skoðað júlí 2010 á* <http://www.yr.no/place/Norway/Svalbard/Longyearbyen/statistics.html>
- Mapsharing.org (2010). *Map of Svalbard. Skoðað maí 2011.* <http://www.mapsharing.org/MS-maps/map-pages-state-map/190-svalbard-map.html>
- Dallmann, W.K., Major, H., Haremo, P., Andresen, A. Kjærnet & T., Nøttvedt, A., 2001: Geological map of Svalbard 1:100,000, sheet C9G Adventdalen, Norsk Polarinstitutt Temakart No. 31/32.