Lateglacial sediments and marine fauna at Saurbær in Kjalarnes

Veronica Piazza

Faculty of Earth Sciences
University of Iceland
2013

Lateglacial sediments and marine fauna at Saurbær in Kjalarnes

Veronica Piazza

10 ECTS project that is part of the
Baccalaureus Scientiarum degree in Geology

Supervisors
Hreggviður Norðdahl
Ólafur Ingólfsson

Faculty of Earth Sciences
School of Engineering and Natural Sciences
University of Iceland
Reykjavík, May 2013

Lateglacial sediments and marine fauna at Saurbær in Kjalarnes
10 ECTS project that is part of the *Baccalaureus Scientiarum* degree in Geology

Abstract

The stratigraphy and the fauna at Saurbær, Kjalarnes, were studied to understand the environmental changes that took place in the area during Lateglacial. A stratigraphic log was drawn and every sedimentary facies described and interpreted. Samples from the three fossiliferous beds were sieved to isolate the fossils. From the section it is deduced that regression occured in the area, causing an evolution from glacimarine environment to littoral environment, where marine and glacifluvial depositions alternated. The shells indicate a deposition in a mid-Boreal to high-Arctic climate at shallow depth, close to the shore. The temperature inferred from the size of *Hiatella rugosa* is around   -1°C – 12°C, cooling slightly down further up in the section. The age of the shells is not known, but they are thought to be from Bølling. Fossil shells were in fact found in similar sediments in other areas in Kjalarnes from that period and the regression episode at Saurbær fits with the Bølling regression in West Iceland. No glacier advance is thought to have occurred in the area during the Younger Dryas chronozone.

Útdráttur

Jarðlagaskipan og fána við Saurbæ á Kjalarnesi voru rannsakaðar til að athuga hvers konar umhverfisbreytingar áttu sér stað á svæðinu á Síðjökultíma. Snið var teiknað, hverri ásýnd var lýst og hún túlkuð. Sýni voru tekin úr þremur lögum sem innihéldu steingervinga og sigtuð til að skilja þá að. Út frá sniði má túlka að afflæði hafi átt sér stað sem olli breytingu frá jökulsjávarumhverfi til strandumhverfis, þar sem strandsetmyndun og jökulársetmyndun skiptast á. Setmyndunin gefur til kynna að hún hafi átt sér stað í mið-Bóreal/há-Artísktu loftslagi á litlu dýpi, ekki langt frá ströndu. Ályktanir um sjávarhitastig voru dregnar út frá stærð *Hiatella rugosa* (rataskel) og var það á bilinu -1°C – 12°C og fór smákólnandi því ofar sem farið var í sniðinu. Aldur skeljanna er ekki þekktur en gert er ráð fyrir að þær séu frá Bølling. Steingervingar skelja hafa fundist í svipuðu seti á öðrum svæðum á Kjalarnesi frá sama skeiði og afflæði við Saurbæ passar við Bølling afflæðið á Vestur Íslandi. Talið er að engir jöklar hafi gengið á svæðinu á Yngra Dryas.

To the dear ones that helped my dream come true.

My Icelandic family,
who accepted me years ago and gave me precious support in every step since I have known
them, making me the person I am now.

My dearest friends, the Capelletti's family,
who started and always warmly supported my Icelandic adventure.

My Italian family,
who let me go abroad to follow my dream.

I hereby announce that this essay is written by me and it has neither partially or complete been handed in before as an element for higher degree of education.

_____

Veronica Piazza

Table of contents

Figures

Tables

Acknowledgments

First of all many thanks to my supervisors Hreggviður Norðdahl, which proposed this project, and Ólafur Ingólfsson for their great help and advice during the elaboration of this thesis. Professor emeritus Leifur A. Símonarson is warmly thanked for his precious help during shell identification and interest in the work.

I would also like to thank my Icelandic family, who always encouraged me and showed interest and support when I needed it. Special thanks especially to my mom Arna Auður Antonsdóttir for her moral and material support during the intense field work back and forth in Kjalarnes. My sister Sigurlaug María Hreinsdóttir and dad Hreinn Pálsson are kindly thanked for their wonderful review and comments in the last steps of this project.

Thanks, last but not least, to the people at Saurbær, who allowed me to work in their land and made the field work even better with their warm hospitality and friendship.

1 Introduction

This BS thesis is an investigation of sedimentary sections at Saurbær, Kjalarnes, in western Iceland, that can highlight the environmental changes that took place during the last deglaciation. The main focus regards climate and sea level changes and is deducted from sediments and marine fauna. Furthermore, the results were also viewed in a wider context when compared with models regarding western Iceland.

1.1 The research area

This project was conducted below a coastal cliff just southwest of the Saurbær church on the northern shore of the Kjalarnes peninsula, facing the Hvalfjörður fjord, western Iceland (64°16'45,63'' N 21°50'38,59'' W) (Fig. 1).

The bedrock outcrops along the shore where the sediments above have been eroded (Fig. 2c-d). The coastal cliffs are generally about 10-20 m high (Hjartarson, 1993) and the cliffs at Saurbær are about 13 m high. South of the farmhouses a ravine runs to the sea so it is possible to have a three-dimensional overview of the outcrop itself. Only sediments exposed south of the river were studied (Fig. 2a-b).

There have been significant changes in the area through time due to coastal erosion, which is still considerable nowadays. Because of this, efforts have been made to restore grass and soil and rock barriers were built to slow down the erosion. The sea still finds its way through them, and it has been shown that the barriers built at Saurbær have been greatly eroded since 1995 (Skipulagsstofnun, 2009). These factors contribute to the risk of slides from the uppermost parts of the cliffs which are very steep and slides are common. Signs of groundwater infiltration and oxidation are also visible in the outcrop.
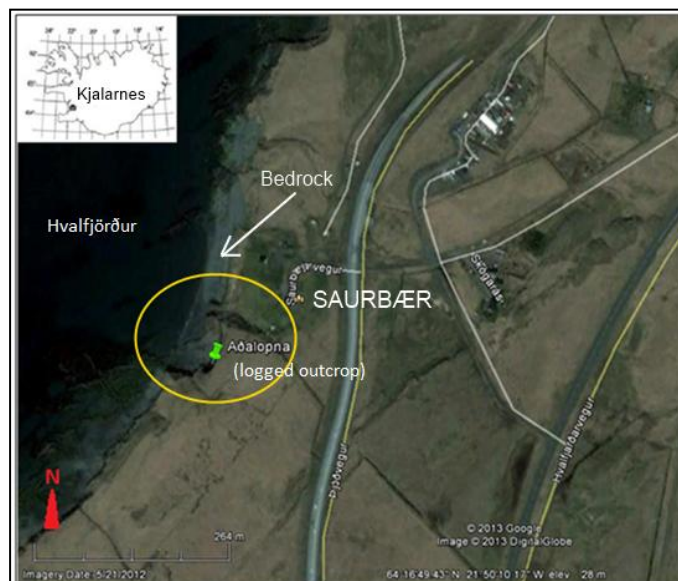
Fig. 1. Location of the research area. The green mark points to the position of the logged outcrop (Google Maps, Veronica Piazza).
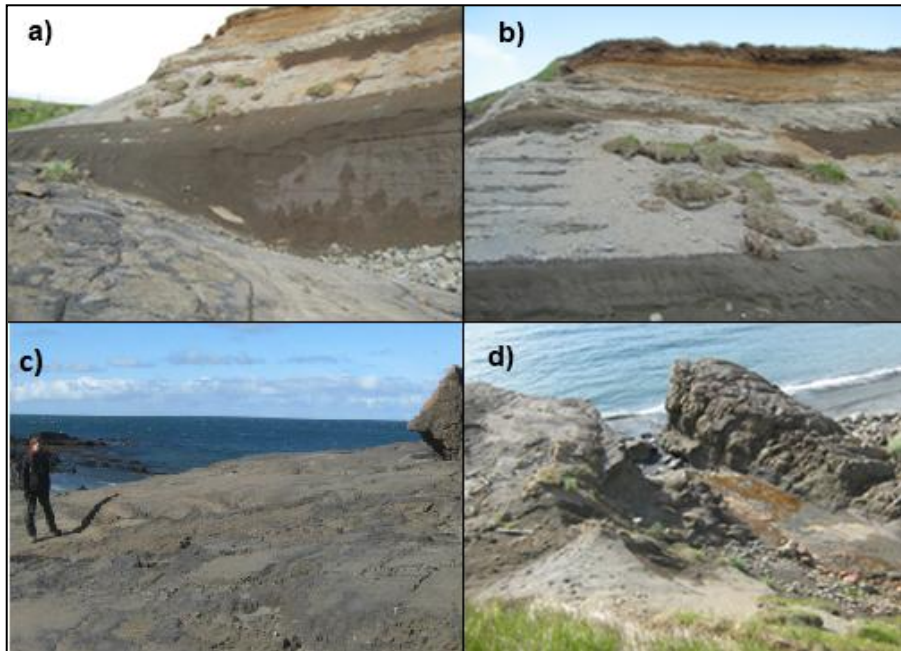
Fig. 2. Overview of the stratigraphic section and bedrock. Images a) and b) show respectively the lower and upper part of the outcrop. The bedrock is shown in images c) and d). Image c) was taken at the base of the section, while image d) at the top. In this last image the ravine is visible.

1.2 Geology of the area

The bedrock in the Hvalfjörður area is thought to have been originated from four central volcanoes, Hafnarfjall, Kjalarnes, Stardal and Hvalfjörður central volcanoes, while the area was still within the volcanic zone (Fig. 3). The fjord itself is the result of glacial erosion. Alternating hyaloclastite (formed during cold periods), lavas and sedimentary rocks (formed during warm periods) suggest alternating volcanism and sedimentary deposition during different climatic periods (Geirsdóttir, 1990).

The tholeiite bedrock visible along the shore along Kjalarnes was formed by the Kjalarnes central volcano, active 2,8-2,1 Ma ago at the end of Tertiary/Early Quaternary. The rocks from this volcano are evolved and show signs of geothermal alteration. This was in fact a very active geothermal area. Dikes, sills and intrusions are common (Friðleifsson, 1974). This central volcano was very

Fig. 3. Position of the main central volcanoes around Hvalfjörður (from Friðleifsson, 1974).

active but the activity finally declined when it drifted away from the volcanic belt. After the activity diminished, the volcano was deeply eroded (Imsland, 1985). The caldera of the Kjalarnes central volcano has been detected by geomagnetic measurements. It appears as a 17 km long and 8 km large magnetic low, lying mostly offshore. The form of the caldera

indicates a sharp beginning of volcanic activity that declined slowly towards southeast, reflecting the shifting in steps away from the volcanic belt (Jónsson & Kristjánsson, 2002).

1.3 Previous researches

Researches have been done in Kjalarnes by Árni Hjartarson in 1993 as a part of an investigation about deglaciation of the Reykjavík area. Hjartarson studied the sediments and collected fossils from the shores of Brekkubakkar, about 2,5 km southwest of Saurbær. Age analysis on shell fragments revealed two different ages. One group of shells was dated to 12,370±130 ^{14}C yr BP while the other two were dated to 10,930±130 ^{14}C yr BP /10,610±150 ^{14}C yr BP. The first group is from the Bølling chronozone and the other from mid Younger Dryas. According to Hjartarson there was no glacier present in Hvalfjörður and at Kjalarnes during the Bølling. Glaciers began to retreat inland of Kjalarnes and into the mouth of Hvalfjörður during Bølling about 13,000-12,000 ^{14}C yr BP. About 11,000 ^{14}C yr BP there was again a cooling in the N-Atlantic Ocean and glaciers grew again and advanced in during the Younger Dryas chronozone until they reached the peak about 10,200 ^{14}C BP but without reaching Kjalarnes and the research area (Hjartarson, 1993).

These results fit with the conclusion of Ólafur Ingólfsson in his researches on glacial history of lower Borgarfjörður, western Iceland (1988). He suggested that the fjord was glaciated during the Older Dryas; a period that he calls the Skipanes Stage. Subsequently the glacier retreated and then advanced again during the Younger Dryas chronozone (Skorholtsmelar Stage), when it pushed up the moraines close to Mount Akrafjall (Ingólfsson, 1988). Kjalarnes was an ice-free region during the glacial peak in Younger Dryas times. Between 10,700-10,200 ^{14}C yr BP, when the climate was as coldest, shell populations would have been favoured in ice-free regions like Kjalarnes.

Other samples of marine shells have also been collected from sediment terraces at Ósmelur, northeast of Saurbær, and Kjalarnes dated to 12,335±140 ^{14}C yr BP and 12,375±140 ^{14}C yr BP (Sveinbjörnsdóttir and Johnsen, 1991). They are one of the oldest shells found from Lateglacial times in southwest Iceland. The presence of these fossils is again an evidence of deglaciation and marine environment in the area during the Bølling chronozone. These terraces have not subsequently covered by glaciers. (Norðdahl & Pétursson, 2005).

1.3.1 Lateglacial and relative sea level changes

Time BP		Period	
^{14}C ár	Calibrated years		
8000	9000		
		Boreal	Holocene
9000	10.000		Holocene
	11.000	Preboreal	Holocene
10.000			
	12.000	Younger Dryas	
11.000	13.000		Lateglacial
		Allerød	Lateglacial
12.000	14.000		Lateglacial
	15.000	Bølling	Lateglacial
13.000	16.000		

Lateglacial, or Late Weichselian time, is the last part of the most recent glacial period the Weichselian, which started more than 100.000 years ago (Stanley, 2009). The Lateglacial spans the period during which glaciers started retreating and until the beginning of the Holocene, about 11,500 years ago. The subdivision of the Lateglacial can be seen in Figure 4.

Fig. 4. Division of the Lateglacial and Early Holocene (Norðdahl, Ingólfsson and Pétursson 2012, translated by Veronica Piazza).

Research on the Lateglacial in western Iceland has especially been focused on relative sea-level changes (RSL) and behaviour of glaciers. Thus it has been possible to reconstruct the environmental history of the area: the environmental changes that took place in the Kjalarnes area is just a piece of the puzzle.

During the Lateglacial raised beaches and glacimarine deposits were formed. Great environmental changes took place so that transgressions alternated with regressions between 12,600 and 9,000 ^{14}C yr BP (Norðdahl, Ingólfsson, Pétursson, & Hallsdóttir, 2008). The curve for the RSL changes in western Iceland is shown in Fig. 5. The position of RSL is connected to glacial movements: when there is a glacier advance a transgression usually occurs because land subsides under the load of the glaciers. The marine limit (ML) is in accordance to the maximum extent of the glacier. This relationship is however somewhat variable but controlled by isostatic movements (Norðdahl, 1990).

The sedimentary and fossil records from Hvalfjörður and Borgarfjörður have revealed marine sedimentary deposition in open coastal areas in environments that are similar to the present ones but with several glacimarine episodes and input of warm water (Eiríksson, Knudsen, & Símonarsson, 2004). Climate changes have proved to be connected to variations in the Polar Front, which separates the cold currents from the warmer ones, due e.g. to changing meltwater input or formation of deep-water. The position of Iceland in the middle of the North Atlantic makes the country especially vulnerable to such changes (Ingólfsson, Björck, Hafliðason, & Rundgren, 1997).

Initial deglaciation took place in West Iceland after 13,000-12,500 ^{14}C yr BP. It was very rapid and glaciers retreated inside the coastline. Ice disappeared in fact in less than 200 years in West Iceland between 12,700 and 12,500 ^{14}C yr BP. It is probable that deglaciation process was accelerated by the input of warm surface water (Norðdahl & Pétursson, 2005). In this sense deglaciation was driven by changes in the current system in the North Atlantic. A further explanation for the rapid deglaciation involves the instability of an ice-shelf when sea-level was rapidly rising and warming of the climate. The timing of deglaciation is concurrent with RSL rise probably due to collapse of other ice sheets (Ingólfsson & Norðdahl, 2001). The ML shorelines that formed at 150 m a.s.l. around 12,600 ^{14}C yr BP are evidence of this rapid deglaciation (Norðdahl, Ingólfsson, Pétursson, & Hallsdóttir, 2008). Following their formation, the RSL regressed when the rate of uplift greatly exceeded the rate of eustatic rise (Norðdahl, 1990). The Bølling climatic optimum occurred at about 12,500 ^{14}C yr BP ago but after that there was a deterioration of the climate during the Allerød. At about 12,200 ^{14}C yr BP the RSL was probably close to 50 m a.s.l. and between 12,200 and 11,500 ^{14}C yr BP it was situated close to present sea level. Consequently to the process of deglaciation and the formation of ML shorelines there was also an increase of shallow and mild marine environment that characterized the so-called Bølling-Allerød interstadial, which lasted for about 2000 years (between 12,600 and 10,500 ^{14}C yr BP) (Norðdahl & Pétursson, 2005).

During the Allerød glaciers were still inside the present coastline of Iceland but ice-free areas existed (Ingólfsson, Björck, Hafliðason, & Rundgren, 1997). Sediments from the Bølling-Allerød have been intensively studied in West Iceland. High-arctic species such as *Portlandia arctica* have been identified in sediments at Heynes on the northern shore of Hvalfjörður, indicating the arrival of cold arctic waters. At that time RSL was rising and at the same time the marine environment was getting increasingly more glacimarine towards the beginning of the Younger Dryas cold period. At the end of the Allerød and beginning of Younger Dryas RSL transgressed due to increasing global sea level rise and loading of advancing glaciers. The marine environments changed from low-Arctic/high-Boreal to

Arctic/high-Arctic with deposition of glacimarine sediments inhabited by molluscs and foraminifera. A decline of summer temperature caused a displacement towards south of the North Atlantic Polar Front during a transition period leading to Younger Dryas glaciations (Norðdahl & Pétursson, 2005).

During the Younger Dryas a new glacial advance took place and at a maximum glacial extent, at about 10,300 ^{14}C yr BP, the glacier margins were inside the present coastline but ice-free areas very likely existed (Norðdahl, Ingólfsson, Pétursson, & Hallsdóttir, 2008). Truncated shorelines indicate that the glacier reached into the middle of Hvalfjörður (Norðdahl, Ingólfsson, Pétursson, & Hallsdóttir, 2008). The cause is probably connected to a southward change of the Polar Front. The RSL was higher than today (Ingólfsson & Norðdahl, 1994). Transgression took in fact place with the glacial readvance during Late Allerød-Younger Dryas times due to increased glacier load and subsequently RSL reached 60 m a.s.l. in Southwest Iceland. During the transition period between the Allerød and the Younger Dryas the extent of coastal marine environments was increased (Norðdahl & Pétursson, 2005).

The glacier retreat after the Younger Dryas is not well known. Studies of Younger Dryas moraines indicate that the retreat took place in steps. It caused land uplift and sea regression until the rapid deglaciation of Younger Dryas glaciers was interrupted by a minor glacial advance in Preboreal time, again with land subsidence, transgression of RSL and advance of the glaciers to a Younger Dryas maximum at about 9,800 ^{14}C yr BP. The RSL rose by some 20 m and shorelines formed some 20-30 m below the Younger Dryas shorelines. The extent of the Preboreal glacier has not been mapped in details in western Iceland, but it is probable that an outlet glacier terminated in the innermost parts of Hvalfjörður.

The most recent fossil shells found are older than 9,400 ^{14}C years BP, indicating that at that time the glaciers had retreated and the RSL had regressed at or below the present sea level (Norðdahl & Pétursson, 2005). It reached a minimum position at about 8,900 ^{14}C yr BP (-40 m below sea level), when only eustatic changes sustained a transgression of sea-level. The extent of glaciers was similar or less than today and they reached their minimum during mid-Holocene (Norðdahl, Ingólfsson, Pétursson, & Hallsdóttir, 2008). The Polar Front became stabile north of Iceland and consequently warmer seasons got milder and longer. The transition from stadial to an interstadial climate was completed at the end of the period (Ingólfsson, Björck, Hafliðason, & Rundgren, 1997).

Fig. 5. Relative sea-level changes during Lateglacial and Early Holocene in West and Southwest Iceland as presented by Norðdahl and Pétursson, 2005. The eustatic curves of Fairbanks (1989) and Tushingham and Peltier (1991) are also shown.

5
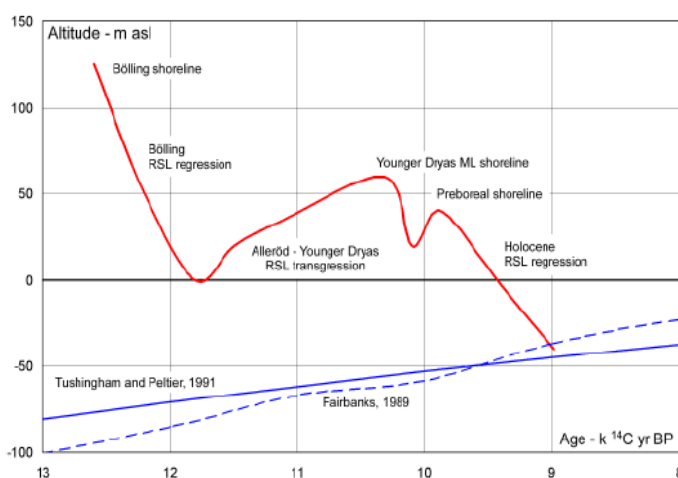
2. Methods and Techniques

The fieldwork was mainly conducted during 8 occasions between June and November 2012. A last field trip was undertaken on the 10th of April 2013 to sample fossil shells. During the first four field trips the study area was explored and described. Three outcrops were originally described but special focus was put on one outcrop which has been logged.

2.1 Tools

All information, e.g. descriptions, drawings and data, were registered in a field notebook. The outcrop had to be cleaned when the logging work was started. This was necessary in order to be able to observe clearly structures and beds in the outcrop. Grain size and sorting were decided with a magnifying class. During the logging process, the Brunton & Tape method was used to determine the thickness of beds (see subchapter 2.3). The compass was also used to measure the direction of glacial striae.

The log was constructed from bottom upwards, first on graph papers in the field and then transferred on the sedimentology program SedLog 2.1.4. Paint and Paint.NET were used to adjust the log, add details and to highlight geological features in pictures of interest.

2.2 Fossil Analysis

Shells and shell fragments were sampled from the three fossiliferous beds for a later classification. They were taken randomly and sediment was included in order not to miss the smaller fragments and avoid breaking of the fossils. Notes were made in the field about size, distribution and preservation and particular features.
After this the sediments were sieved on a sieve no.7 (with opening 2,80 mm) and the largest fragments collected.
The fossils were later identified with the help of Professor emeritus Leifur A. Símonarson, who also identified the smallest fragments under the microscope. The process consisted in sampling whole shells and the largest fragments and grouping them according to the aspect/species. Then the whole shells were counted in order to calculate a minimum ratio between the species. Fragments can derive from one and the same individual, so just the basal parts with the umbo (the parts where the two valves are connected) were considered, since they belong with no doubt to only one individual. It was important to observe if the shells could be paired or not in order not to count the same individual twice. The number of individuals found for every species was finally written down.

2.3 The Logging Process

Because the section is not vertical, bed thickness had to be measured indirectly with the Brunton & Tape method. The tape was stretched between the lower and upper boundaries

of every bed parallel to the cleaned surface. The distance between them was read on the tape. This is the measured thickness. Then, inclination of the tape was measured with the compass (that was rotated to A-V and put parallel to the tape). The dip and strike of strata were not measured directly. The reason for this is that it was observed that the dip of the strata is just a few degrees and it remains more or less constant over all section, so no need was felt of taking measurements of this kind (Eiríksson, 2007).

Calculation of the real thickness depends on how the bed lies. In the observed section, all beds are inclined in the same direction towards the observer and tape inclination is more than bed inclination, as Figure 6 shows. Mertie's formula is generally used:

$T = D*((sin(b)cos(h)) \pm (cos(b)cos(f)sin(h)))$

where T = bed thickness, D = distance between two contacts, b = tape inclination, f = difference between tape and inclination directions and h = bed inclination. As stated before, it was supposed that h = 0 so we get the simplified formula:

$T = D*sinb$
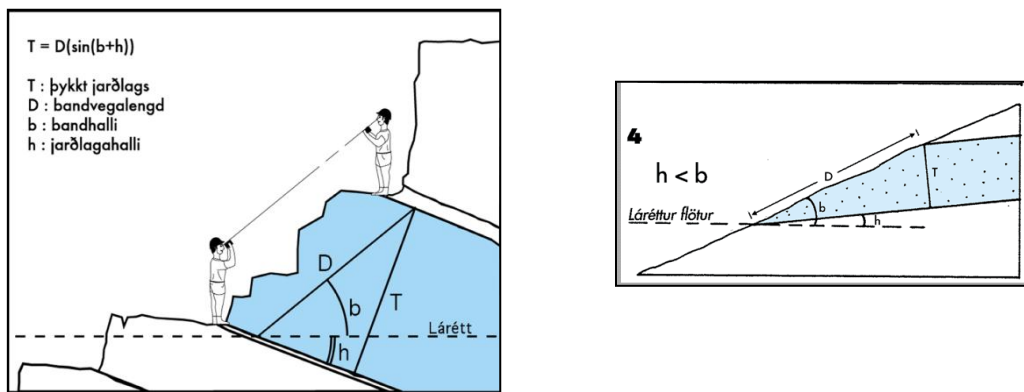
Fig. 6. Images explaining the logging process (from Eiríksson, 2007). The image on the left illustrates the Brunton & Tape method, together with Mertie's formula. The image on the right shows the inclination of beds in the Saurbær section, where h = inclination of the bed, b = inclination of the surface, D = distance between contacts and T = bed thickness(from Eiríksson, 2007).

This method is easy and accurate enough. Anyway the real thickness of a bed can vary laterally so the theoretical value that is found through this equation is an average. Moreover, there is a margin of error that is given by human mistakes (e.g. when reading values on the tape or compass, wrong position of the tape etc.) (Eiríksson, 2007).

During the logging work, each bed was described according to lithology (grain-matrix relationship, grain size, sorting and shape, texture, composition, internal structures), fossils and geometry (types of boundaries, thickness and its lateral variations) (Eiríksson, 2007; Boggs, 2011). All the features that define a bed are presented in stratigraphic logs, which give a visual representation that is easy to understand. A stratigraphic log then becomes a powerful tool that explains and relates lithology, geometry and sedimentary structures.

Each facies in the log gets then a specific code according to its most important features. Facies are not necessarily unique in the section; they can repeat themselves and be divided by erosional contacts that represent changes in depositional environments (Boggs, 2011).

3 Results

3.1 The stratigraphic log

The whole outcrop was divided into units, which have been assigned a letter and a number. Such division reflects the path followed while logging according to various factors, such as surface appearance of sediments, disconformities and steepness of the section (Fig. 7). The easiest way to the top of the section was in fact chosen. These units may be part of a single facies or contain more facies.
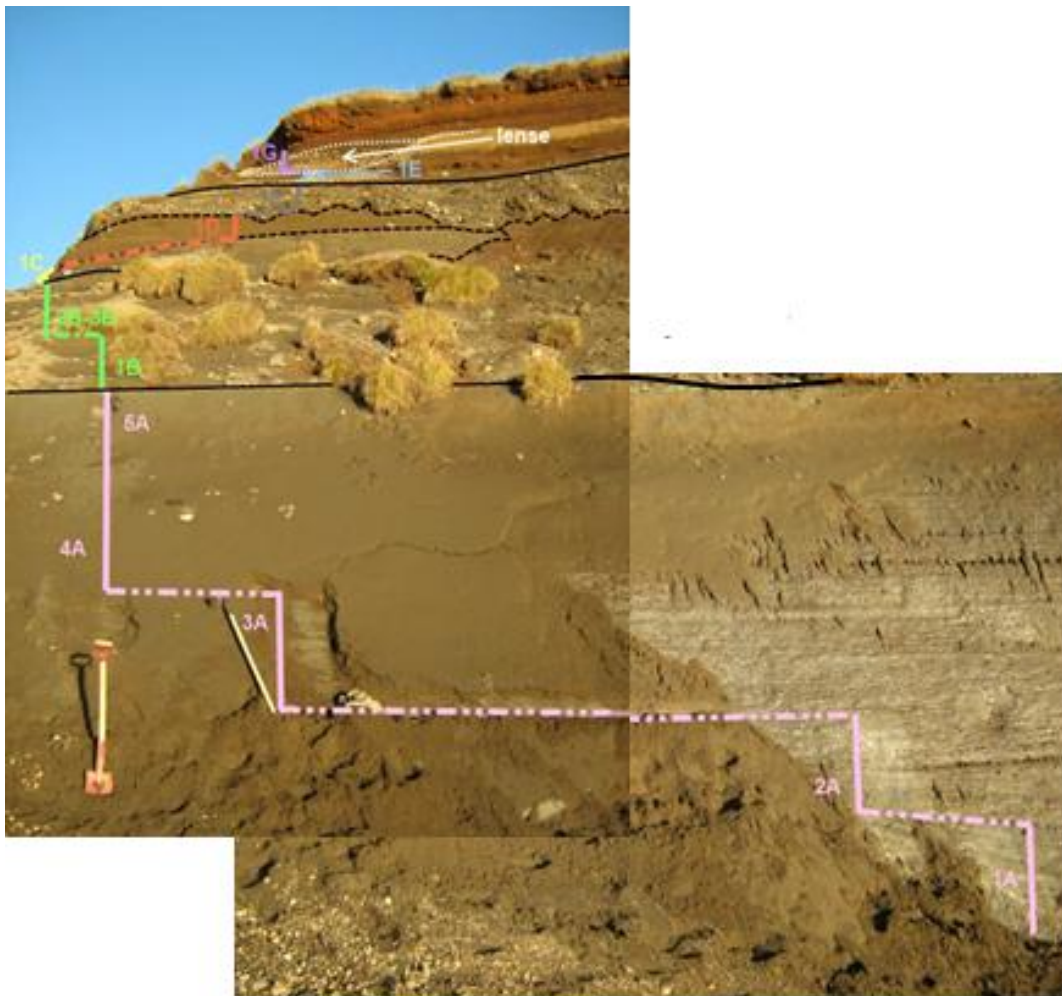
Fig. 7. Overview of the path followed during field work and unit division. The sharp boundaries are marked with a black sharp line while the erosions with a black dashed line.

The stratigraphic log is shown in Fig. 8. The legend explaining the log is shown in Fig. 9 and Table 1.

STRATIGRAPHIC LOG OF THE SAURBÆR SECTION (KJALARNES)

Fig. 8 The stratigraphic log at Saurbær.

Fig. 9. Legend for the log.

Table 1. Overview table of lithofacies codes.

LITHOFACIES CODES	
Diamict sediments	
DmMm₃3	Massive sediments, with a medium grained, silty-sandy matrix; matrix-supported, clast rich. The consistence when moist is firm, difficult to excavate.
DhF m₃3	Heterogeneous sediments, with a fine grained, clayey silty matrix and matrix -supported, clast rich. The consistence when moist is firm, difficult to excavate.
DmF m₁2(b)	Massive sediments, with a fine grained light clayey silty matrix and matrix- supported; clast poor. The consistence is friable, easy to excavate. Highly burrowed and bioturbated sediments with eventually shell fragments.
Dmcc3	Massive sediments, with a coarse grained, sandy gravelly matrix and clast- supported, the consistence is firm.
DgMc3(ing)	Inversely and normal graded sediments, with a medium grained silty sandy matrix but clast supported. The consistence is firm.

Sorted sediments	
Sm	Fine to medium sand, light grey in colour, massive and generally well sorted.
Fim	Silty clay, grey in colour, massive.
Fcm	Clayey silt, light brown in colour, massive.
Skm	Coarse to very coarse poorly sorted sand with fine gravels (< 5 mm), massive; sometimes there are signs of oxidation.
Gm	Clast supported gravel with a sandy matrix, massive.
Gsmt(ng,b)	Inverse grading from fine gravels to medium sand, hummocky cross bedding. Signs of bioturbation occur.
Sh	Slightly horizontally laminated fine to medium sand, mostly massive in the inside and poorly sorted.
St(ng,b)	Trough cross-bedded sand, normally graded with signs of bioturbation.
Sh(ig)	Slightly horizontally laminated sand, inversely graded.
Fm	Layer of fines (silt, clay), grey-green, easily breakable.
Gsm(ng)	Normally graded gravel in a sandy matrix.
Gm/soil	Massive gravel bed mixed with soil.
Sc	Cross bedded fine/medium sand.

3.2 Description of the logging section

0. Bedrock

Basalt is at the base of the section. It is very alterated and calcite and jasper fillings are quite common. No minerals visible at eye sight occur; the basalt is fine grained. The colour is brown/gray. Dikes and column basalts are widespread (Fig. 9a). They are slim and black in colour. Joints are also to be found.

Small scale erosional forms are common, especially well preserved glacial striae (Fig. 10a-b). They cover most of the surface, which is often polished, and the direction is mostly constant. Accounting a magnetic declination of 16°, their direction was on average 253°SW. On the striated bedrock arcuate fractures were found with their horns pointing towards the sea, identified as crescentic gouges, and others with the horn against ice flow, identified as lunate fractures (Fig. 10a). Moreover, it was observed how the bedrock was eroded and polished as the ice flow deformed around obstacles (Fig. 10b).
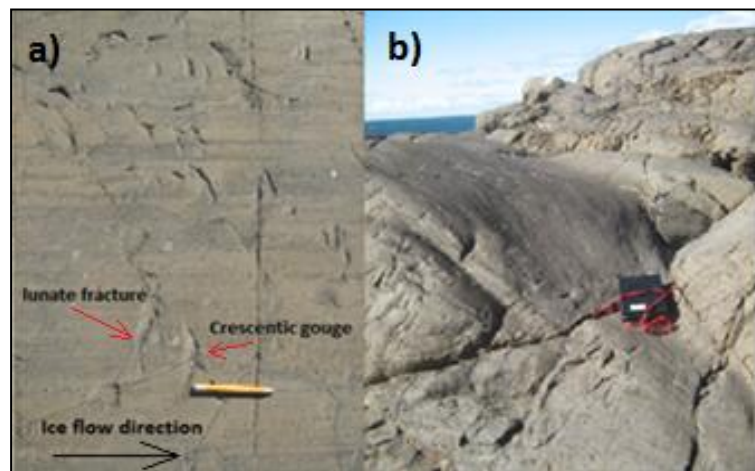
Fig. 10. The bedrock under the sediments. Some of the erosional features are shown in picture a, while the signs of plastic deformation are shown in b. In both images glacial striae are visible.

1. Unit A

This unit is the thickest of all and it was divided in 5 subunits. In the lowermost part that is not covered up with sand and gravel, stratification is clearly visible, despite of groundwater infiltration preventing from observing dry sediments.

The layers are mostly horizontal, although in the lower section they dip when they meet the basalt that lies below. The lower contact of the sedimentary sequence is an erosional boundary. From a preliminary observation, sand and fines were identified as the main sediments of this unit. Outsized clasts are common and folded layers around them have remained though the clasts are gone (Fig. 11c). They are both rounded and angular and the size is variable. In some parts there are cavities that correspond to layers where there is accumulation of pebbles and other coarse sediments (Fig. 11b). These pebbles are of different size and angularity. Further discussion will follow later.

The lowermost bed is very different from the others, although this difference is not visible from the surface. This is a quite thick bed, ~50 cm thick. The sediment is hard and it is difficult to clean it or dig in it. Quite well rounded pebbles are very common in a wet

matrix composed of dark grey fine sand and silt. Their size is variable. The lithofacies code is DmMm$_3$3. It can be seen in Fig. 11a.
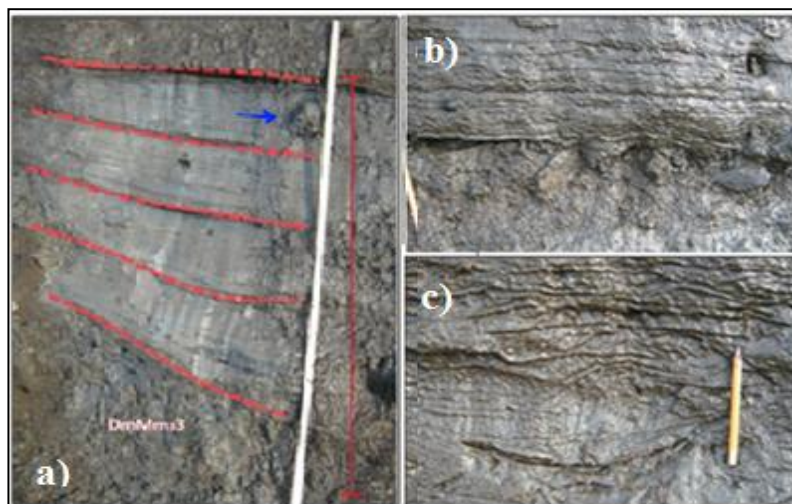
Fig. 11. The lower unit A. The lowest sequence of subunit 1A is delimited by red dashed lines (a). The drop stone is indicated by the blue arrow. The accumulation of coarse sediments is in image (b) and the imprint of dropstones in (c).

Above this bottom facies, sedimentary sequences can be identified (Fig. 11a), especially in the subunits 1A and 2A. Every sequence is delimited by layers of coarser (eventually pebbly) sand while in between there is an alternation of silt/clay and sand layers. All layers are generally massive with no structures. Fine sand is usually well sorted and this is valid throughout the entire unit. Lenses, interbeds (very fine, non continuous laminae with sometimes with variable thickness) and outsized clasts are common features. These outsized clasts are usually small and rounded but there are also big ones, such as the one in unit 1A which is ~5 cm (Fig. 12).

The coarsest beds that delimit these sequences consist of coarse sand with fine/medium and well rounded gravels inside, so the sorting is on the whole poor. Sometimes there are signs of oxidation since the grains have a reddish colour. Lighter grains of different origin are also visible. The colour is generally darker than in the other layers. The grain size is not always the same.

The layers between these coarser ones are alternating sand and silt/clay mix layers with variable thickness. The colour of this mix changes during the section according

Fig. 12. Example of lamination of subunit 1A. The hole is after the outsized clast.

to the proportions of clay and silt, so changes in colour correspond to changes in grain size. The gray mix (silty clay) is in fact finer than the brown one (clayey silt). The two kinds alternate twice in the subunits 1A-2A (lowermost 1,5 m) but upwards the clayey silt gets more prominent, though they can be found together in the same layer. The finest layers contain occasionally lenses of fine sand, of the same kind of in the other layers. The sand layers that are in between have variable grain size but they are anyway finer and usually better sorted than the layers that delimit the sequences. It was noted also that where the

sediments are not well sorted the grains are more angular, although it is not always true. In some layers there are oxidised grains that are red or light in colour. These sequences eventually disappear higher up in the section. It should be noted anyway that the accumulations of pebbles cited before correspond to the coarser layers delimiting the sequences.

From subunit 3A and upwards, it generally gets more difficult to identify the boundaries between layers. Sand and silt/clay are often mixed so that it is actually difficult to distinguish the layers and in those cases the grain size was decided according to the most prominent sediment kind. The grain sizes and the thickness of layers increase. The clayey silt gets prominent respect to the silty clay, which is no longer present. The sand is usually fine and well sorted, light grey in colour. Lenses are to be found, with variable form. In the upper part of 3A (at ~2,8 m) folded beds are found (Fig. 13). They are composed of sand and silt or a mix of both. The fold disappears in the right part of the log section when the beds get united. Next to the fold, which is unique in the whole section, a 3 cm angular stone was found.
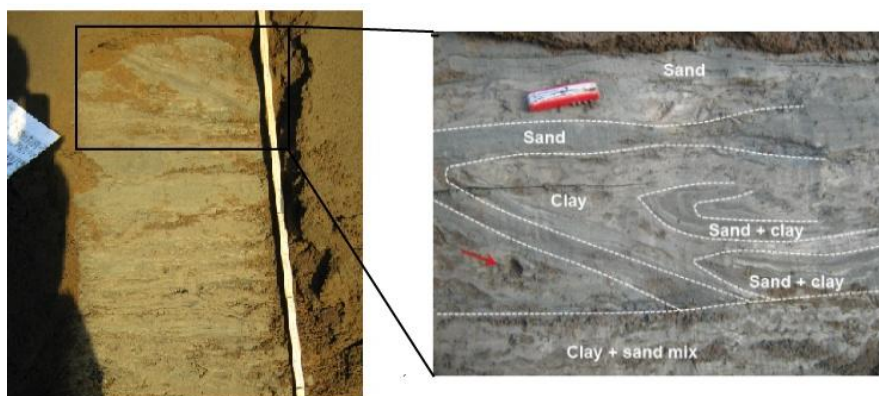
Fig. 13. The folded bed of subunit 3A. The beds are delimited by dashed lines. The red arrow points to the stone found.

The subunit 4A is similar to 3A, composed of alternating thicker layers of sand and silt/clay. The lowest 3 silt/clay layers break easily and are the only ones which present mudcracks.

At ~3,2 m there is an interesting structure (Fig. 14). At the base there is a clay layer with pretty constant thickness that looks like it has been pushed up in the middle. Above it there is a heterogeneous sand layer. Dark sand, which is medium/coarse sand, lies at the top of the clay layer mixing higher up to the light grey sand that is common in the section. Thin (~4/5 mm) clay laminae dip towards the centre. Above there is another clay layer, similar to the one below.
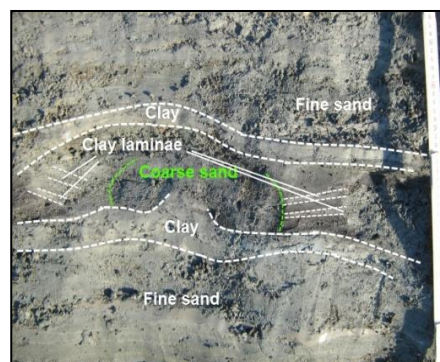
Fig. 14. The structure described in subunit 4A.

Higher up it proved to be difficult to distinguish the different layers. Unclear sand layers have in fact been found that mix little by little with clay towards the centre and in the left part of the log section so that they were not marked as layers. This sand/clay mix continues and gets more prominent, although sometimes clay is more than sand and vice versa.

The last subunit of unit A (5A) is fossiliferous (Fig. 15). It starts with a silt/clay mix that is still very mixed with sand. This part is massive and no relevant structures are visible.

Rounded and subrounded gravels were found. The sediments the shells were found in are coarser than below and not as well sorted. Light grains are found. The colour is brown/grey but when the description was done the sediment was moist.

Shells were found from at least ~4,8 m to the top of the unit 5A in the two uppermost layers, one composed of sand and the other of clay. The beds are very fossil rich. The shells from the sand bed were mostly in pieces but whole and very well preserved shells were also found. They are very easy to break. A case of fossil accumulation was found around a rounded clast. The shells were generally widespread in the bed.
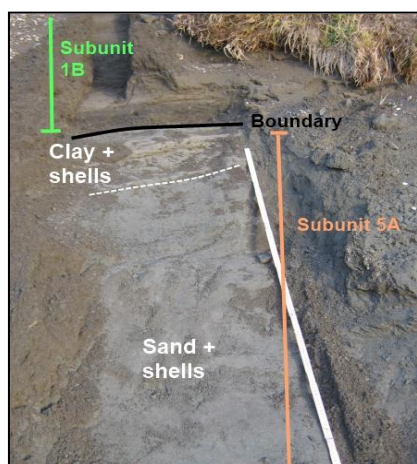
Whole shells were found especially in the clay bed. There are also the biggest fragments of shells. The shells were very well preserved, with both valves attached in the case of bivalves. Occurrence of fossils is though not as high as in the sand bed below. This clay bed is dipping and the characteristics are the same as before. The upper boundary, which signs the beginning of unit B, is sharp.

Fig. 15. The fossiliferous beds of unit A.

2. Unit B

This unit was divided in two subunits. The layers in this unit are generally massive and no relevant structures in them are visible. This unit is coarser than unit A: most of it is medium sand. Horizontal bedding is visible from the surface of the unit: there is an alternation of thicker medium-sand layers and thinner coarse sand layers. In them, signs of intense bioturbation (e.g. burrows) are very common. Over every coarse sand layers there seems to be usually a thin clay layer. Also there is an unclear horizontal lamination on the surface of the medium-sand layers but in the cleaned section no lamination is seen. Shells, shell fragments and stones fallen from above are found loose on the surface. It was not possible to measure the uppermost ~ 40 cm of this unit because the sediments were frozen, so in the log the upper boundary is signed as an erosional contact. Like in unit A, in this unit it is possible to identify alternating sequences of coarse sand - clay - fine sand.

The coarse sand layers are poorly sorted and are in almost all cases pebbly (fine and slightly rounded gravels of different sizes are common), though fine sand can also be found. Thickness is not always constant.

The clay layers above these coarser beds are generally massive. They are not always present, and they also get so thin higher up in the log section (< ~0,5 cm) that it was decided not to include them in the log. They are not always straight and easier to identify in the lower and in the upper part. The medium-sand layers are much thicker than the others. The sorting is generally good and the structure is massive. The boundaries between layers get less sharp and more gradational in the uppermost part of the unit and in fact it was difficult to distinguish the layers. One interesting structure was found in subunit 3B that looks like a burrow. This cylindrical structure is made of fine, brown and hard sediment that was classified as clay. It has a hole in the middle, filled with coarser sand. The boundaries between the coarse sand layer under and above it are neither sharp nor regular.

In the unit just one prominent lens was identified. It is formed by coarse sand at it is up to 4 cm big (as read on the tape) and it is in subunit 1B.

Fossils are found just in the upper part of the subunit 2B. The shells are very broken and dispersed in the bed; they break also easily, so that it was difficult to take specimen of them. No whole shells were found.
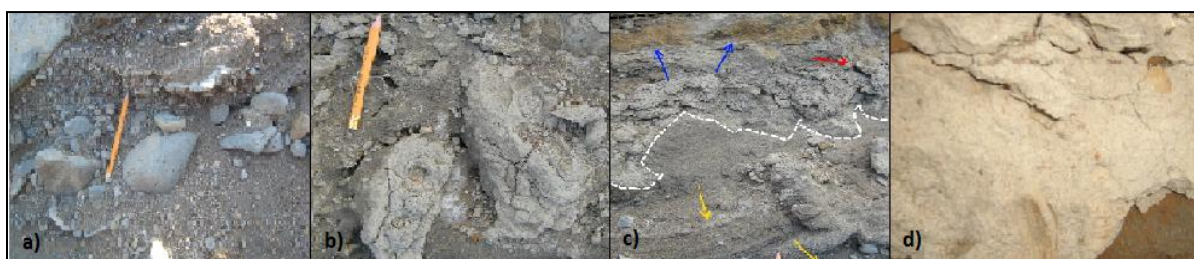
3. Unit C

This unit is coarser than the previous ones. The upper and lower boundaries are sharp, both erosional. The unit is composed of three different beds.

At the base there is a non consolidated bed of gravels of every size, both angular and rounded, and fine sand is the matrix (Fig. 16a). There are no relevant structures but the thickness is though quite variable: the bed seems to thin-out towards south. The lithofacies code is G(h).

Above it there is a pebbly sand bed with visible hummocky cross-bedding, Gm(ig) (Fig. 16c). The lower and upper boundaries are sharp. There is normal grading because the coarsest grains lie on the bottom of every ripple. They are quite rounded but the form is not regular. The colour of the sand in the bed changes: it is gray but from ~8,7 m and above it gets light-brown/dark gray. Coarser gravel can be found more or less at the mark of this colour change. Especially in the darker sand there are signs of a diffuse bioturbation. Some clasts were noticed with a different origin with deformed sediments around them.

The uppermost bed (Fig. 16d) has quite of a particular structure. It consists of a very fine, light brownish matrix (fine-sand/clay) that contains gravels, that are most often fine. The code chosen for this bed is $(DmFm_12)$. The sediment is soft and easy to break. No particular structure are present and moreover the bed doesn't appear to have uniform and constant thickness. This bed spreads in fact out like it has leaked in the sand bed and filled the horizontal gaps between the ripples of the hummocky cross-bedding, since there is visible laminated sand that is surrounded by this kind of sediment. This kind of contact is called loaded and it's sharp. That's why an estimation of the thickness proved to be difficult. The thickness anyway generally tends to thicken to S. Moreover, at the top, the sediment is deformed and eroded. Just under the erosional contact there are browner spots of dark brown sediments with a different origin than the diamicton (Fig. 16c). Signs of intense bioturbation are common, such as burrows (Fig. 16b). Shell fragments and moulds were also found.

Fig. 16. The beds of unit C. The lowest gravel bed (a), burrows (b), hummocky cross bedding (pointed by yellow arrows) and rip up clasts (blue arrows) in c) and shell moulds in the upper diamict (d). In picture c the loaded boundary is marked by the white dashed line.

4. Unit D

This is a sand unit, composed of two distinct beds. Both the upper and lower boundaries are sharp erosions. The lower erosion is clearly visible because the unit disappears towards N until unit E overlies unit C (Fig. 17a). The sediments can on the whole be classified as poorly sorted fine/medium sand.

Just above the lower boundary, where the erosion is, there are coarser grains and granules, though not everywhere. Cross bedding (Sc) is visible from the surface at the bottom of the bed. The colour of the sediments is mostly brown but there are widely quite well rounded light/black/red grains. They also form a lamination pattern (black stripes e.g. at 98 cm-1 m/92-95 cm as read from the tape). The thickest bed is laminated sand Sh. The sand is homogeneous inside but on the outside it is possible to see some kind of horizontal lamination that bends towards unit C (Fig. 17b). This kind of lamination is visible because the grains are coarser. This pattern of lamination persists for ~24 cm from the bottom but it doesn't appear in the logging section.

On the top of the unit there is the second bed, labelled St(ng) (Fig. 17a). It is composed of normally graded and trough-crossed sand. Bioturbation is pretty intense.
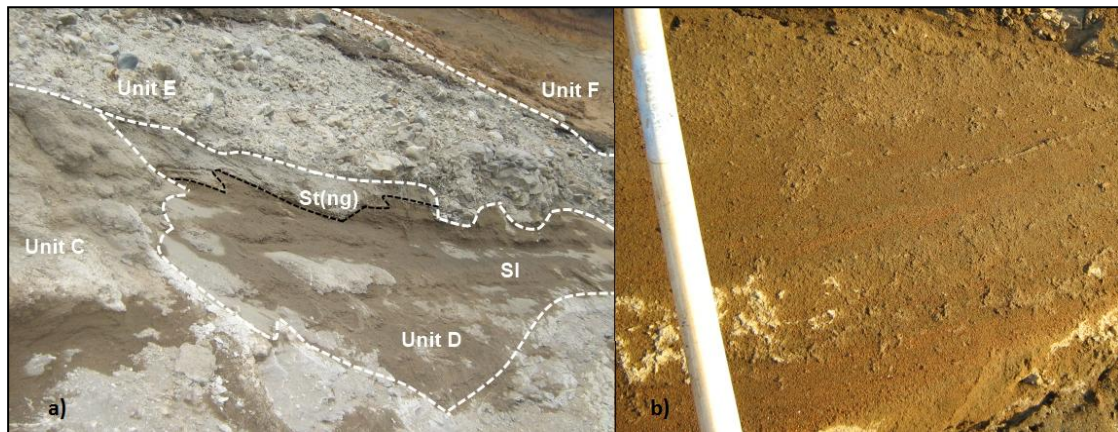
Fig. 17. Overview of the units C, D and E (a). The lamination and the lowermost cross-bedding in unit D are in picture b).

5. Unit E

This is a very coarse unit, consisting of just one bed.

In this conglomerate bed, all grain sizes are present in a finer, light coloured matrix. The matrix is on the whole fine, clay-rich but in some part the unit appears to be clast-supported. Gravels are mostly very coarse and quite well rounded. At the bottom of the unit there are big clay pieces that break easily (Fig. 18a), but in between there is also a kind of diamict that is similar to the one in unit C. The unit is then heterogeneous but massive: no relevant deformations or other structures were noticed. The unit gets two codes because of this heterogeneity: $DhFm_3 3/Dmcc3$. The unit is shown in Fig. 18b.
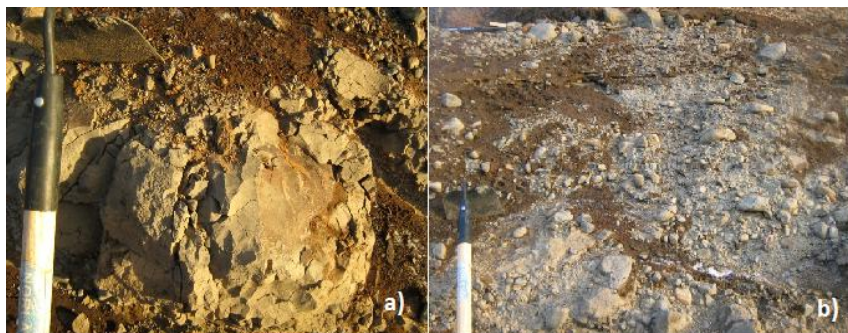
Fig. 18. Unit G. A clay accumulation (a). Overview of the bed (b).

6. Unit F

This is again a sand unit, very similar to D. The lower boundary is sharp while the upper one is gradational. The sand is a bit coarser than the one in unit D; moreover there are some single pebbles that disappear higher up in the unit. The grain size increases somewhat upwards, so the bed can be described as reverse graded. The sediments are generally poorly sorted sediment. An unclear lamination can be identified. Light/red grains, coarser than the ones in the whole section and less rounded are in fact present in thin layers. The code of the unit is then Sl(ig). The thickness is variable because there is a very coarse lens with a U shape above it that disappears on the sides (see the description of unit G for more details). The lens was followed until it reached the smallest thickness to continue the log. Above it there is the unit G.

7. Unit G

This last unit consists mainly of coarse sediments and can be divided in four facies.
The lowermost bed is the lens cited in the previous description of unit F. The lens is clast-supported. Quite rounded cobbles, both very big and smaller, are found but also angular ones are present. The matrix is fine sand. A cobble is to be found that seem to be a piece from the diamicton that was described. A peculiar characteristic of this bed is that the grain size is greatest in the middle and gets finer at the margins, so that both inverse and normal grading is present. The code given is so $DgMc_3(ing)$.
The bed that follows is composed especially of quite well rounded pebbles (on cm-scale) in

a sand matrix (Gsmg/Sm). The coarsest grains are on the bottom, so that the bed is normally graded (Fig. 19a). There are no particular structures but above it there is a soft layer that breaks easily. The thickness is variable; the layer dips towards the observer and gets thinner on the left side of the log section. The colour is gray-green. The code it was given is Fm (Fig. 19b). The uppermost bed is well sorted, with code Gm. Some pebbles are some cm big but the most of them are just some mm. In the uppermost part the sediments mix with soil but still some bigger pebbles could be found in the bed.
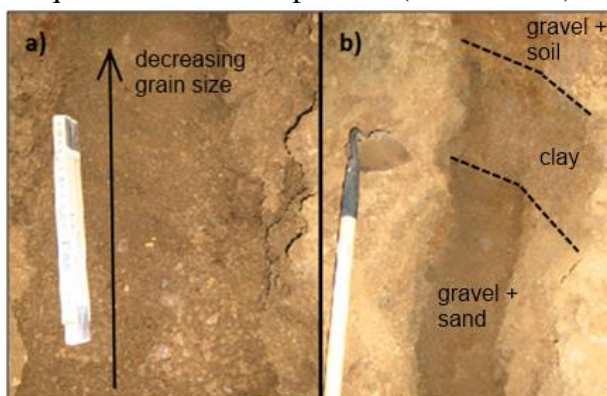
Fig. 19. The upper unit G. The normal grading of upper unit G (a). Overview of the upper part above the lens (b).

3.3 Fossil identification

From the three fossiliferous beds (the sand bed and clay bed of 5A and the sand bed of 2B) six different marine species were identified, belonging to the classes of Bivalvia, Gastropoda and Crustacea. For every species a description, remarks on the species, distribution and ecology are given.
The term "paired shells" was used for valves found united (articulated) in the sediment, "single shell" for valves not united (disarticulated) and "plate fragments" for those fragments without umbo preserved (Símonarson, 1981). They are not counted as individuals. The number of individuals and the percentage in the bed are shown in Table 2.

Table 2. Overview of the number of fossil species found together with percentages.

Species	Sand bed 5A		Clay bed 5A		Sand bed 2B	
	n	*%*	*n*	*%*	*n*	*%*
Hiatella rugosa	15	37,5	5	45,5	1	50
Chlamys islandica	1	2,5				
Macoma calcarea	17	42,5	5	45,5	1	50
Natica affinis	1	2,5				
Deropota pyramidalis	1	2,5				
Balanus balanus	5	12,5	1	9,1		
Total [%] =	40	100	11	100	2	100

-Bivalvia

Hiatella rugosa (Linnaeus, 1767), genus *Hiatella* Bosc, 1801

Material: 15 individuals from the sandy bed of 5A (Fig. 20); just single shells identified. The shells are mostly whole. All the 15 shells have the umbo attached. The size of the whole shells is variable but the smallest ones were considered to be young individuals. 5 individuals were identified from the clayey bed of 5A. They are also single shells with umbo. From the sandy bed of 2B just 1 individual was found. It is a plate fragment. Generally, the form and thickness of shells is different between individuals.

Remarks: At least two types have been identified in the North Atlantic, *H. rugosa* and *H. artica*, according to the forms of larvae. *H. artica* lives more southerly than *H. rugosa* and is not a borer, meaning that it lives on the bottom. *H. arctica* is also smaller. The difference between the two gets less visible with growth of individuals. Also the boring habit is not a determining factor since it depends on the kind of bottom sediment (Símonarson, 2004).
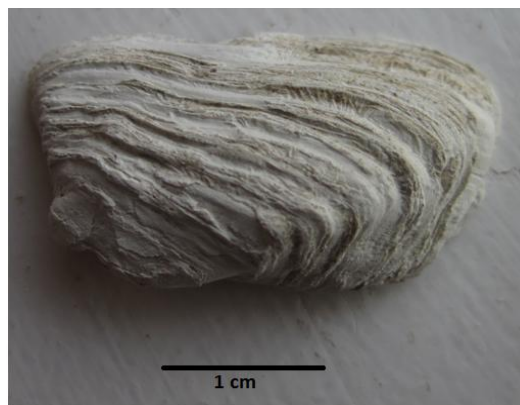
Fig. 20. Example of H. rugosa from the clay bed in 5A.

Description: The individuals belonging to this species have variable shell thickness and convexity and the form can also vary slightly. When alive, they have a white/yellow skin. (Óskarsson, 1982).

Distribution: *Hiatella rugosa* is a boreal, lusitanian and circumpolar species. It is very common in the sea around Iceland and lives at a depth range from the intertidal zone (0 m) to 200 m. Its distribution ranges from the Arctic sea, the North Atlantic to the Mediterranean Sea. It has been found fossil widely in the Northern hemisphere. In the coldest periods *Hiatella rugosa* was more common and was the only species around Iceland during Pleistocene and Lateglacial (Óskarsson, 1982; Símonarson, 2004).

Ecology: This species is infaunal, that is lives below the sediment surface, boring holes or occupying burrows from other animals or fractures in the bottom (Símonarson, 2004).

Chlamys islandica (Müller, 1776), genus *Chlamys* Röding, 1798

Material: 1 plate fragment (Fig. 21) found attached to a rounded clast with an accumulation of *Balanus balanus* in the sand bed of 5A.

Remarks: Previously known as *Pecten islandicus* (Leifur Símonarson 2013, personal information).

Description: This species is characterized by two valves with the typical radial ribs and concentric ridges. When alive, the colour is red/greyish. The triangular extensions or ears on both sides of the umbo are different, being one bigger than the other. The length can be up to 144 mm (Óskarsson, 1982).

Distribution: *Chlamys islandica* is distributed in the Arctic Ocean and North Atlantic (e.g. Norway, Iceland and West Greenland). It is also found in the North Pacific Ocean south to Northern Japan and Canada. The main distribution area is then mid arctic to mid boreal and sometimes circumpolar. This is the species belonging to the *Pectinidae* that is most common in Iceland, though it is uncommon in South Iceland. It lives at a depth range of 2 − 300 m (Óskarsson, 1982; Símonarson, 1981).

Ecology: *Chlamys islandica* is an epifaunal species that lives at the bottom of the sea. It has the capacity to swim to escape from predators by opening and closing quickly the valves, getting enough propulsion to move with jumps (Leifur Símonarson 2013, personal information).
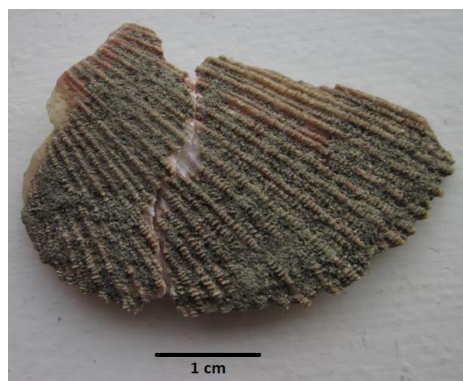
Fig. 21. The plate fragment of C. islandica.

Macoma calcarea (Chemnitz, 1792), genus *Macoma* Leach, 1819.

Material: 20 specimens found in the sandy bed of 5A (Fig. 22), among which 17 single shells were identified as whole individuals. The remnants 3 are plate fragments. From the clay bed in 5A there are 5 individuals; two of them are paired shells. One shell was found open and the other one was closed and filled with sediment. 1 individual plate fragment found in 2B.

It is common to see on the specimens (especially from 5A) the remnants of a delicate brown skin (epidermis) that protect the shells. This skin is made of a hard protein, the conchiolin, and has a light colour when the shell is alive but it darkens and deteriorates when the shell is dead (Leifur Símonarson 2013, personal information). The *Macoma* shells are thin and easy to break. The samples present often holes made by predators (Fig. 22). This is the most common species found in the sediments and has a wide distribution.

Description: This species is characterized by thin, usually white shells. *Macoma calcarea* is usually 30-40 mm long but it can reach a length of 50 mm (Óskarsson, 1982).

Distribution: *Macoma calcarea* lives in the Northern and Western Atlantic and has an arctic, mid boreal and circumpolar distribution. It is in fact found in all arctic seas and extends south to Farøe Islands and northern

Fig. 22. Sample of M. calcarea from the sand bed of 5A. Note the bore hole on the front.

Japan. Their vertical range goes from 0 m in Iceland to 677 m in Western Greenland, though it is most commonly found at a depth range of 0-150 m (Símonarson, 1981).

Ecology: *Macoma calcarea* lives in fine bottoms, mainly clayey or muddy at shallow depth, mixed eventually with sand, gravels and stones; in fact it is an infaunal species that digs under the surface of sediments (Símonarson; 1981).

-Gastropoda

Natica affinis (Gmelin, 1790), genus *Natica* Scopoli, 1777.

Material: 1 whole individual from the clayey bed of 5A (Fig. 23). The specimen is very well preserved, with cavities filled with sediment.

Remarks: Also known with the name *Natica clausa*. (Símonarson, 1981).

Description: *Natica affinis* is composed of 5 whorls. The surface of the shell is even, with no ribs. It can reach a width of 30,5 mm and height of 34,1 mm (Óskarsson, 1982).

Distribution: *Natica affinis* is widespread in the North Atlantic and North Pacific to the Mediterranean Sea. This species lives than in the arctic, boreal, lusitanian and circumpolar areas at

Fig. 23. N. affinis from 5A.

a depth range around Iceland between 0-162 m, thought it has been found at a depth of 2600 m in Algeria. It is common in the Icelandic seas, except for the southern and western areas (Óskarsson, 1982; Símonarson, 1981).

Ecology: *Natica affinis* is one of the most widespread predators and is and infaunal species. It often occurs together with *Macoma calcarea*, in shallow clay or mud bottoms (Símonarson , 1981).
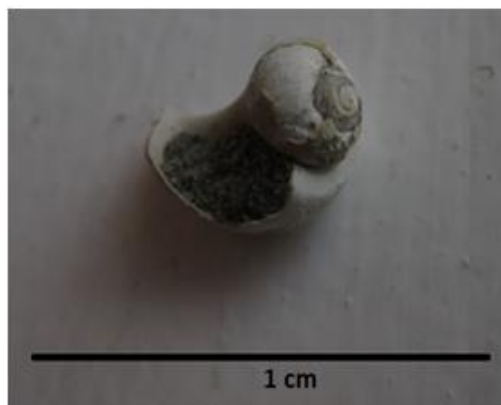
Oenopota pyramidalis (Ström, 1768), genus *Oenopota* Morch, 1852

Material: 1 individual from the sand bed of 5A; very breakable but well preserved (Fig. 24).

Remarks: The genus name was known also as *Bela* and *Lora* (Símonarson , 1981).

Description: *Oenopota pyramidalis* is composed of 8 whorls. The last whorl is slightly longer and ends with a tail (cauda). The surface presents vertical costae. Horizontal spiral ridges can also be observed but they are way less prominent. The colour when alive is pinkish (Óskarsson, 1982).

Distribution: It is common in Iceland in the Faxaflói Bay, though it is also widespread around the other parts of the country except for the eastern part. The depth range at which *Oenopota pyramidalis* is found is between 0-150 m (Óskarsson, 1982).

Fig. 24. O. pyramidalis from 5A.

Ecology: *Oenopota pyramidalis* is an epifaunal carnivore, which prefers soft bottoms (Leifur Símonarson 2013, personal information).

-Crustacea

Balanus balanus (Linnaeus, 1758), genus *Balanus* Da Costa, 1778

Material: 27 fragments collected from the sand bed of 5A (Fig. 25). The total number of fragments was much higher but just the most significant samples were considered. This amount was divided with six (the number of parietal plates) to find the number of individuals, with the result of ~ 5 individuals. From the clay bed of 5A 1 fragment of a wall plate (Fig. 25) was found for a total of one individual. No samples from 2B.

Remarks: There are different species according to the structure of body walls. *Balanus balanus* has tubes and a calc bottom (Leifur Símonarson 2013, personal information).

Description: Barnacles have conical form. Every barnacle is composed of 6 walls (parietal plates), bottom plate and smaller scuta plates (Fig. 25) the animal uses to open and close the upper aperture. The colour when alive is white or light brown. Barnacles can get large, up to 25-30 mm. It is common to find many individuals together, growing one on another on stones or shells (Símonarson, 1981).

Distribution: This species lives in cold water and is distributed in the arctic, circumpolar and boreal areas. It is common in the northern hemisphere. It prefers relatively shallow depth and the range spans between 1-300 m, though it is an uncertain estimate (Símonarson, 1981).

Ecology: When these animals live in fine and soft sediments, like sand or clay/silt, they settle on hard surfaces, such as stones or other shells, in order to avoid the sediment to fill their shell and die. They live on the bottom of the sea, so they are benthic species. They also seem to prefer areas where the currents are strong (Leifur Símonarson 2013, personal information).

Fig. 25. Samples of B. balanus from the sand bed of 5A.One of the scuta plate is on the right.

4 Interpretations

4.1 Sedimentological interpretations

In this chapter an interpretation of every sedimentary facies is given to understand the process of deposition. The same division used to describe the results will be followed.

0. Bedrock
The bedrock presents very clear signs of subglacial erosion and the direction of glacial striae indicates that the glacier flowed from the Hvalfjörður to the sea. The arcuate fractures and the other erosional features described give further information about the subglacial conditions. The arcuate fractures form when clasts under the glacial bed are pushed by ice on the bedrock creating fractures. Their formation is due to the interaction between ice, debris and water under high pressure eventually saturating the glacial till. They are then evidence of the erosion of debris on the glacial bed under meltwater pressure (Benn & Evans, 2010).

1. Unit A
The lowermost bed is a diamict and since the bedrock bears signs of glacial activity this can be interpreted as glacial till. The sediment is very stiff and the pebbles are rounded, so they were transported by water and/or meltwater was present under the glacial bed. The hardness of the sediments can be evidence of dewatering.

The overlying beds of this unit indicate a very different depositional environment. They are very well preserved, except in the higher part where they get mixed together. The good preservation and the fine grain size indicate that deposition took place in a low-energy environment where sediments could settle down undisturbed (Boggs, 2011). The oversized clasts found in the lower unit A were interpreted as dropstones. Sediment bending and on-lap depositions over dropstones are evidence of ice rafting (Benn & Evans, 2010). The repeated coarsening-upward sequences indicate periodical changes in sedimentation rate, since higher the energy coarser the sediments transported (Boggs, 2011). In the coarsest layers, it looks like the finer grains have been washed away while the coarser ones have been left. A shallow glacimarine environment, probably a basin with eventually the bottom of a delta, proximal to glacial front, is the most likely interpretation. In this environment, the glacier was quickly retreating, justifying the presence of dropstones and current changes that would have permitted deposition of coarser sediments.
The fines diminish higher up in the section to eventually disappear towards the top. This means that the energy increased. From a shallow glacimarine environment there is an evolution towards a littoral environment. The increase of energy and the biological activity caused the progressive destruction of the beds. The folded beds described and shown at page 14 can be explained by slumping of saturated sediments (convolute lamination) (Benn & Evans, 2010). The presence of fossil shells and the massive increasing sand beds are evidence of this. A last mention should be done about the fossiliferous clay bed observed at the top of the unit. It could have formed by migrating turbid overflow plumes of fluvial

origin which transported fine sediments to the sea (Hreggviður Norðdahl 2013, personal information; Benn & Evans, 2010).

2. Unit B
This unit was interpreted as the result of deposition in a littoral environment, which is characterized commonly of sandy sediments (Boggs, 2011). As before, the sequences delimited by the pebbly sand layers can be due to periodical energy changes in the environment. The thin clay layers/laminae identified could be also explained by fluvial plume mentioned previously. Biological activity would have been high, since highly bioturbated beds and shells were found.

3. Unit C
The great change in grain size is sign of an abrupt change in the environment of deposition. The coarse gravels at the bottom of the unit seem to form a sort of pavement. The hummocky cross-stratification on the other hand may indicate variable current velocity, as also the repeated normal grading shows (Boggs, 2011). The uppermost bed, identified as diamicton, contains clasts that have a very different origin and composition, called rip-up clasts. They indicate rapid and abrupt transport (Benn & Evans, 2010). The loaded contact indicate that the sediments of this bed had higher density that the bed below so that they soaked in it (Hreggviður Norðdahl 2013, personal information). The sediments got eventually submerged, since intense bioturbation in the sand and in the diamicton is present. The sediments were then eroded by strong currents, as the accumulation of coarser grains, the cross bedding just above the disconformity and the presence of angular sediment clasts of different show.
The unit is interpreted as glacifluvial deposit with variable discharge (Benn & Evans, 2010) that got submerged later by sea.

4/6. Unit D - Unit F
Due to the great similarity these two units are considered together. Both units consist in fact of poorly sorted sand, which indicates that the sediments had been less reworked by water as before. Signs of current activity can be seen at the top and bottom of unit D, where trough cross-bedding and cross-lamination may indicate changes in depth, since ripples would form at less depth, or an increase in stream velocity (Boggs, 2011). This kind of sediments could have been deposited in a littoral environment if the similarities with the sand beds of unit B are taken into account. This interpretation is a consequence of what was said about unit C, since shells moulds and bioturbation would have formed under sea level at a shallow depth (Boggs, 2011). If this is true than the sand unit D would have formed in a littoral environment and then eroded away, as the upper and lower disconformities show. The same interpretation is valid for unit F.

5. Unit E
The sediment of this unit are unstratified, unsorted and with heterogeneous composition. The roundness of the gravels indicates water reworking (Boggs, 2011). The clay clasts, that don't appear anywhere else in the section, could have their origin during fluvial transport. Clay particles transported by the water can in fact accumulate until clay clasts form, that are deposited when the size gets too much (Hreggviður Norðdahl 2013, personal information). For this reason, unit E can be interpreted as a sudden glacifluvial deposit (Hreggviður Norðdahl 2013, personal information; Benn & Evans, 2010), that eroded the underlying bed and created an erosional boundary.

7. Unit G

The coarse diamict bed is similar to unit E and is interpreted in the same way. The depositional change was though not abrupt since the upper and lower boundaries are gradational (Boggs, 2011). The fining-upward sediments in the middle and upper part of the unit could be also be due to a decreasing fluvial activity but they could in addiction have been reworked by cryoturbation, process that pushes the coarser grains upwards little by little (Hreggviður Norðdahl 2013, personal information).

4.2 Palaeontological interpretations

From the kind of fossil assemblage it is possible to reconstruct the zoogeography at the time of deposition, water temperature, and depth and bottom conditions.

The zoogeographical distribution of the species found in every bed was plotted on the chart in Fig. 26. Of all species identified just *Hiatella rugosa* and *Natica affinis* have such a distribution that spans from the coldest arctic environment to the warmer lusitanian environment. *Oenopota pyramidalis* and *Balanus balanus* have a narrower distribution ranging from Arctic to Boreal. *Macoma calcarea* and *Chlamis islandica* are distributed in still colder environments. Comparing their distribution it is possible to identify the common zoogeographical environment for each of the three fossil assemblages found.
The sandy fossiliferous bed of unit 5A, which is the lowermost one, includes species with a common zoogeographical distribution from mid Boreal to mid Arctic.
The clayey bed includes species with a common distribution from mid Boreal to high Arctic. The same is for the uppermost sandy fossiliferous bed in unit B.

Species (Sand bed 5A)	Lusitanian	Boreal			Arctic		
		Low	Mid	High	Low	Mid	High
Hiatella rugosa	▬	▬	▬	▬	▬	▬	▬
Chlamys islandica		▬	▬	▬	▬	▬	▬
Macoma calcarea		▬	▬	▬	▬	▬	▬
Oenopota pyramidalis		▬	▬	▬	▬	▬	
Balanus balanus		▬	▬	▬	▬	▬	▬

Species (Clay bed 5A)	Lusitanian	Boreal			Arctic		
		Low	Mid	High	Low	Mid	High
Hiatella rugosa	▬	▬	▬	▬	▬	▬	▬
Macoma calcarea		▬	▬	▬	▬	▬	▬
Natica affinis	▬	▬	▬	▬	▬	▬	▬
Balanus balanus		▬	▬	▬	▬	▬	▬

Species (Sand bed 2B)	Lusitanian	Boreal			Arctic		
		Low	Mid	High	Low	Mid	High
Hiatella rugosa	▬	▬	▬	▬	▬	▬	▬
Macoma calcarea		▬	▬	▬	▬	▬	▬

Fig. 26. Zoogeographical distribution of fossils at Saurbær divided by bed. (Tables drawn by Veronica Piazza with reference to e.g. Símonarson & Leifsdóttir, 2007; Símonarson, 1981).

From the graphs it is deduced that deposition occurred in a mid Boreal-mid Arctic environment that is a transition between a fully warm and fully cold climate. Fig. 27 shows where this range is located and how it has changes with time.
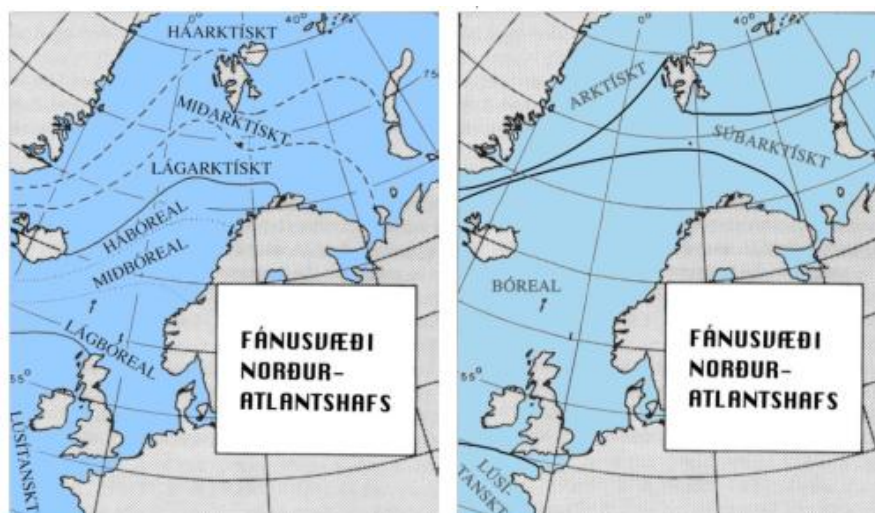

Fig. 27. The zoogeographical division of North Atlantic in the past (to the left) and nowadays (to the right) (from Feyling-Hansen, 1955; Funder et al., 2002).

More information about temperature can be deduced from *Hiatella rugosa.* Strauch (1968) discovered in fact a relationship between the size of *Hiatella* and sea temperature that can be used as a palaeothermometer. He presented a curve (Fig. 28) in which these two variables are plotted and it is deduced that size increases with decreasing temperature. From this relationship it is possible to find the palaeotemperature when a bed was formed if the average size of shells from the bed is known. Though it has been proved that temperature is not the only factor influencing the size of *Hiatella,* Strauch's curve is still a good indicator of palaeotemperature (Símonarson, 2004).

The size of adult individuals of *Hiatella rugosa* from the two beds of unit A was measured, for a total of 3 samples from the lowest fossiliferous bed and 5 for the clay bed above. The average size was then calculated. The smaller shells were considered being younger individuals and not counted. The measurements are shown in Table 3.

Table 3. Size measurements on Hiatella rugosa of subunit 5A.

	Size [mm]	
No. Specimen	Sand bed 5A	Clay bed 5A
1	27	25
2	27	24
3	25	31
4		30
5		25
Average size [mm]	26,3	27

The difference in size between the individuals of the two beds is not very high, though the average size has increased slightly. This indicates that the climate has cooled slightly

25

down. The measured size also indicates that the samples collected did live at shallow depth, not far from the shore (Leifur Símonarson 2013, personal information).

From the curve shown in Fig. 28 a temperature is inferred ranging from -1°C in February to 12°C in August, when the sand was deposited. The clay above it deposited instead in a slightly colder climate.
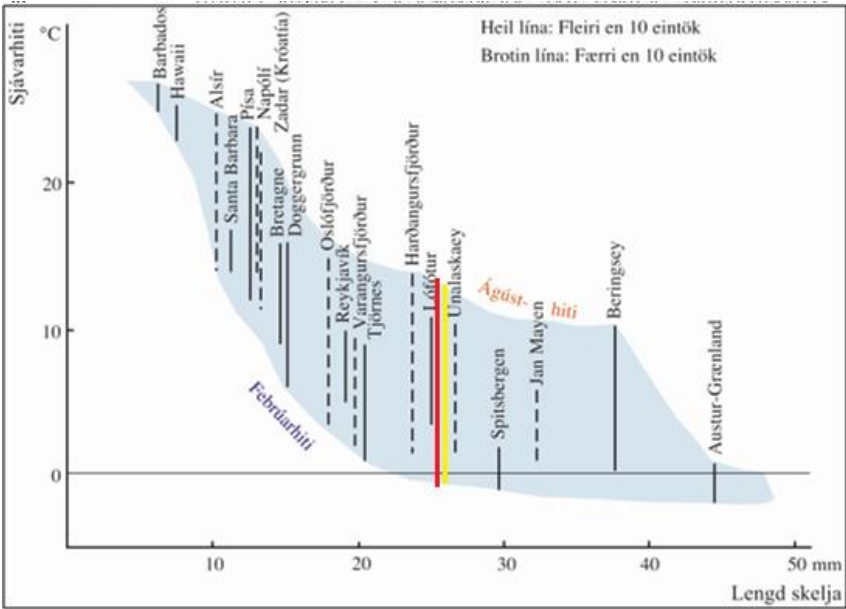

Fig. 28. Strauch's curve (1968). The red and yellow lines show where the average sizes measured are located. The red one is for the sand bed and the yellow one for the clay bed (from Símonarson, 2004).

The same method as before is applied to infer the deposition depth. In Fig. 29 the depth range of every species is illustrated. All of the species live at relatively shallow depth, the half of them living below ~150 m depth while 200 m for *Hiatella rugosa*. *Chlamis islandica* and *Balanus balanus* are the two species that can be found at greater depth, up to 300 m below sea level, though they prefer shallow depth (Símonarson, 1981). *Macoma calcarea* lives at changing depth so it is itself not a good indicator. The depth range that is common for all the species lies between 2-150 m, which is a shallow range. It can be supposed that this was the depth at which deposition occurred. This fits with the observations on sediments.

Fig. 29. Depth range of the fossils at Saurbær (Table drawn by Veronica Piazza with reference to e.g. Óskarsson, 1982).

26

The fossils assemblages in the sand beds of units A and B have in common the facts that shells are broken, disarticulated (though whole individuals were found in the lowest fossiliferous bed) and clearly not in situ. These assemblages can be classified as death assemblages (thanatocoenosis). It means that the shells were transported and reworked by currents and that environmental energy was considerable (Símonarson & Leifsdóttir, 2007). Evidence of this reworking was clearly found in the sand of unit A where a rounded clast was discovered with fragments of *Balanus balanus* and *Chlamys islandica* on just one side, like the shells had been transported and accumulated when the stone acted as an obstacle to transport.

On the other hand, the clay bed of unit A has a different fossil assemblage that can be described as life assemblage (biocoenosis) (Símonarson & Leifsdóttir, 2007). The shells are in fact articulated, undamaged and clearly deposited in situ, so that sediment could fill the space between the valves. The best examples of this are the *Macoma* shells. They are attached by muscles when the shell is alive but then the muscles deteriorate easily after death. The fact that the shells are still attached indicates a low energy environment with little movement after deposition because unless the valves would have be separated. The size indicates that they did live at shallow depth, not far from the shore (Leifur Símonarson 2013, personal information).

About salinity, there are no indications that it was different than it is today and it is not possible to deduce differently from species like *Macoma calcarea* that live at a variable range of salinity. It can be deduced anyway that it was probably slightly lower than today considering the amount of meltwater coming from the melting glaciers.

Shortly, this fauna settle in an environment where the glacier was retreating and the salinity of the area nearest the shore was lowered by the influx of meltwater. This would fit with the temperature range and the zoogeographical distribution. The energy of the environment was high enough for transportation of shells after death that caused them to break and be removed from their original depositional position. The mid fossiliferous bed of clay represents a lower energy environment that permitted in situ deposition of shells and settlement of clay particles. This fits with the hypothesis of a glacifluvial plume deposition. Regarding the bottom conditions, the fauna lived generally at shallow depth, not far from the shore. It is composed of especially infaunal species, boring in the sediments like *Hiatella rugosa*, though species living on the bottom like *Macoma calcarea* and *Chlamys islandica* are also present. *Natica affinis* and *Oenopota pyramidalis* could be the predators that made the holes visible in specimens of *Macoma*. They make these holes with the small teeth on the tongue that are of calc, the same as shells themselves, that is renewable (Leifur Símonarson 2013, personal information).

5 Discussions

This stratigraphic section at Saurbær clearly represents the land uplift and falling relative sea level after the melting of the glacier from the area. The results indicate a transition from a shallow glacimarine environment close to the retreating glacier margins towards a littoral environment, where coarser sediments could be deposited and the influence of glacial rivers was strong. They would periodically change path, abruptly or gradually, creating an alternation between glacifluvial sediments and littoral sands.

The signs of glacial erosion on the bedrock and the glacial till above it indicate that during the Late Weichselian there was an extensive glaciation that reached the area. When the load of ice diminished during Lateglacial, land uplift and regression took place. The consequence was the formation of a shallow glacimarine environment. There is then an evolution towards a shallow marine environment where bioactivity was high. The fossil assemblages from the sands of units A and B give indications of current reworking and transportation of shells, while the energy level dropped during deposition from fluvial plumes as shown by the clay bed of unit A. The sedimentation occurred not far from the shore, since such fluvial plumes lose their energy when they enter the sea and sediments cannot travel far from the injection mouth (Boggs, 2011). The fossil assemblages have in fact the common depth range of 2-150 m. The numerous signs of bioturbation would have been caused by the infaunal species that could have reworked the sediments. Periodical changes in deposition rate also occurred, as evidenced by the sequences in units A (lower) and B (see ch. 4), but the exact cause in not known.

The fossil assemblages indicate moreover a transition climate ranging from mid-Boreal to high-Arctic, which is not as hot as during warm periods but also not as cold as during glacial periods. The slight temperature decrease that was identified analyzing the size changes of *Hiatella rugosa* indicates that the climate slightly cooled down, thought it remained close to -1°C (winter temperature) to 12°C (summer temperature).

The littoral environment evolved into a proper glacifluvial environment with further regression and land uplift. The stronger current activity permitted the transport of coarse gravels that have been ripped away as well as fines. When the braided glacial rivers moved, littoral deposition occurred again.

The age of shells from Saurbær is not known but specimens from Ósmelur have been dated from about 12,700 ^{14}C yr BP (Sveinbjörnsdóttir and Johnsen, 1991). The samples taken in Kjalarnes by Hjartarson's have been dated to Bølling 12,370 ^{14}C yr BP and mid Younger Dryas (10,963 ^{14}C yr BP and 10,610 ^{14}C yr BP). The first specimens were found in glacial till at about 7 m a.s.l and the other two in littoral sediments at about 10 m a.s.l. It is now known that Hjartarson's interpretations of glacial moraine is not correct since the area was not covered by glaciers after Bølling (Norðdahl & Pétursson, 2005). The shells from unit 5A were found at an interval of 4,8-5,5 m a.s.l. and the fossils from unit 2B at about 7-7,5 m a.s.l.

Since the stratigraphic log at Saubær shows a clear episode of marine regression, it can be settled in one of the regression episodes in the curve shown in Fig. 30, which is the same curve shown in Fig. 5 at page 5. The age of the shells found by Hjartarson are plotted on it.

Of the three regression episodes, the last one during Holocene, is the least probable.
If the shells are considered to be from mid Younger Dryas and the average age from the two samples is plotted on the curve it can be seen that it does not fit with the results, since it plots in the Younger Dryas transgression episode. On the other way, if it is supposed that the shells are from Bølling, than their age would plot during the Bølling regression. It fits with the studied log and with the results of other researches like at Ósmelur (Norðdahl & Pétursson, 2005). The slight cooling identified indicated by the size change in the samples of *Hiatella rugosa* would probably be connected to the cooling that happened in Allerød.
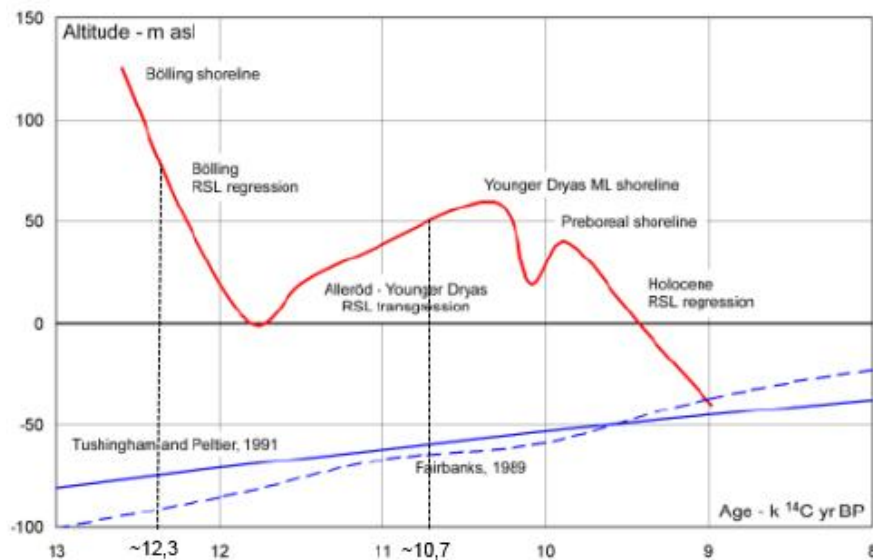

Fig. 30. The age of the fossil shells from Hjartarson (1993) plotted on the curve from Norðdahl and Pétursson (2005) (modified by Veronica Piazza).

Since no glacial till was found upper in the section, no glacial readvance reached the area. As it can be seen in Fig. 30, this fits with the model of Norðdahl and Pétursson (2005) according to which the Bølling sediments at Ósmelur were not overridden by glaciers. In Fig. 31 the hypothetical glacier extent is marked in grey. It occupied just the innermost part of Hvalfjörður. The northern shores of Kjalarnes would have then been ice-free areas that received the input of meltwater from the glacier. This is also the same conclusion reached by Hjartarson (1993).

Fig. 31. Ice sheet extent during Younger Dryas at ~10,3 yr BP in Southwest Iceland (part of the reconstruction from Norðdahl & Pétursson, 2005).

References

Benn, D. I., & Evans, D. J. (2010). *Glacier & Glaciation.* London: Hodder Education.

Boggs, S. (2011). *Principles of Sedimentology and Stratigraphy.* Upper Saddle River, New Jersey: Pearson Prentice Hall.

Eiríksson, J. (2007). Leiðbeiningar um jarðfræðikortagerð. Reykjavík.

Eiríksson, J., Knudsen, K. L., & Símonarsson, L. A. (2004). Lateglacial oceanographic conditions off Southwest Iceland inferred from shallow-marine deposits in Reykjavík and Seltjarnarnes Peninsula. *Boreas, Vol. 33* , pp. 269-283.

Friðleifsson, I. B. (1974). *Jarðhitaleit í Kjalarneshreppi.* Orkustofnun (Jarðhitadeild).

Friðleifsson, I. B. (1985). Jarðsaga Esju og nágrennis. *Ferðafélag Íslands-Árbók 1985* , pp. 141-172.

Geirsdóttir, Á. (1990). Diamictites of late Pliocene age in western Iceland. *Jökull 40* , 3-21.

Hjartarson, Á. (1993). Ísaldarlok í Reykjavík. *Náttúrufræðingurinn 62 (3-4)* , bls. 209-219.

Imsland, P. (1985). Úr þróunarsögu jarðskorpunnar við sunnanverðan Faxaflóa, sprungumyndunarsaga. *Náttúrufræðingurinn 54 (2)* , pp. 63-76.

Ingólfsson, Ó. (1988). Glacial History of the lower Borgarfjörður area, western Iceland. *Geologiska Föreningens i Stockholm Förhandlingar, Vol. 110, Pt. 4* , 293-309.

Ingólfsson, Ó., & Norðdahl, H. (1994). A review of the environmental history of Iceland, 13000-9000 yr BP. *Journal of Quaternary Science 9 (2)* , 147-150.

Ingólfsson, Ó., & Norðdahl, H. (2001). High Relative Sea Level during the Bølling Interstadial in Western Iceland: a Reflection of Ice-sheet Collapse and Extremely Rapid Glacial Unloading. *Arctic, Antarctic and Alpine Research, Vol. 33, No. 2* , 231-243.

Ingólfsson, Ó., Björck, S., Hafliðason, H., & Rundgren, M. (1997). Glacial and climatic events in Iceland reflecting regional North Atlantic climatic shifts during the Pleistocene-Holocene transition. *Quaternary Science Reviews* , pp. 11435-114.

Ingólfsson, Ó., Norðdahl, H., & Hafliðason, H. (1995). Rapid isostatic rebound in southwestern Iceland at the end of the last glaciation. *Boreas, Vol. 24* , 245-259.

Jónsson, G., & Kristjánsson, L. (2002). Þéttriðnar segulsviðsmælingar yfir Reykjavík. *Náttúrufræðingurinn 72 (1-2)* , pp. 42-49.

Norðdahl, H. (1990). Late Weichselian and Early Holocene deglaciation history of Iceland. *Jökull, No. 40* , 27-45.

Norðdahl, H., & Pétursson, H. G. (2005). Relative Sea-Level Changes in Iceland: new Aspects of the Weichselian Deglaciation of Iceland. In C. Caseldine, A. Russel, J. Harðardóttir, & O. Knudsen, *Iceland - Modern Processes and Past Environments* (pp. 25-78). Amsterdam: Elsevier.

Norðdahl, H., Ingólfsson, Ó., Pétursson, H. G., & Hallsdóttir, M. (2008). Late Weichselian and Holocene environmental history of Iceland. *Jökull, No. 58* , 343-364.

Óskarsson, I. (1982). *Skeldýrafána Íslands.* Reykjavík: Prentsmiðjan Leiftur Hf.

Símonarson, L. A. (2004). Rataskel og forn sjávarhiti. *Náttúrufræðingurinn 72 (1-2)* , pp. 29-34.

Símonarson, L. A., & Leifsdóttir, Ó. E. (2007). Early Pleistoce molluscan migration to Iceland - Palaeoceanographic implication. *Jökull No. 57* , pp. 1-20.

Símonarson, L. (1981). Upper Pleistocene and Holocene marine deposits and faunas on the north coast of Nûgssuaq, West Greenland. In L. A. Símonarson, *Grønlands Geologiske Undersøgelse, Bullettin No. 140.* Øster Voldgade 10, DK-1350 Copenhagen.

Skipulagsstofnun. (2009). *Efnistaka af hafsbotni í Hvalfirði.* Reykjavík: Skipulagsstofnun.

Stanley, S. M. (2009). *Earth System History.* New York: W.H.Freeman and Company.