A sedimentological and stratigraphical study of Veiki moraine in northernmost Sweden

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Contents

Cover Picture: Veiki moraine

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THORBJÖRG SIGFÚSDÓTTIR

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Abstract: Veiki moraine is a landform area consisting of rim-ridged subcircular hummocks and plateaus with depressions in between, mostly located within a N-S extending zone of a hummocky landscape. It is believed to have formed during the pre-late Weichselian and survived overriding by ice during the subsequent glaciations. Due to their good preservation, the Veiki moraine provides valuable information on the glaciation and prevailing environmental conditions in northern Sweden during the earlier stages of Weichselian glaciations, as well as the ice dynamics of the late Weichselian ice sheet.

To determine the internal stratigraphy of the moraine plateaus and interpret the depositional environment, excavation into two Veiki moraine plateaus were carried out. The sections investigated were supplemented by morphological data from LiDAR elevation models and GPR profiles. In addition, sorted sediment units within the two Veiki moraine plateaus were sampled for radiocarbon and OSL dating.

The two moraine plateaus investigated seem to consist of massive diamicton in the center. The rim ridges are built up by stratified debris flow units, partly underlain by organic-rich lake sediment. The elevated position of these sediments indicates that the moraines were surrounded by ice at the time of deposition. They are interpreted to have formed by debris and meltwater inflow into depressions on a debris-covered stagnant ice mass. After the surrounding ice had melted they were left standing as high points in the landscape. The moraine plateaus and the surroundings are covered by a thin till bed deposited by subsequent glaciations. Dating of lake sediment suggest deposition around 50,000 years BP. This indicates deposition during the Tärandö II interstadial, which followed the glaciation in MIS 4 during the Weichselian glaciation cycle.

Keywords: Veiki moraine, glacial geology, Weichselian glaciation, northern Sweden, supraglacial lakes.

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En sedimentologisk och stratigrafisk Veikimoränstudie från norra Sverige

THORBJÖRG SIGFÚSDÓTTIR

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Sammanfattning: Veikimoräner är cirkulära moräner med ryggar längs kanterna som kan hittas i norra Sverige. Majoriteten är belägna längs en N-S gående kuperat landskap. Moränerna tros ha bildats under tidig-mellan Weichsel och har överlagrats av glaciärer från efterföljande glaciationer. Tack vare att Veikimoränerna har bevaratas i så gott skick kan dessa moräner ge värdefull information om glaciationer och dåvarande miljömässiga förrhållande under glaciationen i norra Sverige under tidig Weichsel samt inlandsisens dynamik under sen Weichsel.

För att bestämma den invändiga stratigrafin av moränerna samt tolka avsättningsmiljön gjordes utgrävning av två Veiki moräner. Sektionerna undersöktes och kompletterades med morfologisk data från LiDAR höjdmodeller och GPR profiler. Sorterade sedimentenheter i de två Veikimoränerna provtogs för ^{14}C och OSL datering.

De undersökta moränerna verkar bestå av massiva diamikton i de centrala delarna. Ryggkanterna är uppbyggda av stratifierade massflöden delvis underlagrade av sjösediment rika på organiskt material. Den upphöjda positionen av dessa sediment indikerar att moränerna var omgivna av is när de deponerades. De har tolkats som att de bildats när glaciärmaterial och smältvatten har runnit in i en depression som legat på en glaciärmaterialtäckt stagnant is. När omgivande is smälte bort blev dessa landformer kvar som höga områden i landskapet. Moränerna och omgivande område är överlagrat av ett tunt lager av morän som deponerats av de efterföljande glaciationerna. Dateringar av sjösedimenten tyder på deposition vid 50.000 BP vilket korrelerar till Tärandö II inderstadialen. Denna interstadial kom efter MIS 4, under Weichsel.

Nyckelord: Veikimorän, glacialgeologi, Weichsel, norra Sverige, supraglacial sjö.

Ämnesinriktning: Kvartärgeologi.

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1 Introduction

1.1 Previous research; Veiki moraine plateaus and similar landforms

Veiki moraine is a landform area consisting of often rim-ridged subcircular hummocks and plateaus with deep depressions in between. The name is derived from the village Veiki, close to Gällivare in Norrbotten, northernmost Sweden.

Veiki moraine has been frequently studied during the 20th century (e.g. Hoppe 1952; Lundqvist 1981; Lagerbäck 1988), suggesting composition of alternating unsorted and sorted sediments, covered by a till layer (Lagerbäck 1988). Various hypothesis concerning its formation have been proposed, suggesting both subglacial, englacial and supraglacial depositional processes.

The most widely accepted depositional model today was proposed by Lagerbäck (1988), suggesting mostly supraglacial deposition during downwasting of debris covered dead-ice. Accumulation of flowtill and water reworked sediments into ice walled lakes built the main parts of the landform, either with contact to the ground or in depressions in the ice.

Rim ridged, flat topped, circular moraines, similar to those of Veiki moraine have been studied in other parts of the world, mostly in North America, formed in association with the deglaciation of the Laurentide ice sheet (e.g. Ham & Attig 1996; Eyles et al. 1999; Boone & Eyles 2001; Clayton et al. 2008). They have been shown to vary between being almost entirely built up by sorted sediments and mainly of diamicton (Johnson & Clayton 2003). Different depositional models have been suggested for different types of morines.

Moraines consisting mostly of sorted sediments have been described by e.g. Ham & Attig (1996) and Clayton et al. (2008). Their formation is believed to have initiated by formation of supraglacial lakes on top of a stagnant ice. Due to unfrozen basal conditions, the lakes melted through the ice until they became ground based, ice-walled lakes. The rim ridges are built up by delta sediments and debris flow deposits, originating from the surrounding ice (Clayton et al. 2008).

Rim ridged moraine plateaus associated with hummocky moraine have been described by e.g. Eyles et al. (1999) and Boone & Eyles (2001). The stratigraphy of a moraine plateau was investigated by Eyles et al. (1999) and revealed that the core mostly consisted of fine-grained diamicton with infilling of glaciolacustrine sediment that showed anticlinal arching over the rim ridges. Based on their interpretation, the circular rim ridges were formed where the weight of the overlying stagnant ice squeezed underlying till into areas where the pressure was lower i.e. under depressions or hollows in the ice. The presence of the lacustrine sediments was explained by meltwater infill into the hollows (Eyles et al. 1999; Boone & Eyles 2001).

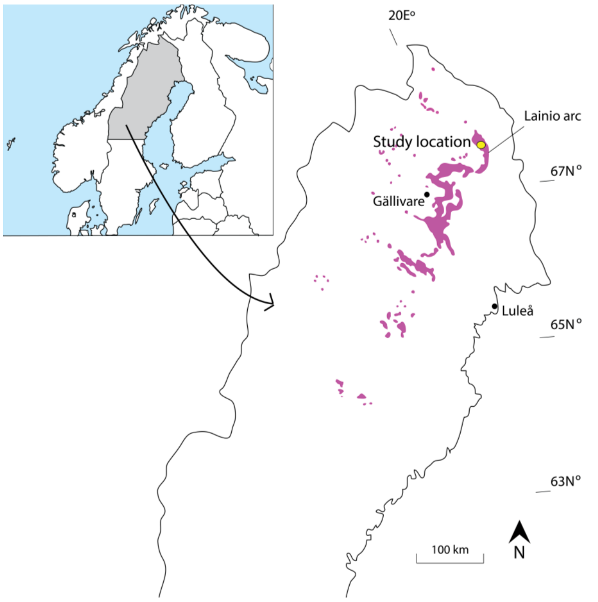

Fig. 1. Map of northern Sweden. The distribution of the Veiki moraine hummocks and plateaus is indicated with a purple color. Modified from Hättestrand (1998).

1.2 Study area

The study site is located at Rauvospakka, ca. 26 km north of the town Junosuando, in the Pajala municipality, in northernmost Sweden. It is situated in the north part of the so-called Lainio arc at an altitude of ca. 320 m.a.s.l (Fig. 1; 2) .

1.2.1 Distribution of the Veiki moraine hummoks and plateaus.

The Veiki moraine hummocks and plateaus are mostly located within a N-S extending zone of a hummocky landscape. The Veiki moraine zone shows a distinctly lobate configuration, the northernmost and the most prominent lobe is called the Lainio arc (Fig. 1). The eastern limit is commonly marked with terminal moraines (Hättestrand 1998). The lobes are suggested to mark a former ice marginal zone. Their location seems to be controlled by the bedrock topography and the ice flow that formed them has followed river valleys to the lowlands where the lobes were formed. This indicates that they were formed after an active phase of a glacier advance, possibly after surgings of the ice margin. Veiki moraine also shows minor occurrences at various other places in northern Sweden (Fig. 1) (Lagerbäck 1988; Hättestrand 1998).

1.2.2 Age of the Veiki moraine

Radiocarbon datings performed on organic material enbedded within moraine plateau sediments have given infinite ages (older than 40-50.000 years) (Lagerbäck 1988). The Veiki moraine belt is thus believed to be pre-late Weichselian in age. No finite datings exist, but based on stratigraphic evidence and cross-cutting relationship, Lagerbäck (1988) suggested that the Veiki moraine belt was formed after the first Weichselian advance, during the

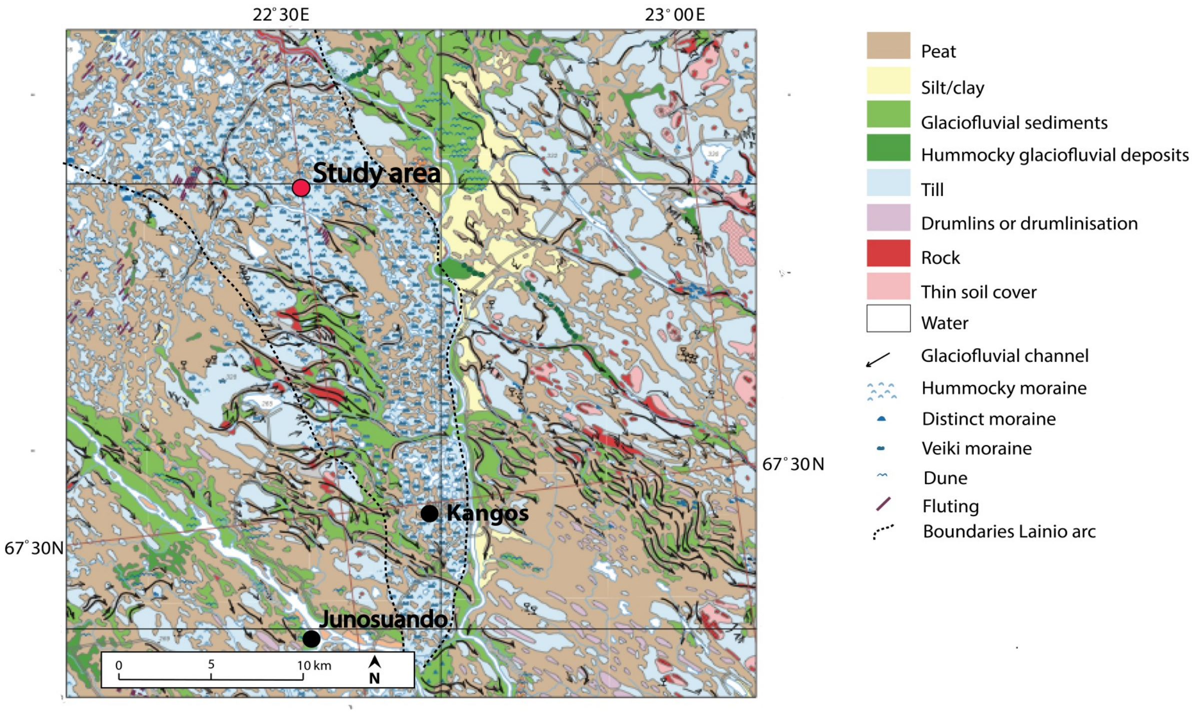

Fig.2. Quaternary map of the study area. The outlines of the Lainio arc is marked with dotted lines. Modified from from SGU

Peräpohjola interstadial (renamed Tärandö I (MIS 5d/5c)). One of the arguments used by Lagerbäck (1988) was that Veiki moraine seems to be related to the NW trending drumlins and eskers in the area, deposited in association with the first Weichselian ice sheet. Hättestrand (1998) challenged that hypothesis by pointing out that from a morphological point of view these two landform elements might not at all be related. Hättestrand (2007) suggested three possible correlation alternatives, based on litho-and biostratigraphical evidence; deposition during the first Weichselian deglaciation (Tärandö I (MIS 5c)), during the second Weichselian deglaciation (beginning of Tärandö II (MIS 5a)) or in the middle Weichselian (MIS 3) (Hättestrand 2007; Hättestrand & Robertsson 2010).

1.3 Geological setting

1.3.1 Quaternary deposits and past ice flow movements

The landscape in northernmost Sweden displays a mosaic of non-glacial and glacial landforms, formed by at least three different glacial flow systems (Hättestrand 1998). The dominant Quaternary deposit in the Pajala district is till, interbedded with interglacial deposits belonging to at least two separate interstadials (Fagerlind 1981; Lagerbäck & Robertsson 1988).

The oldest set of landforms, formed in association with the first Weichselian glaciation comprises eskers, drumlins and other NW trending directional features. Landforms belonging to this ice flow are often extremely well preserved and dominate the glacial landscape in northern Sweden. Thus it is evident that the ice sheet was warm-based and had significant influence on the land surface formed at the ice-bed interface (Hättestrand 1998; Lagerbäck & Robertsson 1988). Small scale lineations and melt water channels, indicating ice flow from south-west, have been correlated to the deglaciation of a second Weichselian ice sheet (Hättestrand 1998). These latter landforms are only found as isolated patches and the existence of this ice sheet has even been doubted (Kleman et al. 1997). However if it did exist, the ice sheet was most likely both thin and cold based (Hättestrand 1998).

The landforms (drumlins and eskers) representing the last glacial phase of the Weichselian show patchy distribution, indicating that large parts of the ice sheet were frozen to its bed, even at the final part of deglaciation. Directional elements formed during the Last Glacial Maximum (LGM) deglacial phase indicate an ice flow direction from S-SW and thus a cross-cutting relation to the NW-SE system. The pressure melting point was reached only in areas displaying the youngest SW-NE system (Hättestrand 1998).

1.3.2 Bedrock

The bedrock in northernmost Sweden is dominated by pre-Cambrian granitic rock. Other bedrock types i.e. sandstone, metabasalt and shales, also of pre-Cambrian age, are found scattered around the region (SGU 2013a).

1.4 Objective

Extensive studies have been performed regarding the

Late Weichselian history of Fennoscandia, whereas much less is known about the earlier history. Work conducted on Veiki moraine and associated landforms in recent years has mostly been focused on the morphology and the distribution of the landforms, and no detailed sedimentological studies have been performed since Lagerbäck carried out his studies in 1988. By studying the stratigraphy of Veiki moraine plateaus, valuable information can be acquired on depositional processes and glacial setting in which these formed and thus the prevailing environmental conditions. In addition, it provides information on the subsequent ice sheets that overrode the moraines.

This study presents sections, excavated into two nearby moraines plateaus with the purpose to determine the internal stratigraphy of the landforms and interpret the depositional environment. The findings will be compared to other studies on similar landforms and Lagerbäck's (1988) depositional model will be tested.

2 Methods

2.1 Area investigation

To find suitable locations for surveying, both LiDAR elevation models and pulse EKKO PRO Ground-Penetrating Radar (GPR) (Sensors & Software) profiles were used. The GPR profiles were collected by Leif Vidar Jakobsen, Helena Alexanderson, Martina Hättestrand and Clas Hättestrand, between the 10th and 11th of July 2012. Data was collected using two frequencies: 100 MHz and 50 Mhz. Post-processing of GPR-data (signal saturation correction) was performed using EKKO_VIEW and EKKO_VIEW Deluxe software (Sensors & Software Inc.). The topography was extracted from LiDAR data.

2.2 Fieldwork

The fieldwork was carried out between the 2nd to 8th of October 2012.

In total, seven trenches were dug with an excavator and thereafter cleaned by hand. The location of each section was measured with a handheld GPS. Five of the sections were logged in a scale of 1:20. Stratigraphical and sedimentological descriptions were made following the data chart of Krüger & Kjær (1999). The observations included sediment textures, structures, compactness and particle sizes. Trench orientations, as well as strike and dip of folds and faults were measured using a compass with a clinometer.

Clast fabric measurements were performed in nine units. The a-axis orientation of at least 25 elongate clasts was measured in each unit. Only those within the size range 2-6 cm and with an a/b ratio >1.5:1 were accepted and the measuring area was kept as small as possible. Clasts with close contact to other clasts and boulders were discarded to avoid interference with nearby clasts.

Six trenches were sampled for further analysis and both bulk and clast samples were taken. The clast samples contained approximately 50 clasts each, ranging in size from 2 to 12 cm.

2.3 Laboratory work

2.3.1 Clast analysis

The morphological characteristics of the clasts provide important information on their transport history as they experience modification by erosion, weathering and transport (Benn & Evans 2004).

Passively transported clasts tend to be more angular and with lower c/a ratio, while those that are actively transported have intermediate angularity values (subangular to subrounded) and higher c/a ratios. However if the transport path of the clast is short there may be many local angular clast incorporated into actively transported diamicton. The percentage of clasts with c /a ratio ≤ 0.4 (C_{40} value) and the percentage of very angular and angular clasts (RA value) have shown to be useful when distinguishing morphological differences between clast populations (Benn & Ballatyne 1994). Striations and polishing of clasts within glacial sediments are often regarded as evidence for subglacial transport (Benn 2003).

Morphological measurements were performed on samples from 17 diamicton units. The long, intermediate and short (a, b and c) axes of each clast was quantified with calipers to obtain the relative dimensions and C_{40} and RA values calculated

The clast angularity was estimated visually following the descriptive criteria of Benn & Ballatine (1994). The absence and presence of striations was noted as well as the level of polishing and weathering on each clast. The C_{40} and RA values were also calculated separately for clasts of granitic origin. That was to avoid bias, as different lithologies can respond differently to similar wear processes (Benn & Evans 2004). The lithology of the each clast was noted and used for sediment correlation and provenance indication. The clasts were grouped into five groups: granite, gneiss, basalt/metabasalt, quartzite and other/ unidentified.

2.3.2 Grain size analysis

The grain size distribution of sediments contains information about the deposition and transport history and can be used as a supplement with other evidence (Benn & Evans 2004).

Grain size analyzes were performed on 16 bulk samples. Each of them had a minimum weight of ca. 1000 g. Fifteen samples were collected from diamicton beds and one from soil cover bed. After the samples had been dried, each of them was weighted. The finest grains were washed through a 0.063 mm sieve and then dried and weighed again. Finally they were all dry sieved through sieves ranging from 0.063 to 22.4 mm and each fraction weighted.

2.3.3 Dating

Sorted sediment samples found in trench nr. 1 were washed through a 2 mm sieve. Macrofossils were collected and two samples were sent to the Radiocarbon Dating Laboratory at Lund University for ^{14}C dating.

Samples were also collected for Optically Stimulated Luminescence (OSL) dating .

2.3.4 Data processing

The trenches and the maps were drawn with the Adobe Illustrator® CS6 program.

For comparing the fabric data the eigenvalue method discussed in Benn & Evans (2004) was used. The results were plotted on a contoured, lower-hemisphere stereonet using StereoNet© software. The principal eigenvalues (S_1, S_2, S_3) and principal eigenvectors (V_1, V_2, V_3), giving the degree and direction of maximum clustering were calculated and presented together with the plots. The clast roundness data were plotted on histograms using the Microsoft Excel®. The clast lithology data are represented graphically using a 100 % stacked bar diagram made in Microsoft Excel®. Grain size distribution was plotted in Microsoft Excel® spreadsheet.

3 Area investigation

3.1 GPR profiles

Two of the GPR profiles used in this study, were collected over the excavated moraine plateaus (Fig. 3) and in addition to these, one GPR profile was made over the fluted terrain (Fig. 16). They indicate complex stratigraphy with anticlinal arching at the ridges but horizontal and thicker beds under the plateaus (Fig. 3). Sharp reflector boundaries are detected under both of the moraine plateaus. By excavation these were confirmed to represent the bedrock surface (see description of trenches 4 and 5). The thickness of the moraine plateaus is similar but the southern moraine plateau appears lower than the northern one as it is situated in a slope, while the northern is on a topographic high. The GPR profile from the fluted terrain (Fig. 16) indicated a thick sediment cover (around 10 m), while the non fluted

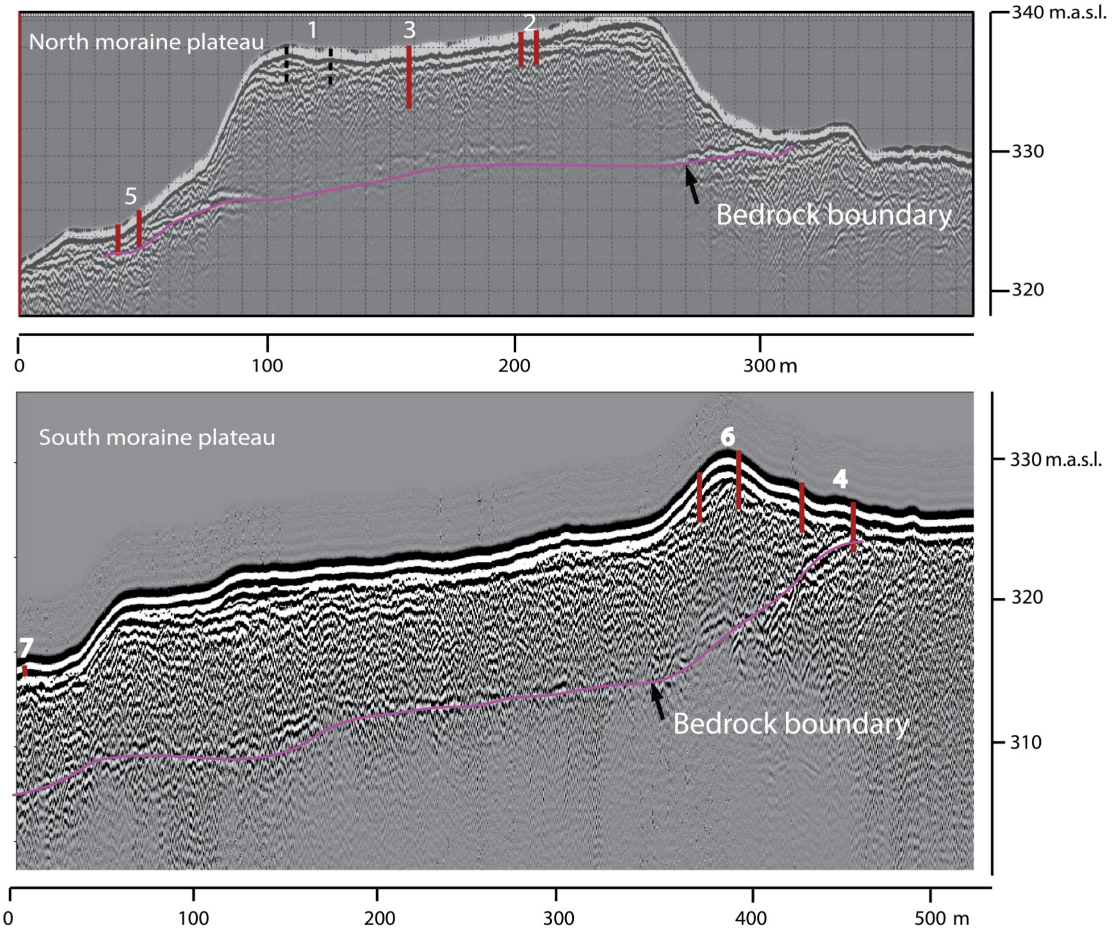

Fig. 3. GPR profiles of the northern and the southern moraine plateaus, as displayed by using 100 Mhz frequency. The approximate location of sections are marked on the profiles and the depth indicated with red lines. Trench nr. 1 is not on the profile but the depth is marked at a similar location using dotted lines. Clear reflector boundaries were observed at ca. 10 m depth, confirmed by excavation to be the underlying bedrock. They are marked on the figure using purple lines. Note that the lateral scale is not the same for both profiles.

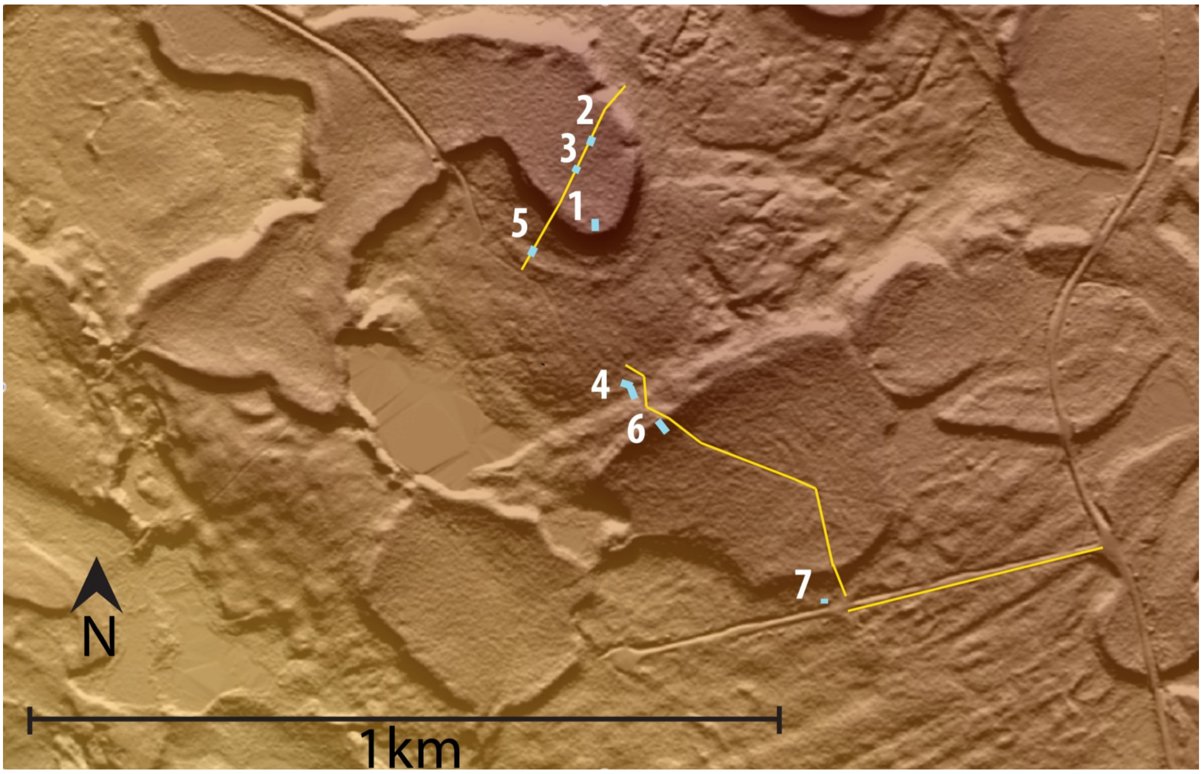

Fig. 4. Hill shaded relief map of the study area consructed from high reolution LiDAR digital height data. The three GPR profiles used in this study are marked on the map with yellow lines. The trenches are labeled and marked on the figure using

area between the moraine plateaus (Fig. 4) seems to have a much thinner sediment cover.

3.2 LiDAR

Two Veiki moraine plateaus were investigated (Fig. 4) and will be referred to as the northern and southern moraine, respectively. At many places there are indications of double rim ridges surrounding them. South of these is a fluted ground surface with a SW-NE orientation.The fluting is not found superimposed on the Veiki moraine plateaus, indicating that the flutes are older.

4 Sediment descriptions and interpretations

Six trenches were excavated into and outside two adjacent Veiki moraine plateaus. Two were dug into the rim ridges (trenches 1 and 6), two at the base of each moraine (trenches 4 and 5) and two trenches into the plateau (trenches 2 and 3). One was dug outside the landforms (trench 7) (Fig. 4). The location of the trenches was chosen after analyses of GPR profiles, LiDAR relief map and field reconnaisance, with the aim to get as good overview as possible on various parts of the landforms.

4.1 Trench 1

The total length of the trench was ca. 18 m, but the logged part was 9 m long (Fig. 6). It was excavated into the inner part of the rim ridge of the northern Veiki moraine (Fig. 3; 4). The coordinates of each end of the trench are: N 67° 39’ 50.7’’, E 22° 30’ 00.3’’ - N 67° 39’ 51.4’’, E 22° 30’ 00.0’’. The internal stratigraphy displays units that are horizontal or slightly dipping towards the center of the moraine plateau.

The section collapsed while it was being logged, and due to that, the units were sampled and fabric analyses carried out on the opposite section wall.

4.1.1 Unit 1A

4.1.1.1 Description

Unit 1A is exposed irregularly at the base of the section (Fig. 6). The unit continues horizontally under the whole section but only small parts could be logged due to instability of the section walls.

The main part is composed of fine, heterogeneous, light grey, silt and sand with reddish-brown lenses. It holds small amounts of organic fragments mostly identified as roots and mosses. A dark, heterogeneous, fine-grained organic sediment-layer with a low mineral content is incorporated into the unit, interfingers with it and appears discontinuously throughout it (Fig. 5). The subfossils retrieved from the organic layer include i.e. sedges and wood pieces. The wood were preliminary identified as *Betula* (Birch) and *Alnus* (Alder) (Hans Linderson pers.comm. 2012). The uppermost part of unit 1A, consist of laminated red and grey silty sand.

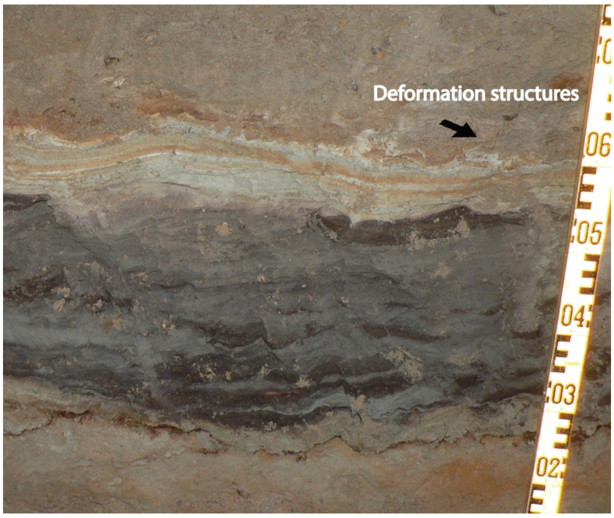

Fig. 5. Dark, organic rich bed within Unit 1A (Fig. 6; 4-5 m). Note the laminated silt and the deformation structures at the upper boundary. Photo by Helena Alexanderson.

Two samples were collected from the unit for ^{14}C dating and two were sampled for OSL dating. A *Salix* leaf, retrieved from the grey silt gave modern age, while the wood piece found in the organic rich unit gave infinite age (>48,000 years) (Table 2). Preliminary results from the OSL dating gave the age 53,000 ± 5000 from the sand in the lowermost part and 45,000 ± 6000 years BP for the grey silt (Table 1). The location of where the samples were retrieved is marked on Fig. 6.

4.1.1.2 Interpretation

The sorted sediments in Unit 1A are interpreted as lake sediments due to their horizontal configuration an high organic content, and as it is now situated at a high point in the landscape it is evident that it was surrounded by ice at the time of deposition. The macrofossils found in the unit suggest deposition during a relatively warm episode and the high amount of organics and some fairly large pieces of macrofossils indicate that the nearest surroundings of the lake were vegetated at the time of deposition. The unit was found lying horizontally through the entire section, which indicates that it was deposited *in situ* and not brought into the sediment basin by later glacial processes.

The changes in the grain size and organic content reflect changes in the depositional environment, varying between colder conditions to warmer conditions with lower sediment input. The discontinuity of the organic sediment could be explained by deformation processes from below, i.e. melting of underlying ice. It is however unlikely that it was deformed due to the deposition of the unit above because of the relatively undisturbed, horizontal laminated silt layer there between.

Radioarbon (^{14}C) dating suggests that the unit was deposited earlier than 48,000 years BP. The OSL dating from the lower sand gave the age 53,000 ± 5000 years and from the upper silt 45,000 ± 6000, indicating deposition ca. 50,000 years BP. That timing correlates with the Tärandö II interstadial according to alternative A2 (MIS 3) of Hättestrand & Robertsson (2010). The most likely explanation for the modern age of the *Salix* leaf is that the sample became contaminated during the sampling process. No other leaves were found in the unit, which supports contamination.

4.1.2 Unit 1B

4.1.2.1 Description

Unit 1B consists of a matrix-supported, silty-sandy diamicton. The lower boundary is rusty colored, sharp and slightly wavy. Small-scale flame structures are present at the boundary (Fig. 5). The average thickness of the unit is approximately 1.5 m and is here divided into two subunits; 1B1 and 1B2:

Unit 1B1 is heterogeneous, friable and has brownish-grey color. The clasts are mostly subrounded to subangular (Fig. A.2.1), the RA value is 8 % and the C_{40} value is 16 % (Granite: RA: 12 %, C_{40}: 12 %).

Unit 1B2 is partly stratified, firm to friable, fissile and slightly more reddish and more compact than Unit 1B1. It also holds somewhat more gravel-sized clasts. The lower boundary is gradational and could not be followed through the whole section. The clasts are also mostly subrounded to subangular (Fig. A.2.2), the RA value is 20 % and C_{40} value is 19 %. Fabric analysis revealed relatively strong cluster fabric with S_1 : 0.738 and V_1: 135°/2° (Fig 10).

4.1.2.2 Interpretation

The clast morphology analysis, showing mostly clasts

Table 1. Results from OSL dating of organic material from Unit 1A.

Lab no.	Age (ka)	Dose (Gy)	N acc./total	Dose rate (Gy/ka)	w.c. (%)
Lund 12056	45± 6	130.9±15.6	20/45	2.92±0.12	16
Lund 12057	53±5	152.6±13.3	23/39	2.89±0.12	15

Table 2. Results from radiocarbon (^{14}C) dating of Unit 1A.

Sample	Lab no	Obtained ^{14}C age (yr BP)
Rauvospakka 1:07 grey	LuS 10373	104.1 ±0.6
Rauvospakke 1:08 black	LuS 10374	>48.000

of intermediate angularity, together with the strong fabric, fissility and compactness suggest a subglacial source (Kemmis 1996; Krüger & Kjær 1999). However, both stratification and the relatively intact sediments below, and the fabric orientation does not align with the past ice flow in this area (Kleman et al. 1997; Hättestrand 1998).

Another possibility, and more likely with regards to the stratigraphic position (discussed further below), could be that the diamict was deposited by mass flow movements. Debris flow deposits can display strong fabric, parallel to the flow direction, especially in the proximal part were the flow is extending (Lena Adrielsson pers. comm. 2013). Sedimentary structures like folds, thrust and shears are common at the base of debris flow deposits and the contacts are often marked with flame structures, tilted downflow (Benn & Evans 2010). The small deformation structures at the lower basal contact (Fig. 5) could therefore support debris flow deposition. As the unit must have been at a low point when the deposition occurred, this would indicate that the moraine plateau was surrounded by ice at that time.

4.1.3 Unit 1C

4.1.3.1 Description

Unit C consists of matrix-supported, homogeneous, friable, silty-sandy, greyish diamicton with a rather sharp lower boundary and an average thickness of ca. 1.5 m. No sedimentary structures were visible in the unit. Many of the sampled clasts are subangular (Fig. A.2.3) .The RA value is 27 % and C_{40} is 15 % (Granite: RA: 36 % and C_{40}: 12 %). A fabric analysis displays a weak fabric (S_1: 0.534) with the principal orientation V_1: 318°/10° (Fig. 10).

4.1.3.2 Interpretation

The sharp lower boundary of the unit could indicate erosion prior to deposition. Although the clasts are slightly more angular than in the units below they are nevertheless mostly subangular, which could indicate a subglacial origin (Benn & Ballantyne 1994). The lithological composition of the clasts is also similar to the unit below (Fig. 17). The weak fabric would generally suggest supraglacial deposition (Kemmis et al. 1996) but as subglacial tills can also show weak fabric this is not a reliable evidence for supraglacial origin (Bennett et al. 1999). The general appearance is similar to units forming the uppermost part of other section (2C, 4D, 5E and 6F), implying that they all are parts of the same till layer. These units will be discussed further below (chapter 5.3).

4.2 Trench 2

Trench 2 was excavated in the northern Veiki moraine plateau (Fig. 7). It was ca. 6 m long and the central 4 m were logged. The coordinates of each end of the trench are: N67° 39’ 55.1’’, E22° 30’ 01.7’’ – N67° 39’ 54.9’’, E22° 30’ 01.5’’.

4.2.1 Unit 2A

4.2.1.1 Description

Unit 2A consists of matrix-supported, heterogeneous to stratified, silty-sandy, fissile, greyish diamicton. The compactness varies laterally in the unit and silty lamina was noted in the lowest part. Most clasts are subrounded to subangular (Fig A.2.4), the RA value is 12% (Granite: RA: 17 %), and many clasts have smooth, polished surfaces. The C_{40} value is 12 %. (Granite: C_{40}: 10 %) A fabric analysis shows moderate fabric strength, S_1 :0.674, V_1: 230°/1° (Fig. 10).

4.2.1.2 Interpretation

The low RA value, polished clast surfaces and low C_{40} ratio all suggest a subglacial origin of the material (Benn & Ballantyne 1994) Although it does show some characteristics of subglacial till it is, due to its stratigraphical position and similarities to unit 1B, interpreted as a debris flow deposit. This will be discussed in more details below (see chapter 5.3). The clast fabric in this unit and unit 1B do not have the same prefered orientation. However, both were directed approximately transverse to the nearest rim ridge at each place, which has also been described in upper layers of other Veiki moraine plateaus (Hoppe 1952). That indicates that the the debris flows originated from ice located at the nearest ice margin at each place and flowed towards the center of the moraine plateau to be.

4.2.2 Unit 2B

4.2.2.1 Description

Unit 2B consists of a matrix-supported, silty-sandy, very clast-rich, heterogeneous, friable diamicton with a gradational lower boundary. The thickness is roughly 0.5 m. Clast analysis shows that most clasts are subangular to subrounded (Fig A.2.5). The RA-value is 16 % and C_{40} is 18 %. (Granite: RA: 21 %, C_{40}: 15 %).

4.2.2.2 Interpretation

The lithology of clasts is similar to the underlying unit, but it contains slightly more angular fragments. This unit could therefore be originated from a similar source as the unit below. The clast content of the unit is very high, which could indicate debris fall deposits as clast accumulation is often found at the base of a depositional slope (Benn & Evans 2010). The unit was not found in trench 3, which indicates that it does not extend much further into the moraine, also supporting deposition by debris fall. The origin of the sediment unit was probably the same as the unit below, from ice that was located behind the nearest rim ridge, NE of the trench (Fig. 4).

4.2.3 Unit 2C

4.2.3.1 Description

Unit 2C consists of a matrix-supported, friable to

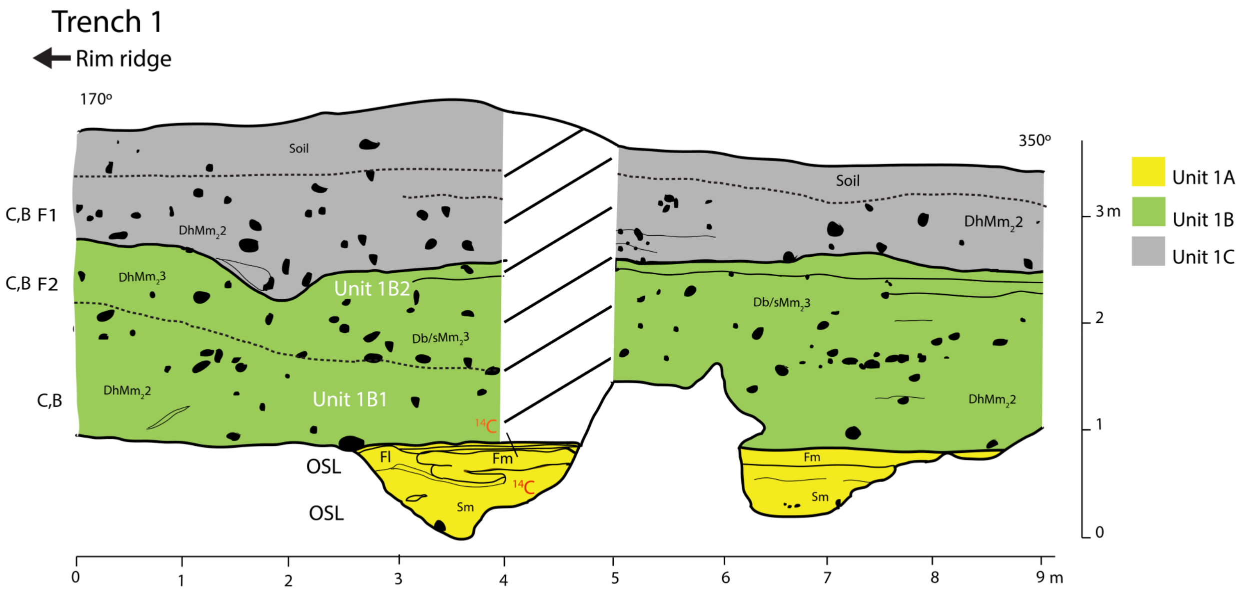

Fig. 6. Section drawing of trench nr. 1, showing the stratigraphy of the inner rim ridge of the northern moraine plateau. For location, see Fig. 4. Lithofacies codes can be found in Table A.3.1 and descriptions in Fig. 8.

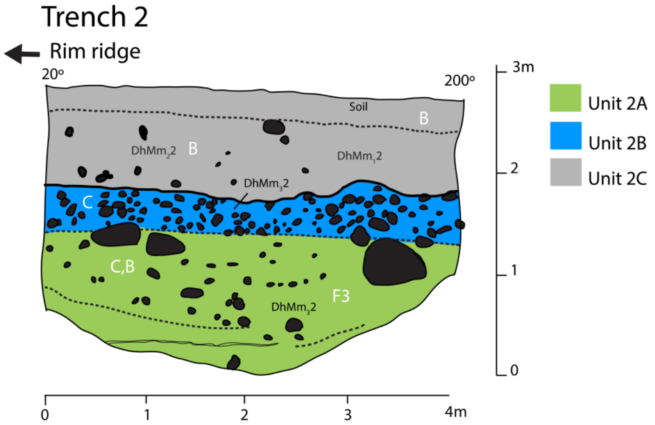

Fig. 7. Section drawing of trench nr. 2, which was excavated into the central part of the northern moraine plateau. For location, see Fig.4. Lithofacies codes can be found in Table A.3.1 and descriptions in Fig. 8.

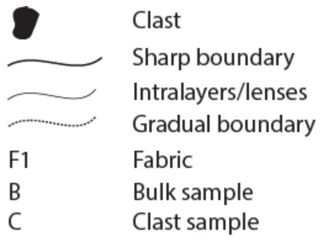

Fig. 8. Descriptions for section drawings.

loose, silty-sandy, clast-poor, heterogeneous, about 1 m thick, reddish brown diamicton with a sharp lower boundary.

4.2.3.2 Interpretation

Data are insufficient for a genetical interpretation. The sharp lower boundary could indicate that some erosion occurred prior to deposition. The stratigraphic position could also suggest that it is a part of the same till as unit 1C and other uppermost units in other trenches, as discussed further below.

4.3 Trench 3

Trench 3 was excavated into the northern Veiki moraine plateau, close to Trench 2 (Fig. 4). The coordianates of the trench are N 67° 39’ 53.5’’, E 22° 29’ 59.1’’. The depth of it was 4.70m. The purpose was to check if any sorted sediments were present in the middle part of the Veiki moraine. No detailed sediment description was performed.

Observation showed that relatively homogeneous greyish diamicton made up the entire section walls. No sorted sediments were detected nor were any indications of unit 2B.

4.4 Trench 4

Trench 4 is approximately 30 m long and was excavated into the base of a Veiki moraine plateau. Two parts were logged, covering 14 m in total (Fig. 9). The coordinates of each end of the trench are: N 67° 39’ 43.7’’ E 22° 30’ 03.4’’ – N 67° 39’ 44.4’’ E 22° 30’ 01.7’’.

4.4.1 Unit 4A

4.4.1.1 Description

Unit 4A consists predominantly of clast-supported, very angular/angular boulders with weathered, unpolished surfaces. Associated with the fragmented boulders are coarse, poorly sorted sand and gravel lenses. The boulders almost all consist of red granite.

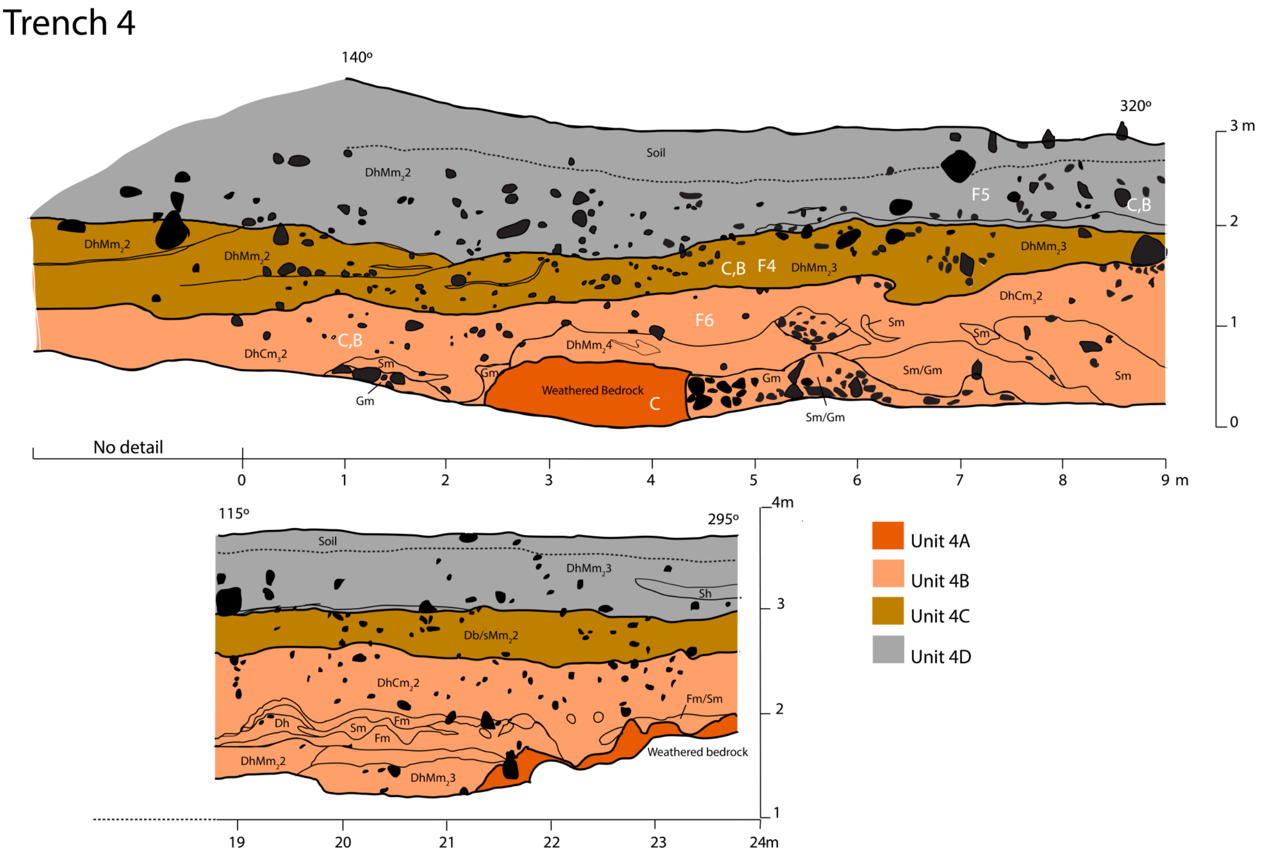

Fig. 9. Section drawing of trench nr. 4, which was excavated into the base of the southern moraine plateau. For location, see Fig 4. Lithofacies codes can be found in Table A.3.1 and descriptions in Fig. 8.

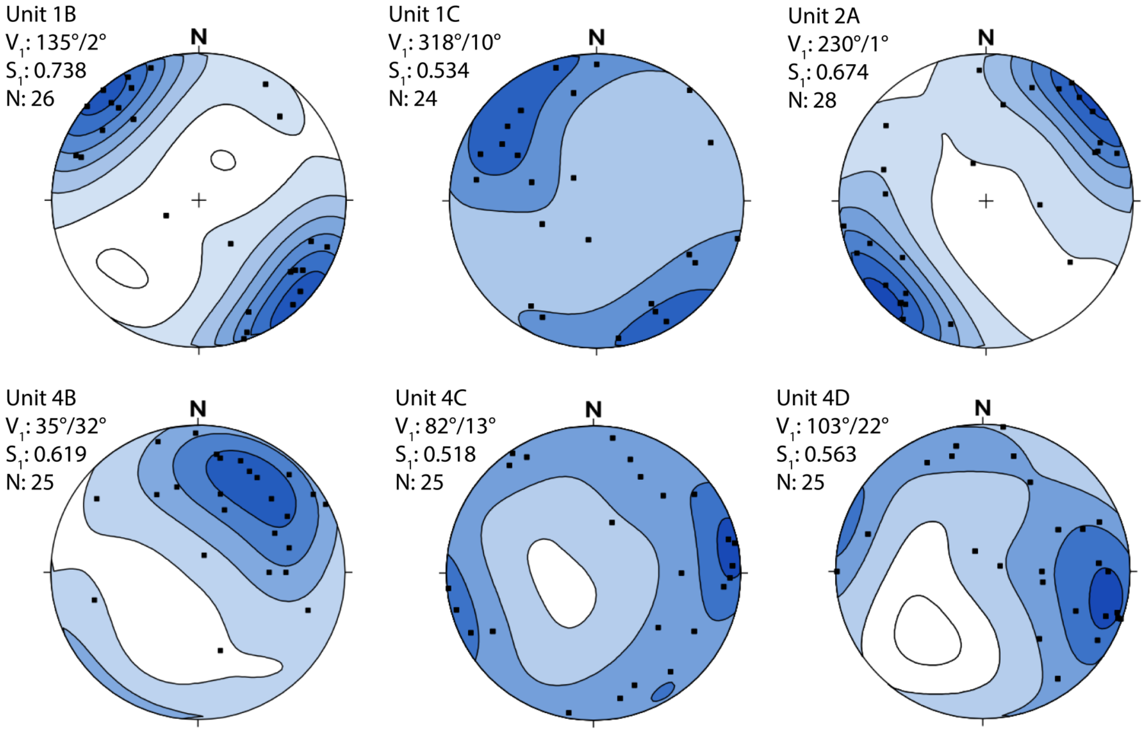

Fig. 10. Fabric diagrams from the units in trenches 1-4. All data are plotted as Schmidt equal– area, lower hemisphere projections and contoured according to the Kamb method at 2σ intervals. V_1: Principal eigenvector (strike/dip), S_1: Principal eigenvalue, N: number of measured clasts.

The C_{40} value of the fragments is 22 % and the RA value is 95 %.

4.4.1.2 Interpretation

The weathered and angular granite boulders are interpreted to be the uppermost part of the local bedrock. This is supported by the GPR profiles (Fig. 3), showing distinctive reflector boundaries at this depth and also confirmed by the excavator operator.

4.4.2 Unit 4B

4.4.2.1 Description

Unit 4B is a matrix-supported, sandy, very heterogeneous, friable, red and grey diamicton. Numerous, silt, sand and gravel lenses are present. Some contain angular fragments of the same lithology as found in the unit below (Unit 4A), while other consist of sorted, less angular sediments, partly containing clast of different lithology than the underlying bedrock. Most of those are sand lenses but in the lowermost part (Fig. 9; 3-4 m)) is an accumulation of boulders of different lithology than the underlying bedrock. The lenses become less frequent upwards the unit (Fig. 9, 19-22 m). The lower unit boundary is wavy and intergrades with fragments from the bedrock below. The average thickness is about 1 m. A number of folds were observed in the unit associated with the sand lenses. Clast roundness varies significantly, angular clasts are most frequent but rounded fragments were also found (Fig. A.2.6). RA value is high (43 %) and C_{40} value is low (13 %). Clasts originating from granite show a higher RA value (50 %) but a lower C_{40} value (6 %). Grain size distribution displays a somewhat higher degree of sorting than the other diamictons in this study (see Fig A.1.7).

Fabric analysis indicates a rather weak fabric S_1: 0.619 and V_1: 35°/32° (Fig. 10). The largest fold in the unit (Fig. 9, 19.5 m) is symmetrical and approximately 0.5 m high, having a strike/dip of the fold axis at 343°/9°. The unit follows the bedrock surface and seems to dip downwards under the rim ridge of the Veiki moraine plateau.

4.4.2.2 Interpretation

The large lenses and folds found in the lower parts of the unit indicate that the unit has undergone deformation at the time of, or after, deposition. The steeply plunging rather weak, cluster fabric could also be an indicator of subglacial deformation (Dowdeswell & Sharp 1986). The folds could also be present in the upper parts of the unit, but not visible due to lack of sorted sediments. Based on the basal contact and folding, this unit is interpreted as a subglacially deformed traction till. The unit is more sorted than other diamictons in this study and has higher amounts of rounded clasts , despite the high RA value. This can be explained by mixing with preexisting, sorted sediments that most likely became incorporated into the diamict by subglacial deformation. The sorting and the variance of grain sizes between different lenses could suggest that the preexisting sediment was a fluvial deposit. The relatively high amount of both angular and rounded clasts can thus be explained by mixture of the original diamicton with the fluvial sediments and the local angular fragments from the bedrock below.

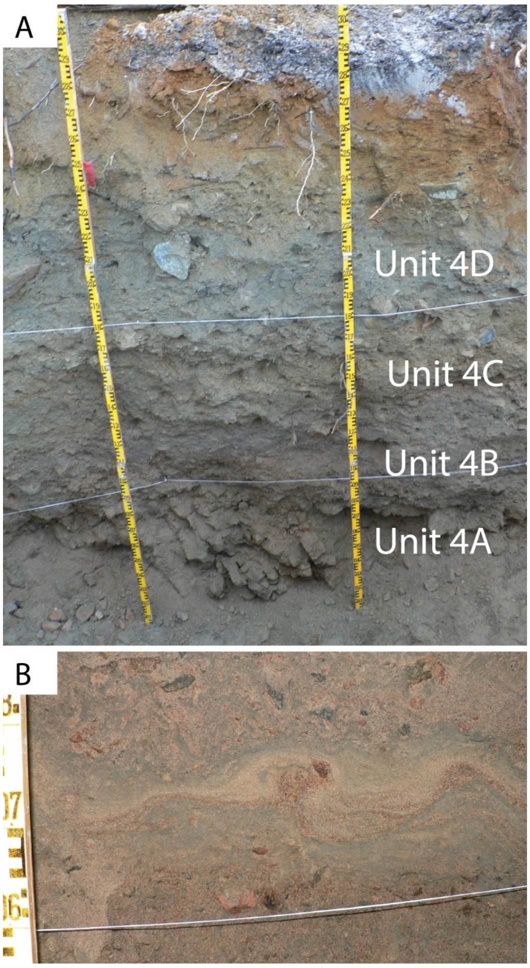

Fig. 11. A: Photo of the section wall in trench 4, (Fig. 9; 3-4m). B: Small folds of sand lenses within unit 4B (Fig. 9; 20-21 m). Photos by Helena Alexanderson.

The symmetrical shape of the folds gives two possible interpretation of compression, either from SW or NE, and as the picked-up material is found at both sides of the exposed bedrock it does not give any direct indication of the ice flow.

4.4.3 Unit 4C

4.4.3.1 Description

Unit 4C is a matrix-supported, silty-sandy, heterogeneous, partly stratified, firm, brown diamicton with rather sharp lower boundary. The average thickness of is ca. 0.5 m. The unit thickens towards the central part of the Veiki moraine plateau and was measured to 1.5 m in the SE end of the section (3 m outside the logged part). Some sand lenses occur, but they are much fewer and thinner than in the diamicton below (Unit

4B). The largest sand lenses are in the SE part, and most of them show a parallel configuration and contain laminations within them. In one of them (Fig. 9, 0-1 m), there appears to be alignment of clasts along the lense.

Clast roundness analysis show that many of the clasts are subangular to angular (Fig. A.2.7). The RA value is high (43 %) and C_{40}: 10 % (granite: RA: 50 % and C_{40}: 11 %). The clast sample contained many reddish colored granite clasts with rough, unpolished surfaces. A fabric analysis shows very weak fabric (S_1: 0.518, V_1: 83°/13°; (Fig. 10).

4.4.3.2 Interpretation

The high content of angular reddish granite suggests that a large part of the unit originates from the underlying bedrock, and might be in contact with the bedrock at other places close to the trench. The configuration of the sand lenses might suggest subglacial stacking of the sediment and the alignment of clasts along the boundaries could be the result of shearing (Evans et al. 2006). The unit does not follow the bedrock surface under the moraine like the unit below (Unit 4C) and thickens in the SW part (closest to the rim ridge), (Fig. 9). This could indicate that its deposition was associated with the formation of the Veiki moraine plateau. Both the lithology and clast morphology suggest source from the underlying wethered bedrock and resembles unit 4B. This unit is interpreted to be subglacial traction till, based on the characteristics mentioned above.

4.4.4 Unit 4D

4.4.4.1 Description

Unit 4D is a matrix-supported, silty-sandy, heterogeneous, firm, grey diamicton, about 1m thick, and with a sharp boundary that could easily be followed along the whole section. Brown and grey silt laminas, located above the lower boundary, could be followed through large parts of the section. A large massive sand lens was observed in the NW part of the section (Fig. 9, 23-24 m). No deformation structures were observed.

Clast roundness analysis show that most of the clasts are subangular (Fig. A.2.8). RA value is 20 % and C_{40} value is 25 % (granite: RA: 26 %, C_{40}: 26 %). The surfaces of the clast are well polished.

Fabric analysis showed a weak fabric S_1: 0.563 and V_1: 103°/22° (Fig. 10).

4.4.4.2 Interpretation

This unit shows different characteristics, compared to the two units below in the trench, such as more massive appearance, no deformation structures, lower RA value and more polishing of the clast surfaces. Although the diamicton is rich in red granitic fragments, they were rather well modified. That might suggest subglacial origin of the material (Benn & Ballantyne 1994). The sharp lower boundary suggests erosion and halt in deposition from the underlying units. As this unit displays similar characteristics as other uppermost units documented in this study (1C, 2C, 5E and 6F), it is interpreted to be a part of the same till unit. These units will be discussed further below (see chapter 5.3).

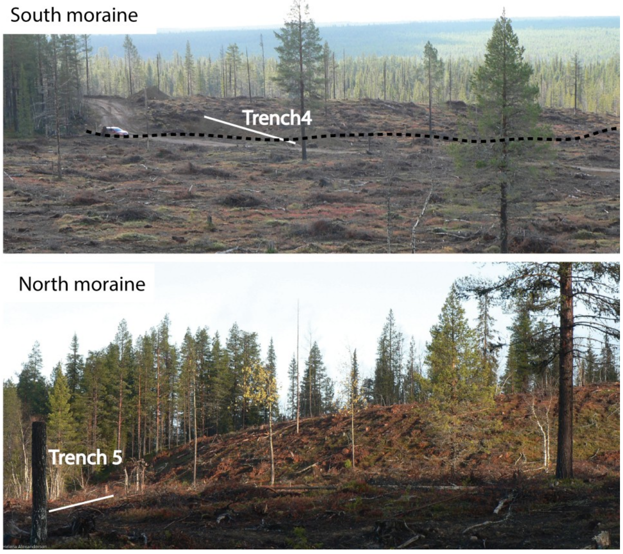

Fig. 12. Photos of the Veiki moraine plateaus, the lower boundary of the southern moraine plateau is marked with a dotted line for clarification. Photos by Helena Alexanderson.

4.5 Trench 5

Trench 5 is ca. 8 m long, excavated into the base of the northern Veiki moraine plateau. The coordinates of the endpoints are: N 67° 39’ 50.3,’’ E 22° 29’ 53.6’’ – N 67° 39’ 50.7’’, E 22° 29’ 54.6’’. The units in the trench dip downslope, out from the moraine plateau, except from unit 5D that dips in the opposite direction (Fig. 13).

4.5.1 Unit 5A

4.5.1.1 Description

Unit 5A consists of unsorted sand, gravel and very angular granitic boulders with rough, unpolished surfaces.

4.5.1.2 Interpretation

These weathered and angular granite fragments are interpreted to be the uppermost part of the local bedrock and therefore the same unit as 4A. That is supported by GPR profiles (Fig. 3), showing sharp reflector boundary at this depth.

4.5.2 Unit 5B

4.5.2.1 Description

Unit 5B is a matrix-supported, heterogeneous, partly stratified, sandy, friable, red and grey diamicton with a wavy, intergraded lower boundary. The thickness varies considerably, from few cm to 0.5 m. Sand lenses are frequent, especially in the lowest part of the

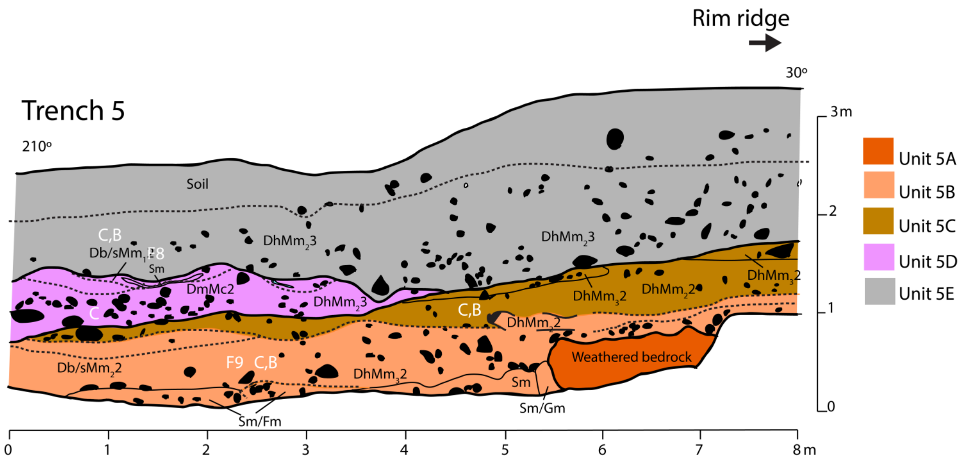

Fig. 13. Section drawing of trench nr. 5, which was excavated into the base of the northern moraine plateau. For location, see Fig 4. Lithofacies codes can be found in Table A.3.1. and descriptions in Fig. 8.

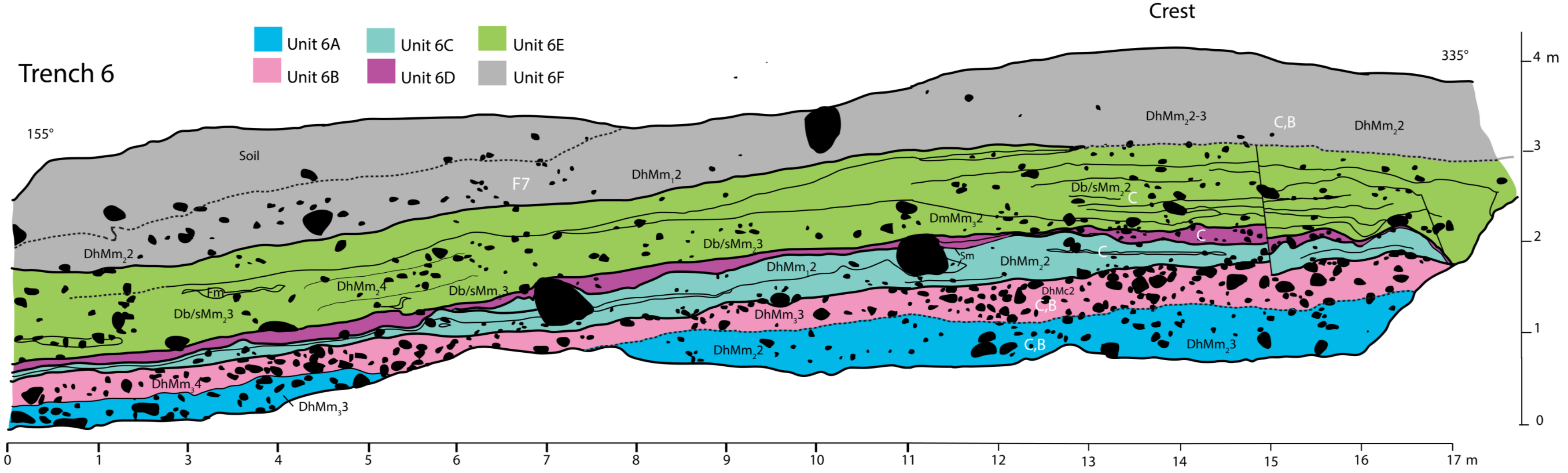

Fig.14. Section drawing of trench nr. 6, showing the stratigraphy of the rim ridge of the southern moraine plateau. For location, see Fig. 4. Lithofacies codes can be found in Table A.3.1 and descriptions in Fig. 8.

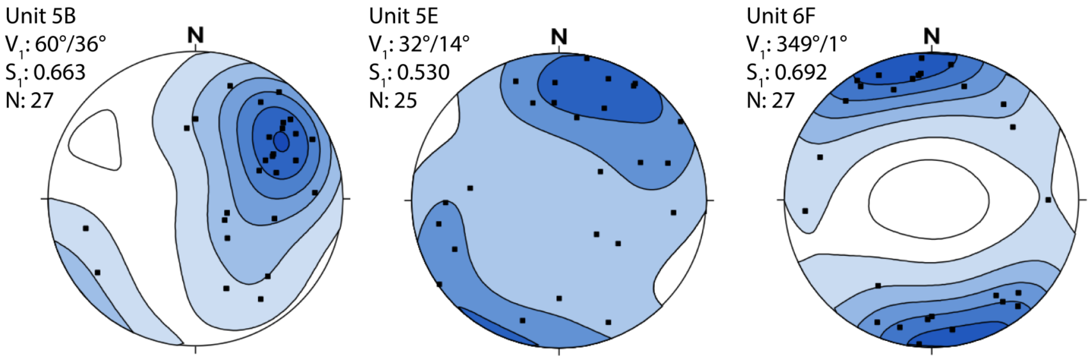

Fig. 15. Fabric diagrams from the units in trenches 5 and 6, plotted as Schmidt equal– area, lower hemisphere projections and contoured according to the Kamb method at 2σ intervals. V_1: Principal eigenvector (strike/dip), S_1: Principal eigenvalue, N: number of measured clasts.

unit. They mostly consist of coarse sand of the same lithology as the bedrock. Stratification increases upwards.

Clast analysis shows that most of the clasts are subangular to very angular and have rough, poorly polished surfaces. RA value is high (59 %) and C_{40} is 12 % (Granite: RA: 66 % and C_{40}: 14 %). A great majority of the clasts are also of the same granitic origin as the bedrock below (Fig. 17).

Fabric analysis showed moderate fabric strength (S_1: 0.663) and V_1: 60°/36° (Fig. 15).

4.5.2.2 Interpretation

The high content of angular granites, derived from the underlying bedrock, could be explained by a short transport path of the clasts as the unit is in contact with the bedrock. The coarse sand and gravel lenses have most likely an origin from the weathered bedrock below and became incorporated into the unit by deformation processes. The moderate, steeply plunging cluster fabric could also indicate subglacial deformation (Dowdeswell & Sharp 1986). This unit is therefore interpreted as deformed subglacial traction till. The orientation of the fabric is SW-NE. Due to stratigraphic position and similar characteristics this unit is interpreted to be the same unit as 4B.

4.5.3 Unit 5C

4.5.3.1 Description

Unit 5C is a matrix-supported, stratified, sandy, firm-friable, brown diamicton, with a gradational lower boundary. Sand lenses are abundant, although not as many as in the unit below (Unit 5B). They mostly contain fine-grained sand. The average thickness is around 0.5 m, only a few cm in the distal part of the moraine but thickens towards its center.

Clast analysis indicates that most of the clasts are angular (Fig. A.2.10) with rough surfaces. The RA value is 50 % and C_{40} is 10 % (Granite: RA: 63 %, C_{40}: 11 %).

4.5.3.2 Interpretation

The high content of angular granitic clasts indicates that a high portion of the diamicton derived from the local bedrock, indicating a short transport paths and formation in contact with the underlying bedrock. Many lenses are present, but unlike the unit below (Unit 5B) they are thin and do not seem to consist of the angular fragments from the bedrock below, indicating that they are rather primary structures than a result of up-picking from the bedrock below. The gradational lower boundary indicates that a mixing between these two units occurred, suggesting active deposition. Based on this the unit is interpreted as subglacial traction till. This unit has very similar characteristics as unit 4C, both with regards to texture and composition. They are also lying at the same stratigraphic depth. Therefore unit 4C and 5C are interpreted as being parts of the same subglacial till unit. Both of these units seem to thicken towards the outher margin of the moraine, which could incate that they were formed in association with the moraine plateau formation.

4.5.4 Unit 5D

4.5.4.1 Description

Unit 5D is a matrix to clast-supported, heterogeneous, partly stratified, sandy-silty, firm diamicton with a sharp lower boundary. It contains some rather large massive sand lenses. The RA value is 22 % and C_{40} is 17 % (Granite: 29 %, C_{40} : 21 %). It is only present in the SW part of the section, below the outer rim ridge of the Veiki moraine plateau (Fig. 4) and does not continue below the main part of the landform .

4.5.4.2 Interpretation

Only small parts were visible in the section, making genesis interpretation difficult. As it is only appearing below the outer rim ridge it could be associated with its formation. The clasts are considerably less angular than those in the units below, suggesting subglacial source (Benn & Ballantyne 1994). The stratification, large sand lenses, high clast content and the limited distribution might indicate that it represents a debris-fall deposit.

4.5.5 Unit 5E

4.5.5.1 Description

Unit 5E is a matrix-supported, heterogeneous, silty-sandy, firm, grey diamicton with a sharp lower boundary that can easily be recognized along the whole section. The unit contains many small sand lenses. The average thickness of the unit is approximately 1.5m. Clast analysis shows that most of the clasts are subangular (Fig A.2.12). RA value is 24 % and C_{40} is 16 %. Fewer clasts are from the underlying granitic bedrock than in unit 5B and 5C.

Fabric analysis showed weak fabric S_1: 0.530 and V_1: 32°/14° (Fig. 15).

4.5.5.2 Interpretation

The low angularity of the clast and a low C_{40} value indicates subglacial origin of the material (Benn & Ballantyne 1994). The sharp lower boundaries might indicate that erosion occurred between the deposition of this unit and the units below. This unit might, based on its stratigraphic position and similar attributes, be related to the uppermost units in other trenches (1C, 2C, 4D and 6F) and is therefore interpreted to part of the same unit. These units are discussed in more details below (see section 5.3).

4.6 Trench 6

Trench 6 is about 17 m long, dug through the rim ridge of the southern Veiki moraine plateau. The coordinates of the endpoints are: N 67° 39' 41.7'', E 22° 30' 05.8'' - N 67° 39' 42.5'', E 22° 30' 04.8''**.** The whole section was logged. The stratigraphy consists of many thin units that all dip out from the rim ridge (Fig 14).

4.6.1 Unit 6A

4.6.1.1 Description

Unit 6A is a matrix-supported, clast-rich, heterogeneous, partly banded, friable, silty-sandy, brown diamicton with a sharp to gradational lower boundary. Banding and stratification varies laterally. The clast content is high, especially in the southern part of the section (furthest from the crest of the rim ridge).

Clast roundness shows that most of the clasts are subangular (Fig A.2.13). The RA value is 23 % and C_{40} value is 30 % (Granite: RA: 41 %, C_{40}: 32 %). A relatively few clasts represent the granitic, local lithology (Fig. 17).

4.6.1.2 Interpretation

The high clast content and accumulation of boulders at the lower parts of the slope could indicate debris fall deposit (Benn & Evans 2010). The clast roundness indicates that the clasts are somewhat abraded, suggesting subglacial source of the material (Benn & Ballantyne 1994). However it contains both the highest C_{40} value and highest number of non-granitic clasts of all of the documented unitts.

4.6.2 Unit 6B

4.6.2.1 Description

Unit 6B is a matrix to clast supported, heterogeneous, firm, silty-sandy greyish-brown diamicton with a gradual lower boundary. The unit is about 0.3 m thick. A clast roundness analysis shows that most of the clasts were subangular (Fig. A.2.14). The RA value is 23 % and C_{40} is 9 % (Granite: RA: 32 %, C_{40}: 13 %).

4.6.2.2 Interpretation

The lithology is similar to the unit below (Fig. 17) although the clast roundness data suggest more clast modification prior to deposition. This unit is thin and contains numerous clasts, which could be an indicator of a debris fall deposit (Benn & Evans 2010).

4.6.3 Unit 6C

4.6.3.1 Description

Unit 6C is matrix-supported, and contains several, very thin diamictons and sorted sand horizons with distinct boundaries. Each individual layer could be

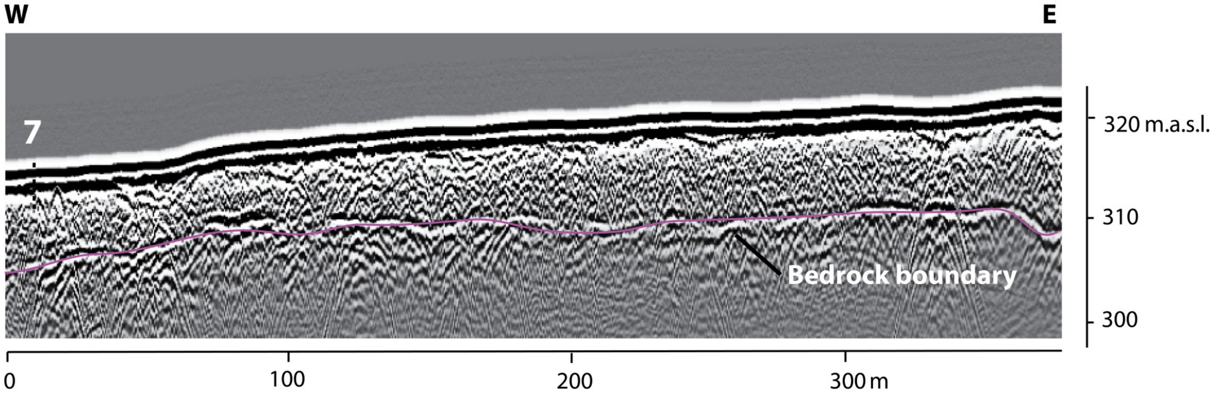

Fig. 16. GPR profile from the fluted-till, south of the study area (see Fig. 4). The profile was collected using a 50 MHz frequency. The approximate location of trench 7 and the interpreted bedrock boundary are marked on the figure using a purple color.

easily followed through the whole section. The color is alternating grey and brown, clast richness and cohesiveness varies for each layer. Small lenses of sorted sand were also detected. The unit is thickest under the rim ridge-crest where it is around 0.5 m but thins out and is only around 0.1 m thick in the SE part (furthest away from rim ridge). Two big boulders with diameter of ca. 0.5 m were exposed within the unit (Fig. 14; 7 and 11m).

A clast analysis shows that most of the clasts are subangular (Fig. A.2.15). The RA value is 20 % and C_{40} values are 16 % . The lithological analysis implies, similarly to the units above and below, relatively high content of exotic clasts (Fig. 17).

4.6.3.2 Interpretation

The lithology of the particles is similar as in the units above but possesses much more subtle banding and lower clast content. These thin layers could indicate episodes of debris flows which probably contained higher water content than those that build up the diamicton layers below as the sorted sand lenses found in the unit suggest water reworking. The low RA and C_{40} values indicate that it is deposited by sediments that had experienced some modification by subglacial processess before deposition (Benn & Ballantyne 1994).

4.6.4 Unit 6D

4.6.4.1 Description

Unit 6D is a matrix and clast-supported, stratified, clast rich, friable, sandy, dark brown diamicton with sharp lower boundaries. It is a very distinctive unit and can easily be traced through the whole section. Sorted sand laminas are found associated with it.

A clast analysis shows that many of the clasts are subangular (Fig. A.2.16) RA ratio is 24 % and C_{40} 12 % (Granite: RA: 28 %, C_{40}: 10 %).

4.6.4.2 Interpretation

Both the lithology and clast morphology of unit 6D resembles the stratified unit below, suggesting that these unit have the same origin. The thin apperance of the unit, high clast content and sorted sediments could all indicate debris flow deposit interbedded with water reworked sediments.

4.6.5 Unit 6E

4.6.5.1 Description

Unit 6E is a matrix supported, banded/stratified, clast-poor, firm-friable, silty-sandy diamicton with a sharp lower boundary. The color alternates between grey and brown. The horizons within the unit were discontinuous and could therefore not be followed through the whole section. The unit displays significantly more stratification in the NW part, under the rim ridge, than in the SE part. The RA-value is 22 % and C_{40} is 20 % (Granite: RA: 23 %, C_{40}: 16 %).

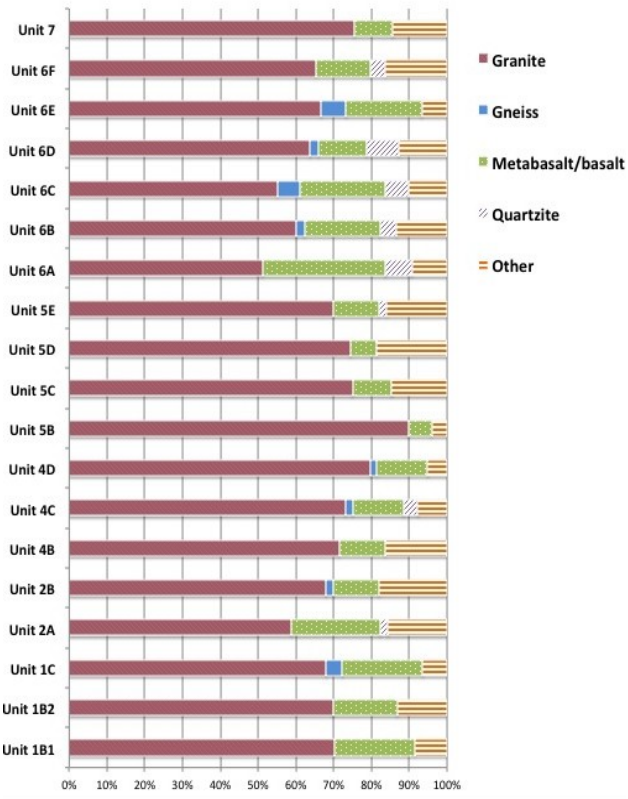

Fig. 17. Results from the lithology analysis of the clasts sampled from all of the units.

4.6.5.2 Interpretation

Despite the high stratification it is distinguishable from the stratified sediments below by the much thinner and more discontinuous sublayers, higher compactness and lower clast content. The lithology and clast morphology show similar characteristics as the underlying units, suggesting the same source of the sediments. The stratification and sorted sediments found within the unit indicate that this unit is also a debris flow deposit. Also this unit is startigraphically lying at the the same position, and shows similar characteristics as units 1B and 2A (in the nothern moraine). It could therefore be correlated with those units.

4.6.6 Unit 6F

4.6.6.1 Description

Unit 6F is a matrix-supported, heterogeneous, clast-poor, friable to firm diamicton with a gradational-sharp lower boundary. The unit shows gradual, lateral changes. In the SSE part it is greyish- brown and has a sharp lower boundary, in the NNW part (under the rim ridge-crest) the boundary is gradational. The unit also shows vertical changes, as the sediments in the upper part were both looser and had slightly different texture than the lower part. Most of the clast are subangular (Fig A.2.18), RA-value is 30 % and C_{40} is 8 %. Many clasts are weathered and freshly broken.

A fabric analysis displayed moderate fabric ($S_{1:}$

0.692) dipping towards north, V_1: 349°/1° (Fig. 15).

4.6.6.2 Interpretation

Due to the lack of stratification and visible structures, unit 6F appears to be very different from the underlying units. The lithology and clast angularity are similar to the other units in this section indicating similar source.

As it is the uppermost unit in the trench and does possess similar characteristics as uppermost units found in other trenches (1C, 2C, 4D and 5E) it is likely that it is a part of the same till layer as these units. This was however the only of these unit in which the fabric analysis displayed preferred orientation of the clasts. That could indicate subglacial deposition (Benn 1994). The direction aligns with the reconstructed ice flow direction of LGM (Kleman et al. 1997; Hättestrand 1998) which might indicate that it was deposited during the last glacial cycle.

4.6.7 Fault

One fault was found in the section, under the rim ridge. It penetrates units 6B to 6E. It is possible that the fault extends into unit 6F, although it could only be detected at the lower boundary of unit due to its massive appearance. The fault displacement is 18 cm and the dip 80°. The strike is oriented approximately parallel to the crest line (60°). The fault might either have been formed due to melting of underlying ice or by slope failure. The first option is more likely as such steep faults rarely are formed by marginal collapse (Lena Adrielson pers. comm. 2013).

4.7 Trench 7

Trench 7 was an approximately 2 m deep hole, excavated in the fluted terrain outside the Veiki moraine landforms (Fig. 4; 16). The coordinates of the trench are N 67° 39' 33.1'', E 22° 30' 20.6''. This trench could not be logged due to groundwater inflow into the trench.

4.7.1 Description

Visual observation revealed a greyish-brown, matrix supported, massive-heterogenous diamicton. Samples were collected ca. 50 cm below the surface. The clasts were mostly subangular (Fig. A.2.19), the C_{40} value is 8 % and RA is 24 % (Granite: RA: 27 % and C_{40}: 9 %). Many clasts were weathered and broken.

4.7.2 Interpretation

The trench could not be properly investigated. However as it is the uppermost unit in a fluted terrain (Fig. 4) it is very likely subglacial till, the intermediate angularity of the clasts also supports that. The lithology analysis of the clasts revealed somewhat higher amount of granitic clasts than in those found in the units building up the landforms.

5 Discussion

5.1 Source of the sediments

Clast morphology, lithology and grain size distribution display similar values for all units observed in the plateaus and the rim ridges (Trenches 1, 2 and 6) (see figures in A1 and A2). The clasts are mostly blocky (low C_{40} values) and have intermediate angularity values. The bulk C_{40} values are varying from ca. 10-30 % and RA values from ca. 10 to 25 %. This indicates that the material that built up these units have a similar source. Both the low C_{40} values and the angularity values would suggest a subglacial origin (Benn & Ballatyne 1994; Benn 2003).

The lithological analysis showed that the clasts in the diamicton units, found in the moraines plateaus and rim ridges, were mostly granitic (ca. 50-70 %) with smaller fractions of other lithologies, mostly metabasalt (Fig. 17). Because the clasts were dominated by coarse-grained granites it was difficult to detect any striations and therefore that could not be used as an evidence for subglacial origin.

The units exposed in trenches 4 and 5, at the base of the moraine plateaus, show different characteristics than the units building up the plateaus and rim ridges. The clasts are more angular and less polished, the matrix is less well sorted and more of the clast are granitic (ca. 70-95 %) (Fig. 17).

This was especially the case for the lowermost units in the sections (4B, 4C, 5B and 5C) that are interpreted as subglacial deformation till. The bulk RA values of the clasts in these units varied from 43-59 % indicating little modification. However, the C_{40} values were low (6-12 %) which is not what is expected for subglacially transported clasts (Benn & Ballatyne 1994). That can partly be explained by the rather low C_{40} value of the clasts from the underlying bedrock itself (22 %).

The material in these units could have a different source than the units in the other trenches. As they are in direct contact with the underlying bedrock, these differences could be explained by a shorter transport path and mixture with the underlying, granitic bedrock (Benn & Ballatyne 1994).

5.2 Fabric

Fabric analysis was performed in nine units (1C, 1B2, 2A, 4B, 4C, 4D, 5B, 5E and 6F). The strongest fabrics were detected inside the rim ridges of the moraines (Units: 1B, 2A and 6F) and in unit 5B. The fabric orientations are inconsistent and do not all align with the reconstructed past ice flow movement in the region (Kleman et al. 1997; Hättestrand 1998).

The fabric measured in other units showed weak orientation and will therefore not be used for reliable directional interpretation.

Fabric analysis has shown to be a valuable tool for reconstructing past environment and depositional processes (Benn & Evans 2004). However the reliability for genesis interpretation has been questioned (Bennett et al. 1999).

5.3 Depositional processes

The cores of the moraines appear to be mostly built up by massive diamicton, based on excavation in the upper parts of the northern moraine (trenches 2 and 3). The GPR profiles indicate massive sediment down from there to the bedrock (Fig. 3), although the lack of stratification might also be due to loss of signal. The upper parts of the plateaus and rim ridges (Trench 1,2, and 6) consist of stratified diamicton beds. In the rim ridges there were layers of sorted sediments as well.

It has been suggested that Veiki moraines and similar landforms were deposited by downwasting and melt-water infill into supraglacial depressions on a debris-covered stagnant ice (e.g. Clayton & Cherry 1967; Lagerbäck 1988; Ham & Attig 1996; Clayton et al. 2008). As will be discussed below, the findings of this study mostly agree with that interpretation.

Only one lake sediment unit was observed in this study (Fig. 6), close to the southern rim ridge of the northern moraine. As not found in other parts of the moraine, this indicates that a lake sedimentation did not play a significant role in building the northern plateau. No excavations were carried out in the plateau of the southern moraine. However the GPR profile (Fig. 3) shows horizontal, stratified sediments at the southern margin, which might indicate that lake sediments are present there also. Despite its limited distribution, the lake sediment does provide important information about the formation of the landforms and the prevailing environmental conditions.

The lake sediment in trench 1 is now situated at a topographic high, confirming that the lake was surrounded by ice at the time of deposition (Fig. 18A). The lake could either have been formed supraglacially, or in contact with the ground (ice walled lake). As parts of the units contain organic material (i.e. pieces of *Betula* and *Alnus*), subglacial deposition seems improbable. It also indicates that the debris cover on the ice, surrounding the lake, was vegetated. It has been shown that a debris covered ice can host a wide variety of plant species (Caccianica et al. 2011) The lake was most likely only present at the margin of the former basin and did not cover the whole area where the plateau is now. However, there is also a possibility that the lake sediments were removed by later activities, such as erosion by mass flows from surrounding ice. As the inner south slope (where the lake sediments were found) faces north it was shielded from direct solar insolation, which might have resulted in less melting of underlying ice and therefore more stable conditions compared to the north slope (Clark 1987).

Although the thickness of the organic layer is only about 30 cm, the deposition could have taken a fairly long time. In comparison, a deposition rate of 0.5 cm/year has been suggested for laminated organic sediments in other Veiki moraine plateaus (Lagerbäck 1988). That indicates deposition during a period with very little sediment input into the lake. The upper, laminated part of the unit indicates higher sediment- and meltwater influx to the lake at a late stage of its deposition.

Debris flow units are found above the lake sediments (Units 1B2-1) (see below), implying that after the deposition of the lake sediments, the environmental conditions shifted towards favoring debris flow depositions (Fig 18 B).

Loss of vegetation cover following colder climate could negatively have affected the stability of the surrounding slopes and increased erosion, causing more frequent occurrences of debris flow events (Marston 2010). Lowering of the lake level could also have caused slope instabilities due to high pore-water pressures and consequential groundwater outflow from the surrounding sediments. Additionally, melting of underlying ice could have caused downslope failures (Eyles et al. 1987 and references therein). This could be supported by deformation within that was found within the lake sediments and indicates that the lake was formed supraglacially but not in contact with the ground.

The stratified diamicton units in the northern moraine (1B and 2A), are, due to their similar attributes and stratigraphical position interpreted genetically alike. They display some characteristics that have been described as indicators for subglacial melt-out till, such as strong, flat fabric, compactness and stratification (Kemmis 1996; Krüger & Kjær 1999). However, their stratigraphic position, the strong to moderate inconsistent fabric and the relatively intact sediments below (Unit 1A) do not support deposition from an overriding, later stagnating glacier. As discussed earlier, the fabric orientation is aligned transverse the the nearest rim ridge at each site.

A transverse fabric, which suggests association with the form of the landform, as observed in these units, has previously been described in other Veiki moraine plateaus (Hoppe 1952). He interpreted the moraines as subglacial landforms, formed by subglacial debris transport into cavities in, or under the ice. This was mainly based on observed fabric pattern and characteristics of sediments in the plateaus. However, as the lake sediments below (Unit 1A) are most definitely deposited supraglacially, it seems very unlikely that overlying units were deposited in a cavity. They are therefore most likely not subglacial.

Debris flow deposits can display a strong fabric, parallel to the flow, especially in the proximal part were the flow was extending (Lena Adrielson pers. comm. 2013). These units are therefore interpreted as debris flow deposits. The debris flows most likely derived from the nearest ice margin at each place, explaining the fabric pattern. Due to similar characteristics and stratigraphical position, unit 6E is also correlated with these units.

The rim ridge is built up by diamiton units (Fig. 14), interpreted as mass flow deposits. All units dip from the rim ridge towards the center of the moraines.

The rim ridges thus, most likely formed at the ice margins where most of the material accumulated. The arching of the sediments in the rim ridges might have formed after the loss of supporting ice from the margins resulting in collapse of the outer parts of ridge (Fig. 18C). A normal fault was observed to penetrate trough a large part of the sediment sequence under the rim ridge (Fig. 14, ca. 15 m). This fault is interpreted to have formed after melting of underlying ice but might also have formed during slope failure, after loss of surrounding, supporting ice.

The lowermost units (6A and 6B) below the rim ridge are very clast rich and are interpreted as debris fall deposits. The upper units are interpreted as debris flow deposits, indicating increased melting processes with time.

Smaller outer rim ridges/terraces are often found encircling the moraine plateaus. Such features have previously been described as associated with Veiki moraine plateaus and interpreted as a result of subglacial squeezing (Hoppe 1952), while Lagerbäck, (1988) described similar features as a result of slumps from the moraine slopes.

Trench 4 covered the lowest part of the terrace on the north slope of the southern moraine plateau and trench 5 the inner part of the outer rim ridge surrounding the northern moraine plateau (Fig. 4). The origin of these two ridges do not appear to be the same, although both are related to the moraine plateaus. As can be seen on Fig. 4, the terrace surrounding the northern moraine plateau is not attached to the main landform and the underlying unit was interpreted to be a debris fall deposit (Unit 5D). The debris fall could either have had its origin from the Veiki moraine plateau or from surrounding ice after it has back-wasted from the moraine (Fig. 18C). The terrace north of the southern moraine is connected to the landform and more pronounced than the one found encircling the northern moraine (Fig. 4). Below, there was a thickening of subglacial till (Unit 4C, Fig. 9). Therefore, the formation of the terrace could partly be explained by subglacial processes, although slumps or debris flows could have added to the thickness.

In his studies, Lagerbäck (1988) suggested that subglacial processes might have participated in the formation although not explaining how in any details.

There are some indications that subglacial processes were associated with the moraine formation. The lowermost units found in the base of the moraine plateaus (4B, 4C, 5B and 5C) are interpreted as subglacial traction tills. There are indications of thickening and stacking of subglacial till in the moraine-proximal part of trench 4 (Fig. 9) and also possibly in trench 5 (Fig. 13). The subglacial till was not exposed in trench 6. Thus, if it extends under the Veiki moraine plateaus it lies below the debris flow deposits in the rim ridge.

The stacking of sediments and the configuration of lenses might indicate subglacial deformation (Evans et al. 2006). Gravitational squeezing of a clay-rich, deformable bed at an ice marginal zone has been described e.g. in Eyles et al. (1999) and Boone & Eyles (2001). The squeezing causes the underlying material to move from the higher pressure under the ice towards the ice margin where it stacks up and causes deformation in the underlying till.

However, the subglacial till documented in this study (Units 4A-B and 5A-B) is not very clay rich (Fig. A.1.6- 7 and A.1.10-11) and does therefore not meet the usual requirements of a highly deformable sediment. Thus, it is very unlikely that gravitational squeezing accounted for translocation and deposition of significant parts of the moraine plateaus although it might have resulted in some subglacial till thickening at the ice margins (Fig. 18A). If gravitational squeezing was responsible for the deformation in units 4B and 4C, a fabric aligned parallel to the stress direction, approximately perpendicular to the moraine plateaus margins would be expected (Eyles et al. 1999). The fold measured in unit 4B indicated compression from the opposite direction (from SW) (Fig. 4). However, it is possible that these structures of the subglacial sediments was caused by subglacial deformation by overriding ice, possibly by the same advancing ice that later deposited the Veiki moraine.

The flutes observed south of the study area are interpreted to be older than the moraine plateaus (Hättestrand et al. 2012), based on the fact that the flutings are not found superimposed on the Veiki moraine plateaus. The direction of the flutes (ca. 65°-245°) lies perpendicular to the eastern margin of the Lainio arc, indicating a dynamic relation between these features and that the ice that formed the end moraines at the eastern margin of the Lainio arc also formed the flutes (Hättestrand et al. 2012). As they are roughly perpendicular to the fold axis in unit 4B and parallel to stress direction indicated by fabric orientation in unit 5B, the deformation of those units might have occurred during that same advance. The sediment stacking might therefore be due to thrusting of sediment which has been described as to form under advancing glacier, especially during surge events and under polythermal glaciers (Hambrey et al. 1997; Evans & Rea 1999), (see discussion below). More evidence would however be needed to confirm that.

As mentioned above, the core of the Veiki moraine plateaus seems mostly to consist of massive diamictons. They might be deposited by mass flows deposited from downwasting ice into depressions prior to the lake formation (see description Trench 3). It is also very likely that the lower parts of the moraine plateaus consist of subglacial till. As discussed above, subglacial gravitational squeezing could not have accounted for a significant part of the moraine formation.

However, it is possible that large parts of the sediment under the plateaus were existing prior to the Veiki moraine formation. A sharp reflector boundary interpreted as the bedrock surface, is

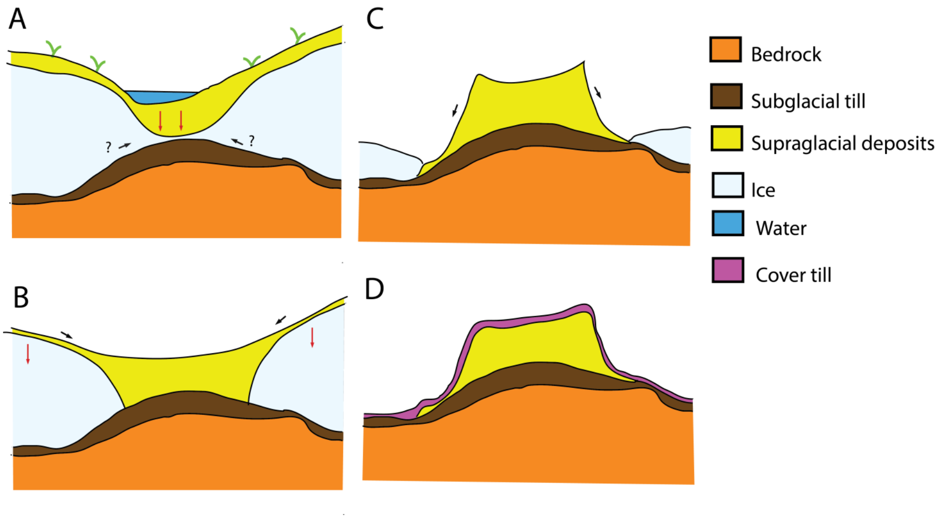

Fig. 18. Depositional model. A: Lake sediments are deposited into ice depressions during a warm period, the lake slowly melts through the ice. Possibly the weight of the surrounding glacier squeezes some material into the area of lower pressure, under the depression. B: Mass movements from the surrounding ice cover the lake sediments. C: The ice back-wastes from the moraine plateau so it is left standing as a high point in the landscape. Slope failures might have occurred after loss of the supporting ice. D: The moraine is overriden by a sluggish ice which remolds it and leaves behind a thin till layer on top of the moraine.

detected on the GPR profile from the fluted terrain, at approximately 10 m depth (Fig. 4; 16). It is likely that the fluted till also occurs below the moraine plateaus and could therefore account for a large part of the sediment pile in the lower parts of the moraines plateaus.

No detailed documentation could be performed on the diamict in the lower-sediment pile of the Veiki moraine plateaus. Therefore it is not possible to conclude how much of the sediments below the moraine surfaces was deposited by supraglacial processes vs. subglacial processes.

The uppermost units in all trenches (1C, 2C, 4D, 5E, 6F and 7) are interpreted to be part of the same covering till. This interpretation is based on similar clast morphology and characteristics, such as color, massive appearance and lack of sediment structures. Sand lenses found in some of the units (4D and 5E) could support a melt-out interpretation (Krüger & Kjær 1999). The clasts have abraded edges and have similar composition as the clasts found in the units below, that could support a subglacial interpretation and therefore local origin of the clasts (Benn & Evans 2004). The fabric analyses from these units reveal weak fabrics except in unit 6F where the preferred axis orientation is parallel to the direction of the ice flow that overrode the region during the LGM (Kleman et al. 1997; Hättestrand 1998). The lower boundaries of these units are generally sharp, indicating a halt in deposition and that some erosion occurred after the underlying units were deposited. These uppermost diamictons are interpreted as parts of a subglacial melt-out till unit, deposited by the ice that overrode the region during the Late Weichselian glaciations. As the landforms, including the flutes between the moraine plateaus, mostly stayed intact, suggests that the overriding glacier was frozen to its bed, resulting in minimal erosion and remolding of the underlying landforms (Kleman 1994).

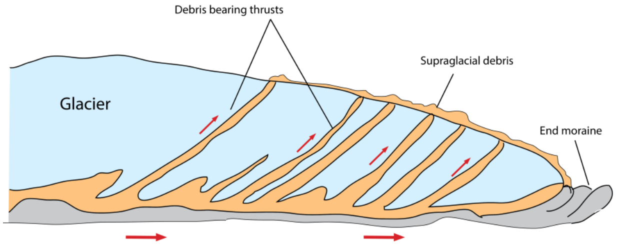

Fig. 19. Subglacial thrusting of sediments. Subglacial deformation occurs at the base and thrust moraines form at the margin. After stagnation of the ice, hummocky area is deposited below where the debris is accumulated on the ice. Redrawn and simplified from Hambrey et al. (1997).

5.4 Sediment transport

As, a substantial amount of the sediment building up the Veiki moraine volumes was deposited by supraglacial processes, large volumes of sediments would need to have been present at englacial/supraglacial positions of the glacier.

That could probably not have been caused by passive melt-out of englacial debris alone, indicating that subglacial debris was brought up to the surface of the ice. That is supported by the apparent modification of the clasts sampled from the upper layers of the moraines, suggesting a subglacial origin of the materials, later deposited in a supraglacial position. Englacial thrusting can take place near ice margins where large quantities of debris is elevated to englacial or supraglacial position due to compressive flow (Fig. 19). Thrusting is particularly common at fronts of surging glaciers, but can also form under other conditions, i.e. in polythermal glaciers at a transitional zone from warm, fast-moving to slower-moving, cold-based ice (Sharp 1985; Hambrey & Dowdeswell 1997; Hambrey et al. 1997; Evans & Rea 1999).

It has previously been suggested that the Veiki moraine were formed after an ice-marginal surge (Lagerbäck 1988; Hättestrand 1998). Zones of hummocky landscape, similar to the Lainio arc and located upglacier from a thrust moraine, have been described at other places associated with stagnation after a marginal surge (Ham & Attig 1996; Evan & Rea 1999). However, the circular shape of the Veiki moraine plateaus and the relatively undisturbed sediments within them stongly suggest deposition by stagnant glacier. Therefore, it is suggested that after the debris was actively brought to a supraglacial position, the ice became stagnant.

Veiki moraine plateaus within the Lainio arc show a tendency towards becoming larger in their dimensions towards east; the largest plateaus are found approximately 2 km from the eastern Lainio arc margin (Hättestrand et al. 2012). The largest moraine plateaus might thus represent the location below which most of the englacially thrusted material was accumulated, and later deposited by supraglacial processes (Fig. 19).

5.5 Supraglacial lake formation

After debris accumulation on top of the ice differences in the thickness of the sediments would cause variations in ablation, resulting in high relief ice surface topography (Boulton 1967). As the slopes steepen debris starts to slide in the depressions (Benn & Evans 2010). Meltwater inflow into such depressions can form supraglacial lakes, especially where the surface gradient is low and the mass balance of the glacier is negative (i.e. on a stagnant glacier) (Reynolds 2000). After the lake is formed warm bottom conditions in the lake can cause melting through the ice until it becomes an ice walled, not ice-floored lake (Clayton et al. 2008; Ham & Attig 1996). The thickness of the debris cover on surrounding ice has a large impact on the formation of such ice walled lakes.

Similar landforms studied in North-America are commonly associated with high relief hummocks between the moraine plateaus. (Johnson et al. 1995; Ham & Attig 1996; Clayton et al. 2008). However, in the Lainio arc, the area between the moraines have a low relief. That fact, as well as the flutings that are observed in the south part of the area, indicate that very little material was deposited between the moraine plateaus at the time of their formation .

Clayton & Cherry (1967) described two end member forms of ice walled lake plains; one formed in a stable environment where the supra-glacial debris cover was very thick, and often associated with thick lake sediment sequences and surrounding high-relief hummocks, while the other type was formed in an unstable environment where the debris cover was thinner. The ice-walled lakes formed in an unstable environment are often associated with low relief hummocks, well defined rim ridges and sedimentation dominated by debris flows instead of lake sedimentation.

Compared to the ice walled lake plain that have been described from North-America, which are up to 20-50 m high and have up to 30 m thick lake sediment sequence (Clayton et al. 2008), the Veiki moraines investigated in this study are rather low (10 -15m from bedrock). This indicates that the ice from which the Veiki moraines were formed was much thinner and melted quicker. (Clayton & Cherry 1967) Lakes, thus, did not have as long time to develope, although the conditions must have been fairly stable during the lake deposition when the area was vegetated.

It might also be possible that the location of the moraines to some extent is topographically related. High points in the landscape can cause selective thinning of the overriding ice above them, favoring supraglacial lake formation above it (Eyles et al. 1999; Boone & Eyles 2001). This could be the case for the northern moraine plateau, which makes it appear higher than it is (Fig. 3).

5.6 Age of the Veiki moraines

Radiocarbon (^{14}C) dating of wood retrieved from the lake sediment (Unit 1A) indicates that its deposition occurred earlier than ca. 48,000 years BP (Table 2). The results from the OSL dating, also from the lake sediments, suggest deposition 53,000 ± 5000 and 45,000 ± 6000 years ago (Table 1). High macrofossils contnent was found in the unit. That indicates deposition during a relatively warm interstadial period. These ages fit well with the Tärandö II interstadial, in one alternative of Hättestrand & Robertsson (2010), placed into MIS 3.

5.7 Suggestions for future research

The aim of this study was to give an overview on the stratigraphy of Veiki moraine plateaus and associated sediments and landforms. The emphasis was on covering as many parts of the landform as possible while still gather data detailed enough for genetical interpretation. More detailed investigations could however, add to deeper understanding of the stratigraphy.

The origin of the stratified diamicton units (1B, 2A, 6E), interpreted as debris flow diamicton could be investigated further. That could be achieved by carrying out more fabric analyses to test if the “perpendicular to rim ridge” fabric is a general trend on the moraine plateaus. Also, if these units were deposited from debris flows, that would probably mean that the debris was lying on top of the ice during the same interstadial as when the lake deposit was formed. Therefore it might be possible to find pollen incorporated into the diamicton, which would further support a supraglacial origin of these sediments.

In future research it could be interesting to examine the relationship between the subglacial units at the base of the moraine plateaus and the debris flow units in the plateaus.

It would also be interesting to make trenches in the fluted terrain and in the middle part of the Veiki moraine plateaus to find out if it would be possible to correlate the diamictons found there and also if any lake sediments can be found in the southern moraine plateau.

It should be noted that there large spread in morphological shape and size variances between different Veiki moraine plateaus, subsequently it might be that not excatly the same processes formed all the Veiki moraine plateaus in the region.

6 Conclusion

- The Veiki moraine plateaus investigated in this study mostly seem to consist of massive diamicton in the center. The rim ridges and the upper parts of the plateaus are built up by mass-flow deposits, partly underlain by lake sediments.

- Although deposited supraglacially, both the amount of sediments required for the moraine formation and the modification of the clasts, suggests a subglacial source of the material. This indicates that englacial thrusing brought subglacial debris up to supraglacial position on the ice, possibly during ice marginal surge.

- After the glacier advance, the ice became stagnant. Supraglacial debris accumulated in depression on the ice and later, during a warm period, supraglacial lakes formed in depressions.

- Radiocarbon and OSL dating of the lake sediment suggest deposition around 50.000 years BP. That indicates that the lake formed during the Tärandö II interstadial, in MIS 3.

- Later the ice below the lake and the underlying massflow sediments melted and it became ground based (ice walled lake). Possibly due to the ice melting or after loss of the surrounding vegatation cover, debris flow events became more frequent.

- During the LGM the area was covered by sluggish ice leaving behind a till layer superimposed on the moraines and the surrounding areas. It did however not reshape the landforms to any great extend, indicating cold based ice.

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Appendix I

Grain size distribution diagrams. The percentage of finer material is on y-axis and the grain size in mm on x-axis.

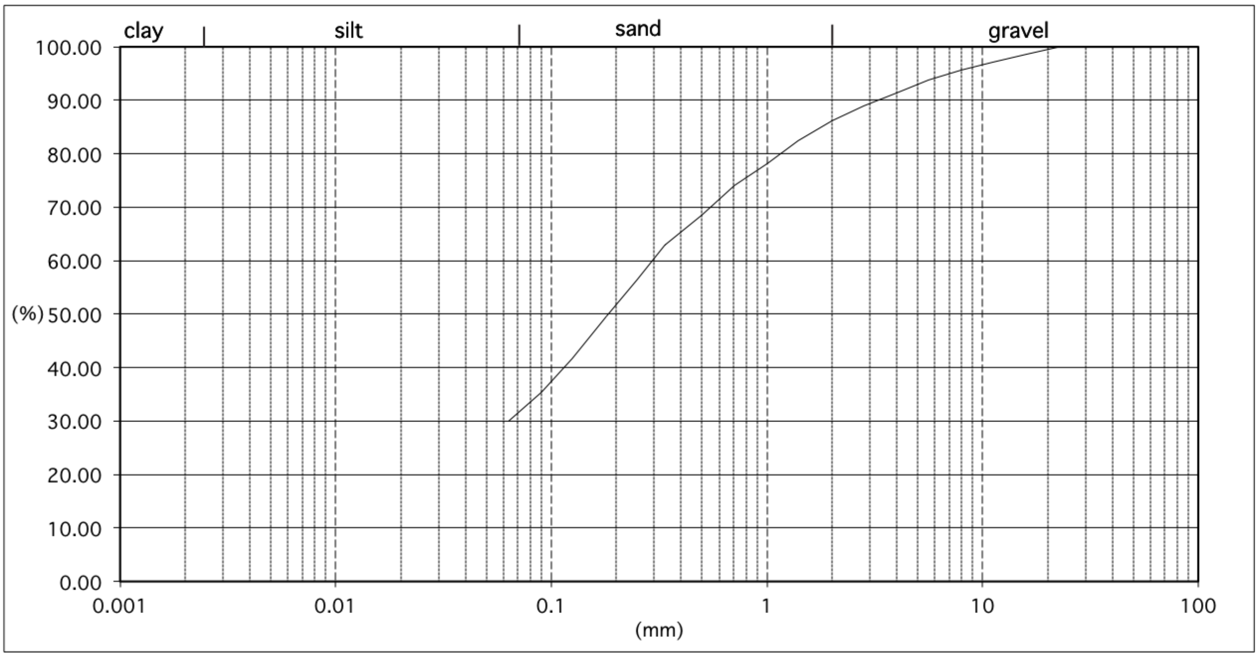
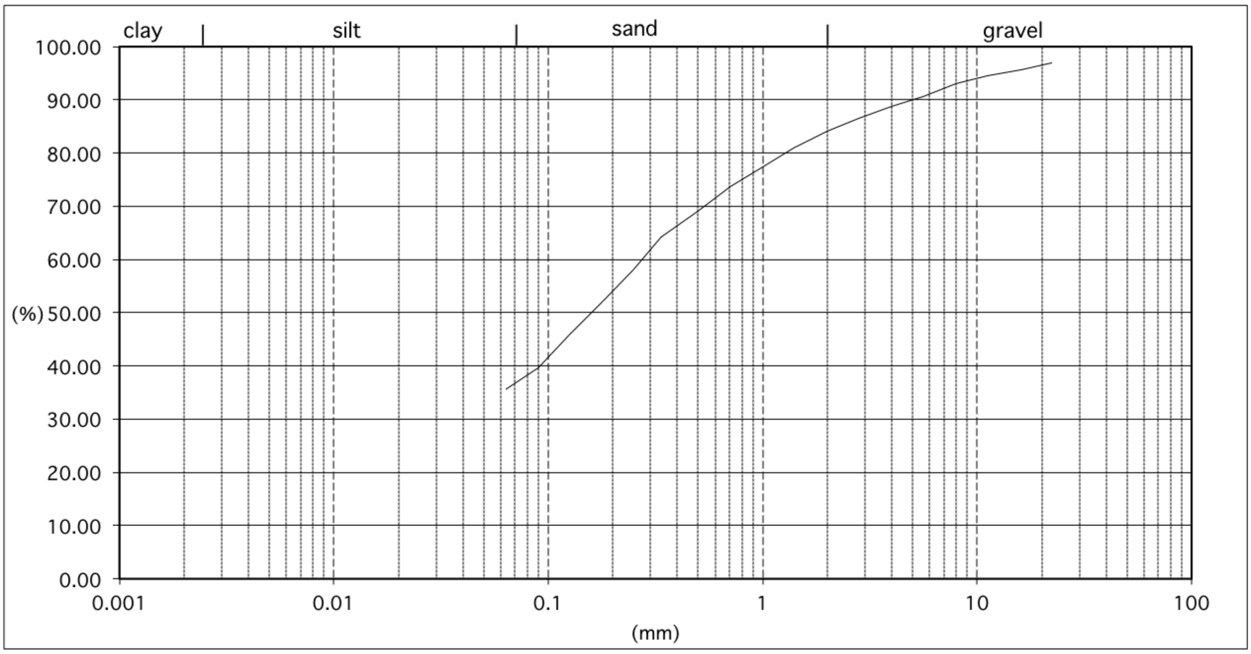


Fig. A.1.1. Unit 1B1



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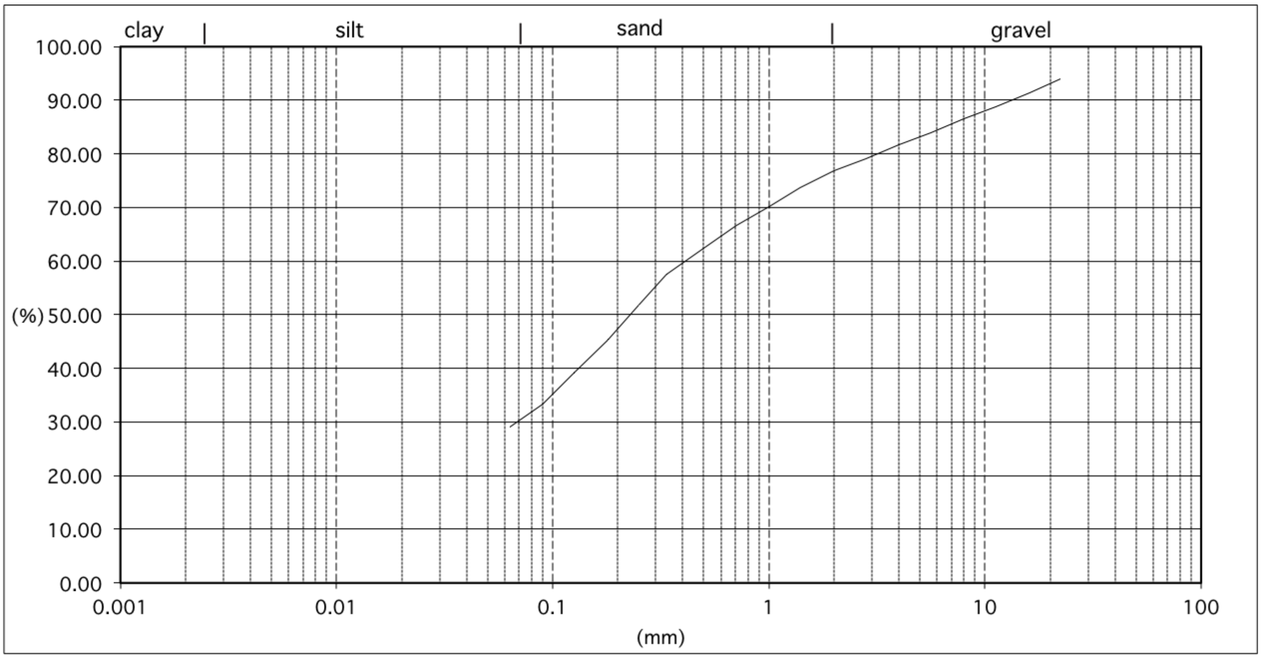


Fig. A.1.3. Unit 1C-diamicton

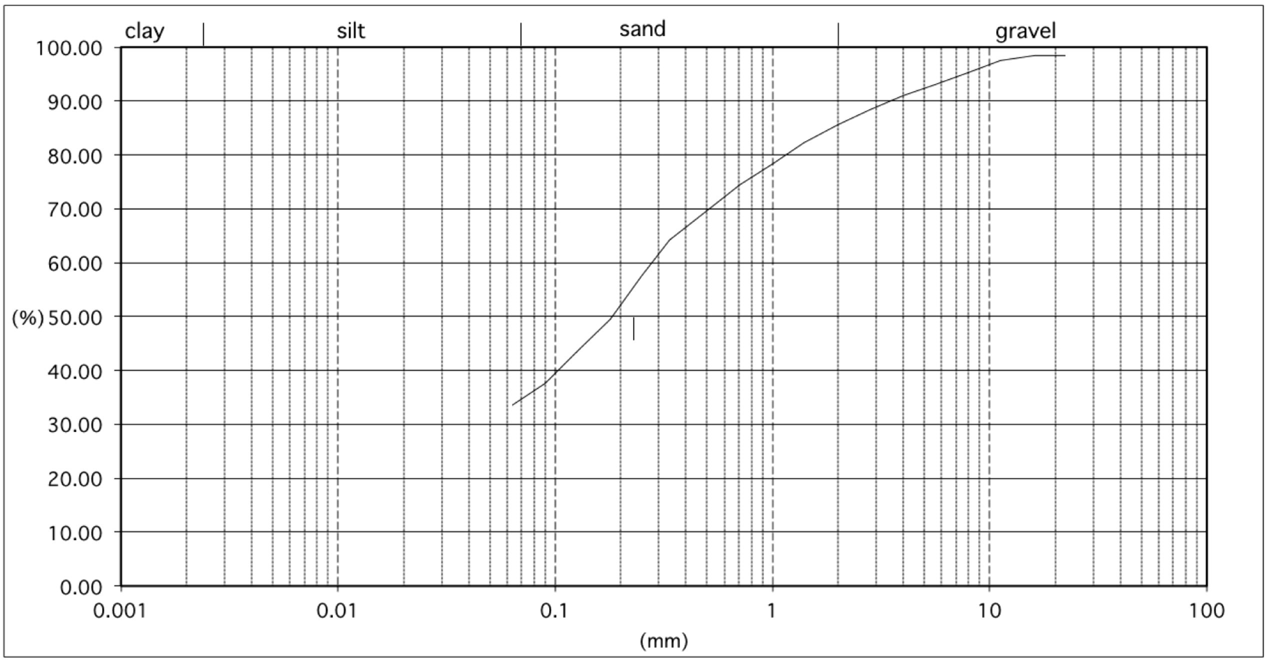


Fig. A.1.4. Unit 2A-diamicton

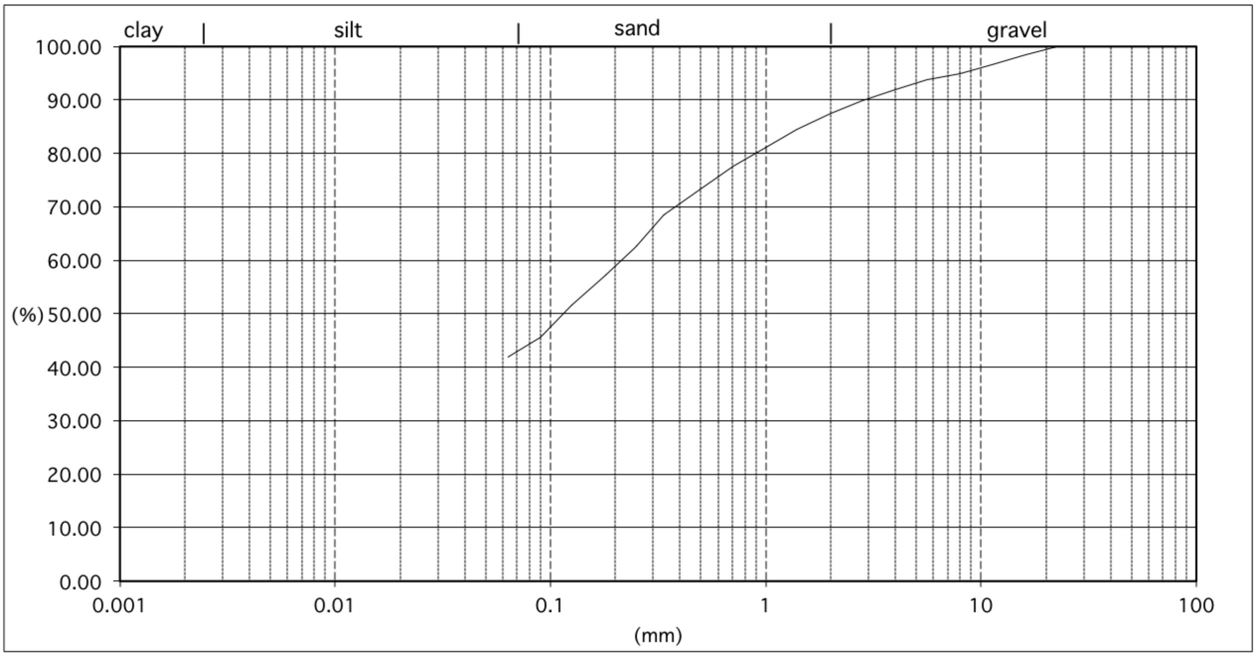


Fig. A.1.5. Unit 2C-diamicton

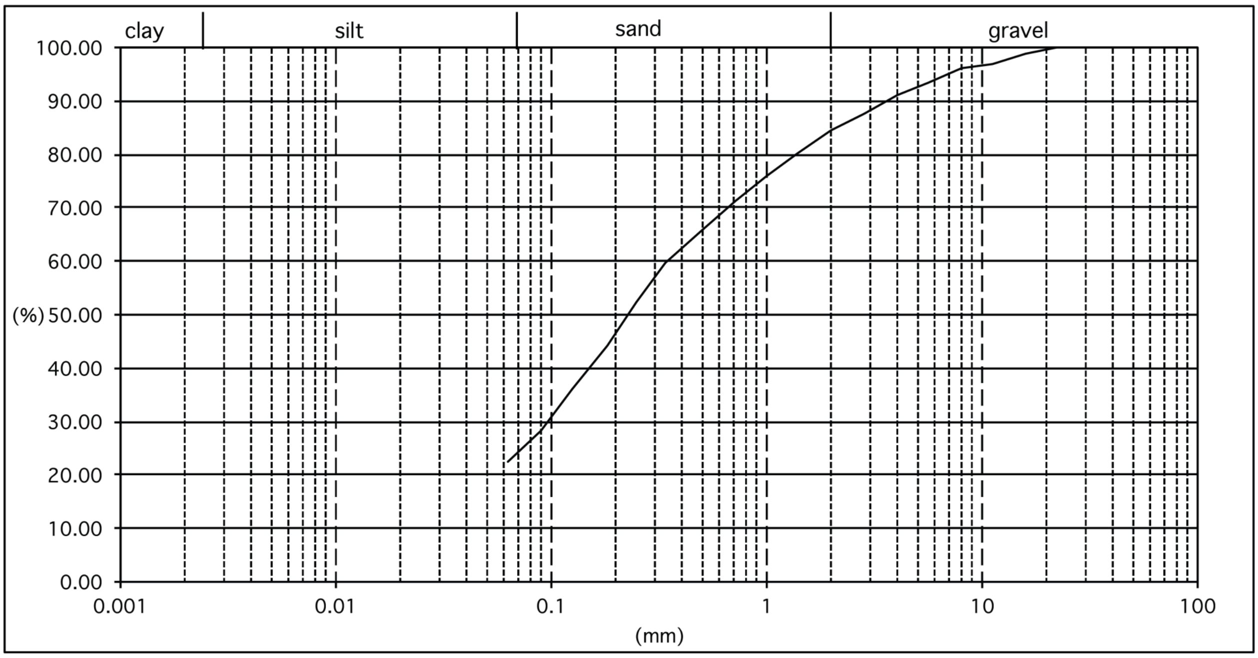


Fig. A.1.6. Unit 2C-Soil cover

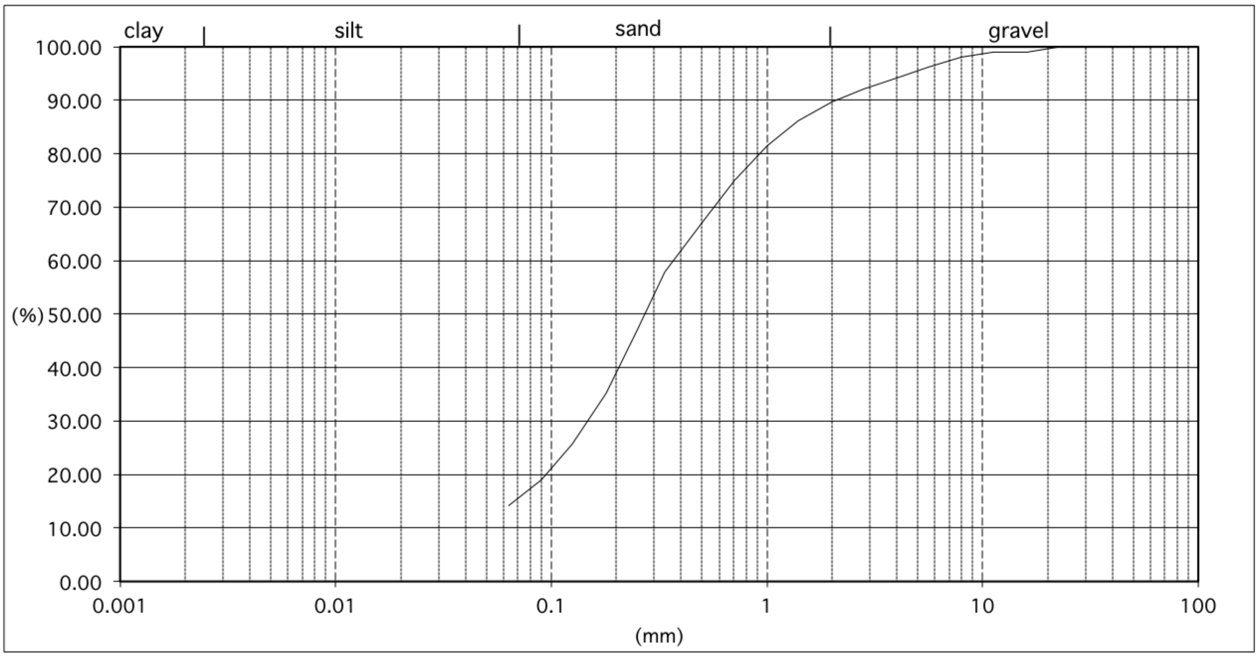


Fig. A.1.7. Unit 4B-diamicton

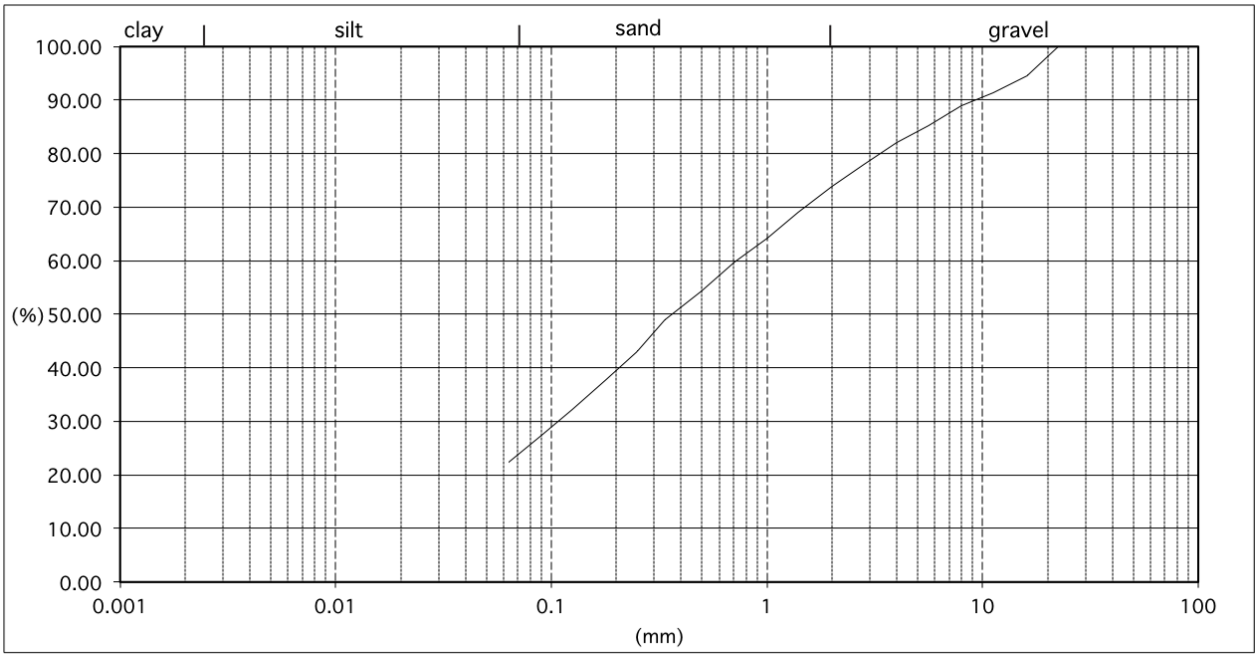


Fig. A.1.8. Unit 4C-diamicton

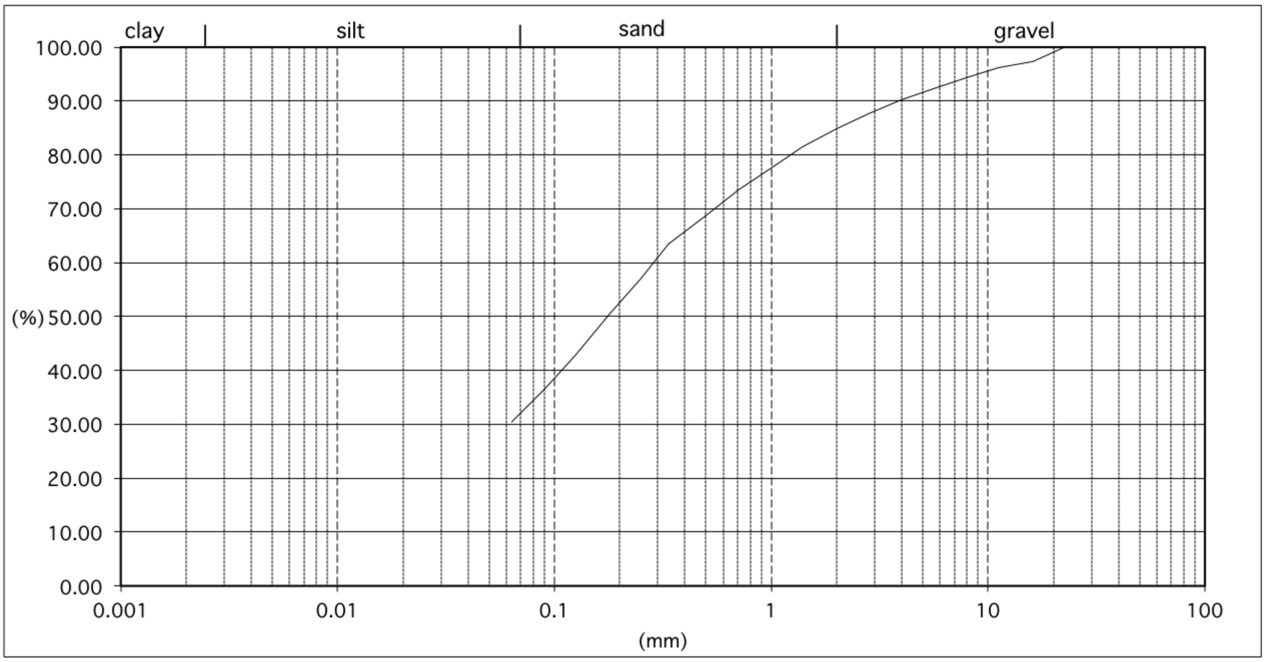


Fig. A.1.9. Unit 4D-diamicton

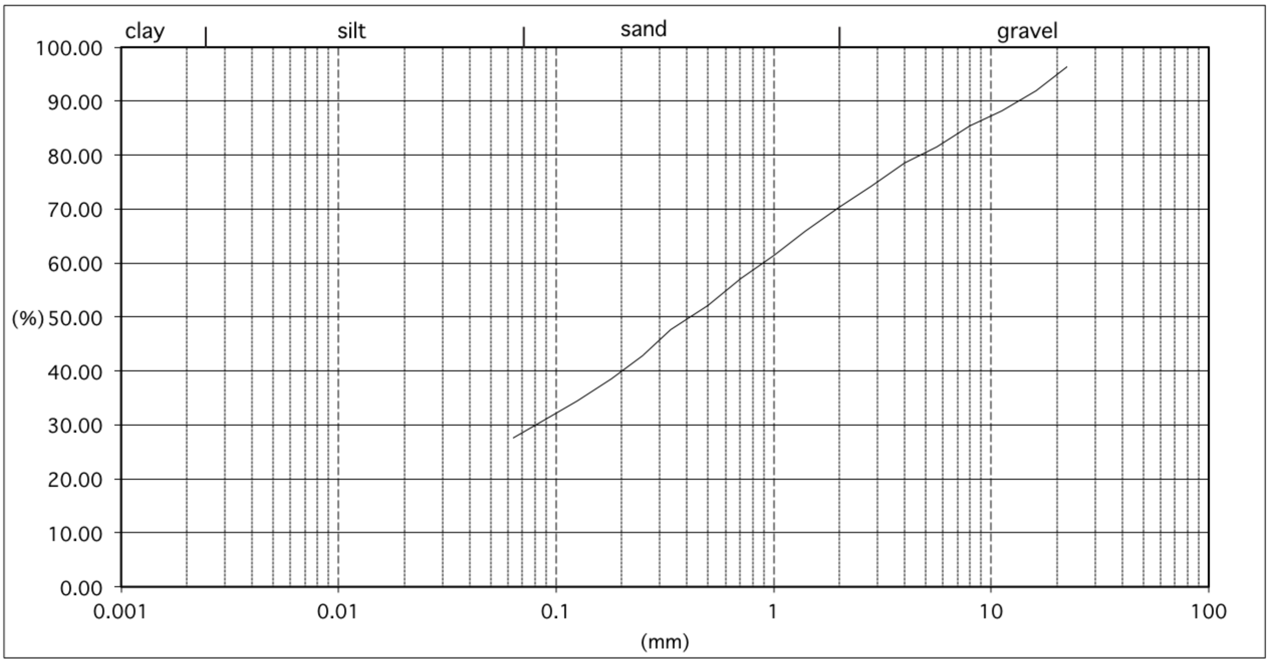


Fig. A.1.10. Unit 5B-diamicton

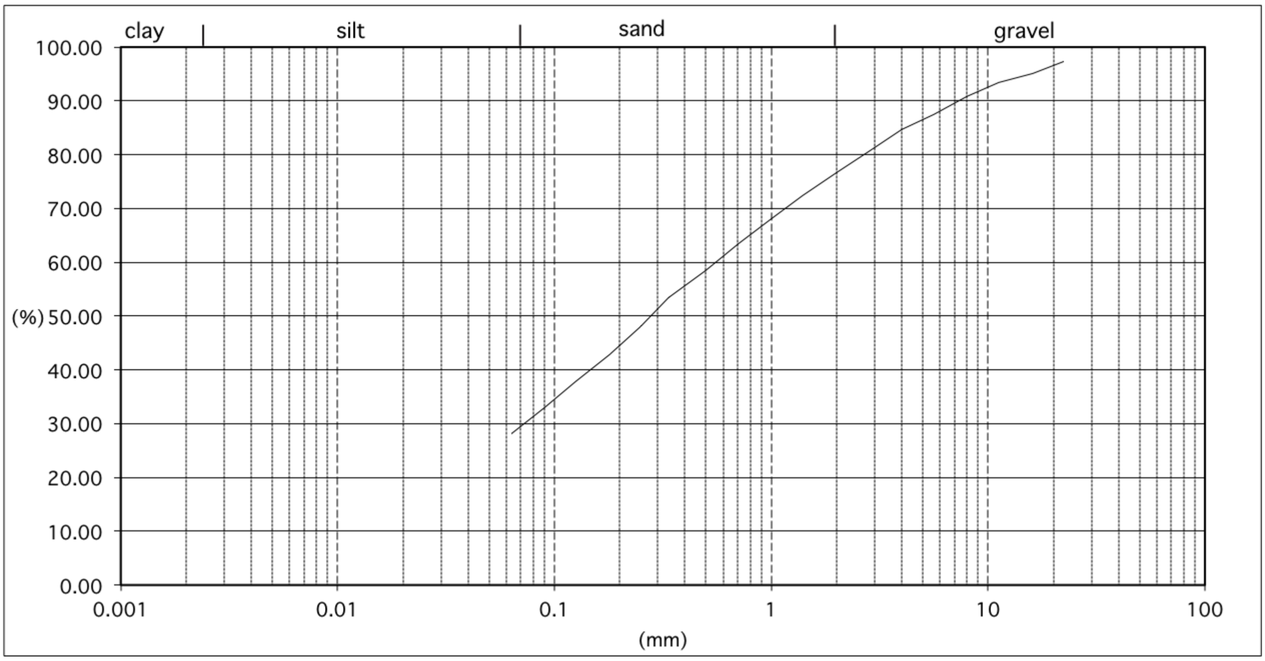


Fig. A.1.11. Unit 5C-diamicton

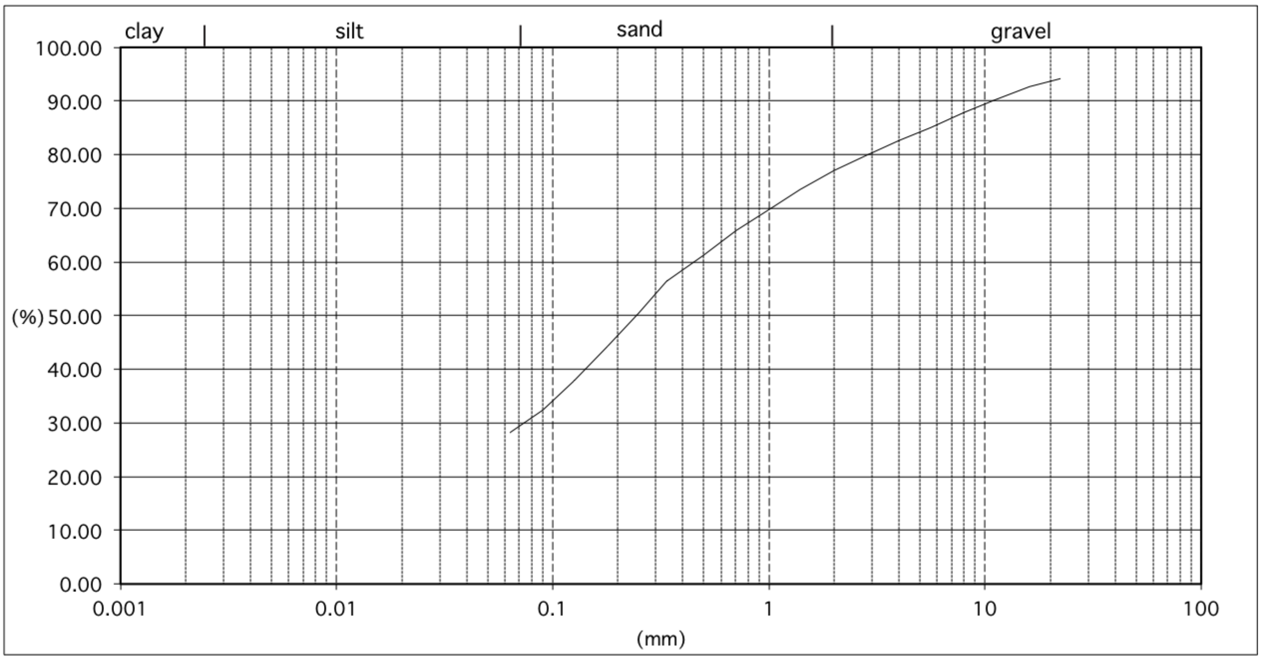


Fig. A.1.12. Unit 5E-diamicton

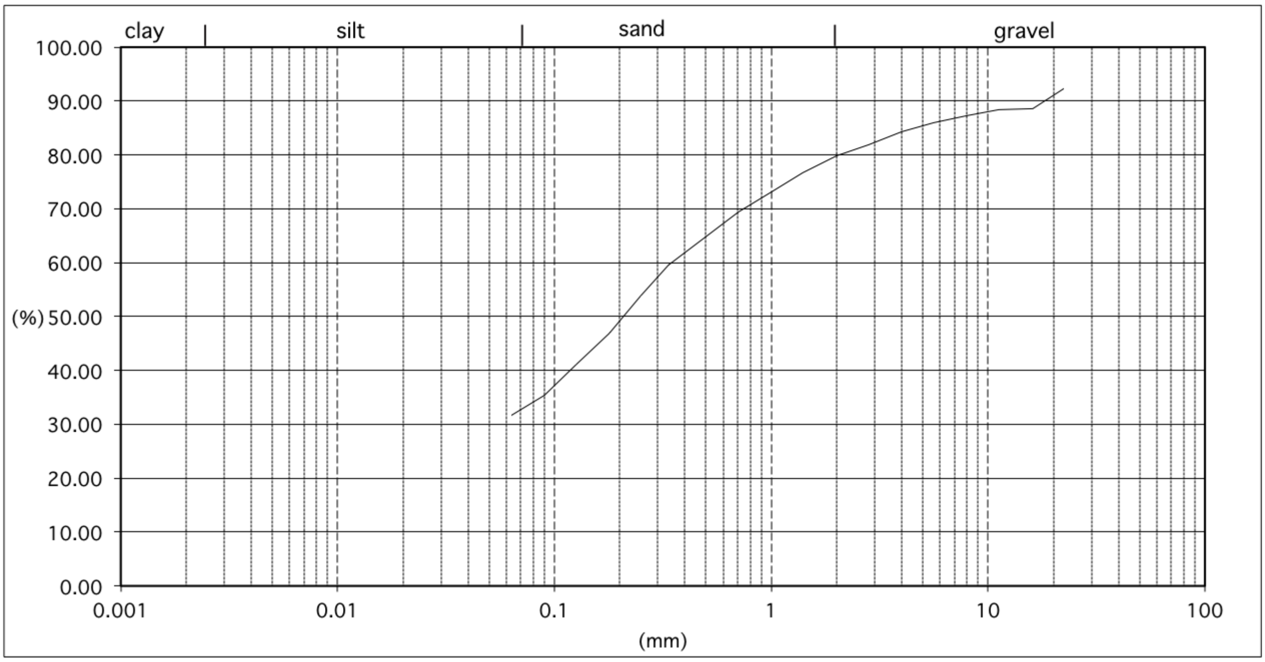


Fig. A.1.13. Unit 6A-diamicton

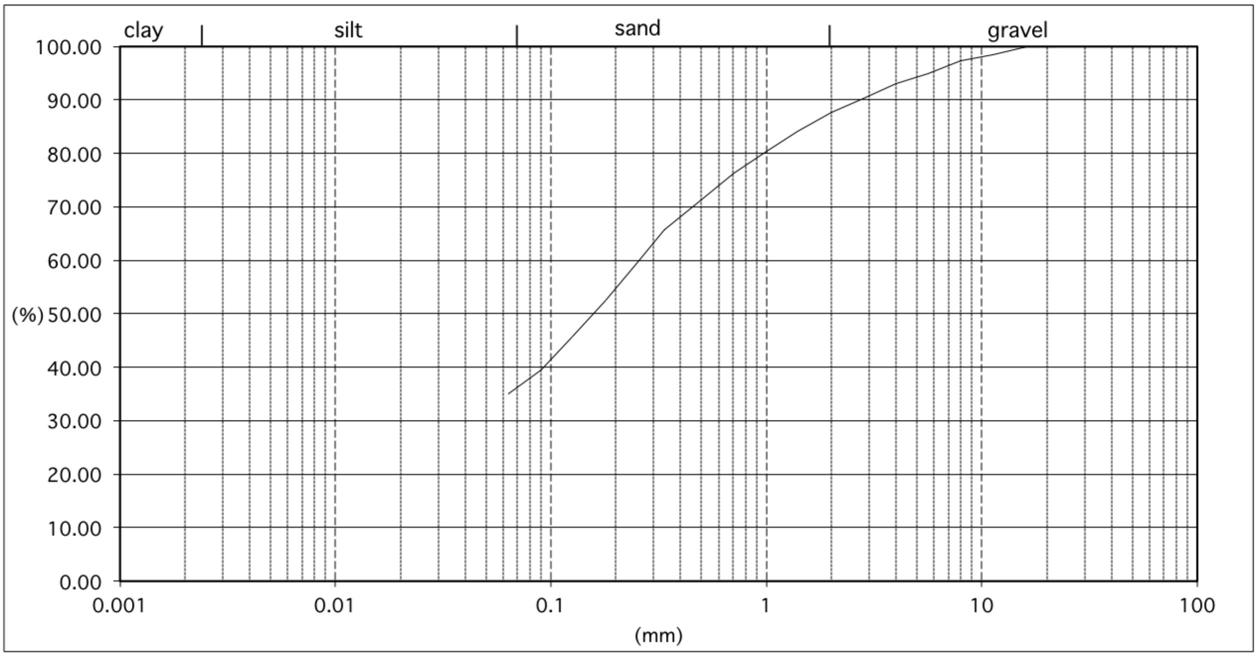


Fig. A.1.14. Unit 6B-diamicton

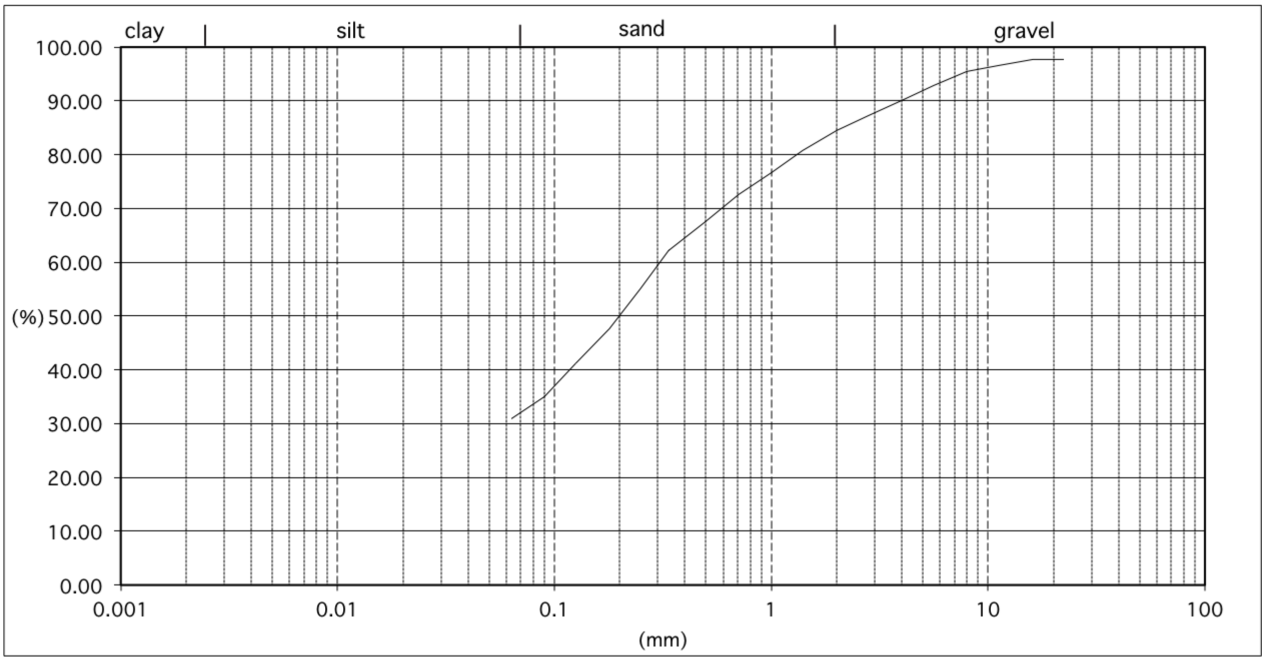


Fig. A.1.15. Unit 6F-diamicton

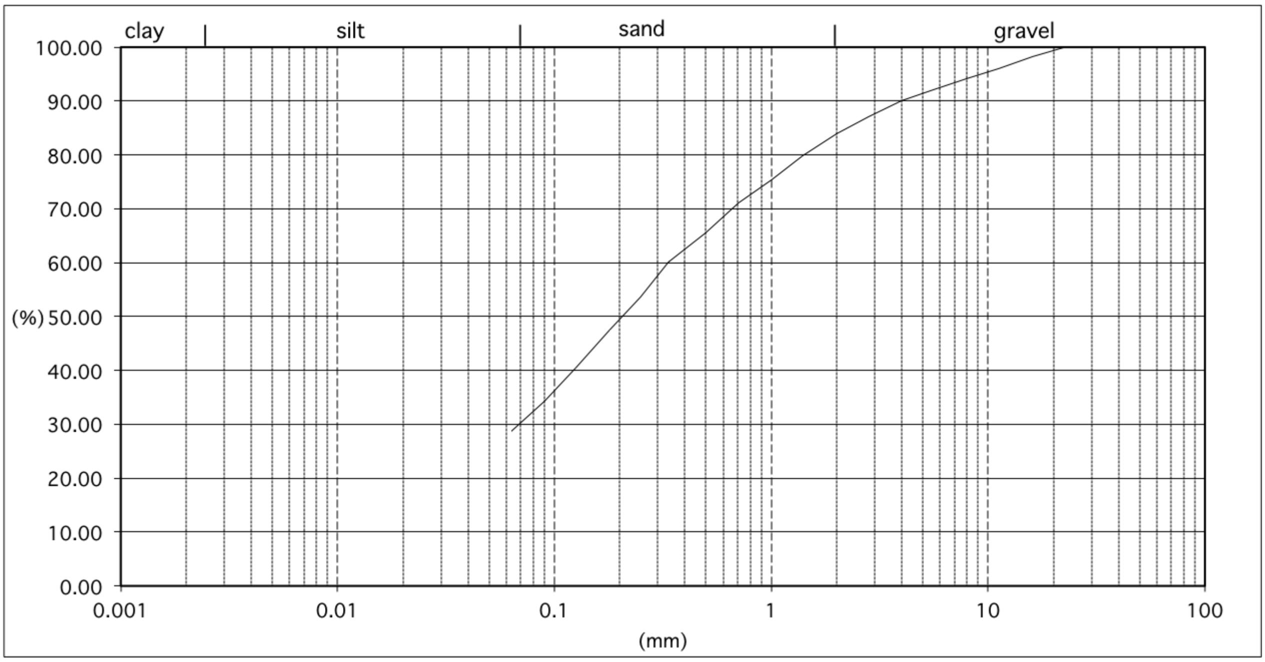


Fig. A.1.16. Unit 7-diamicton

Appendix II

Clast angularity charts. The number of clasts is on y-axis and clast angularity values on x-axis (VA: Very angular, A: Angular, SA: Sub-angular, SR: Sub-rounded, R: Rounded, WR: Well rounded)

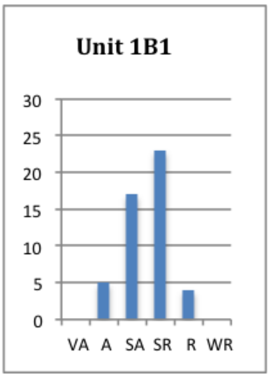
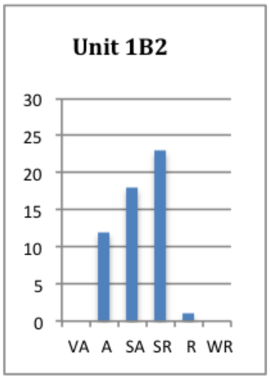


Fig. A.2.1. Unit 1B$_1$



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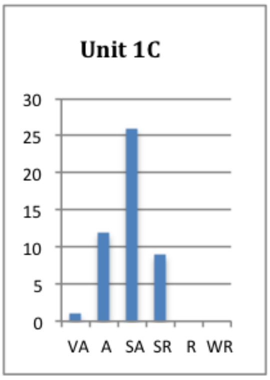
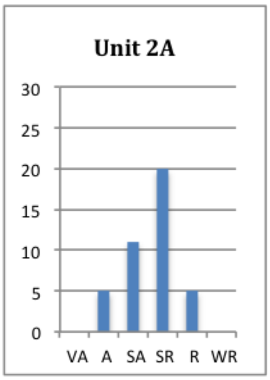


Fig. A.2.3. Unit 1C



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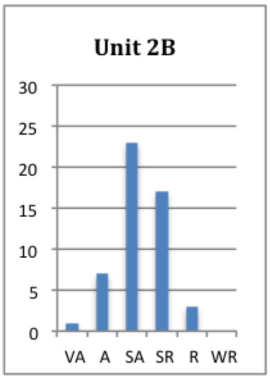

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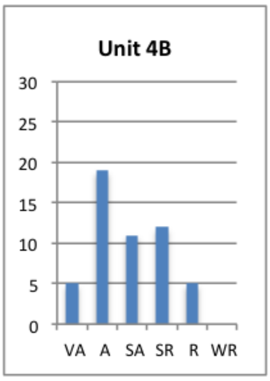

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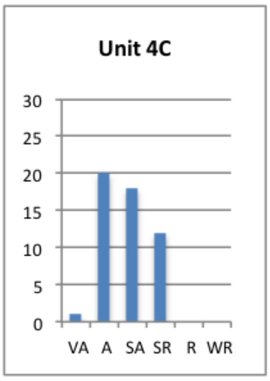

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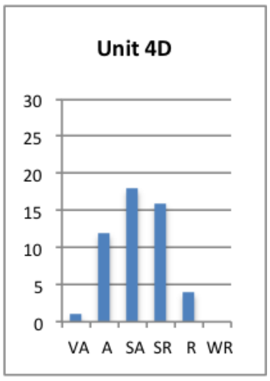

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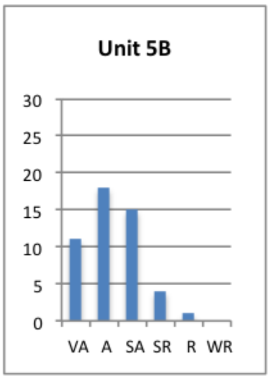

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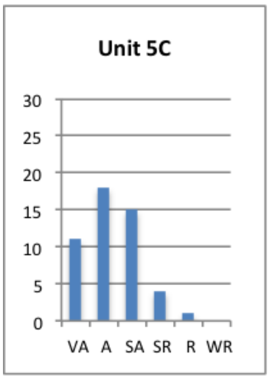

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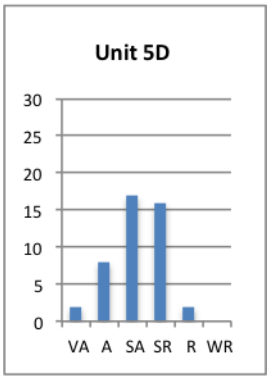

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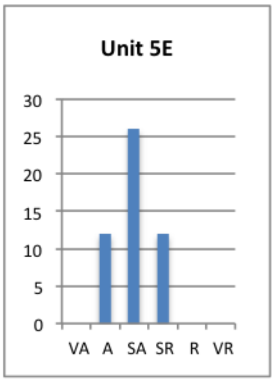

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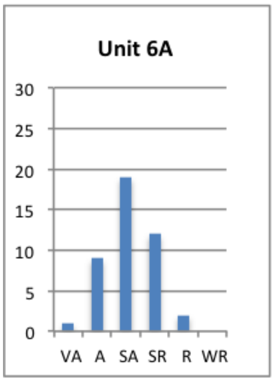

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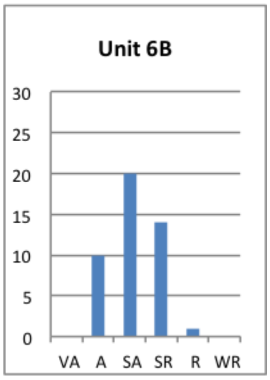

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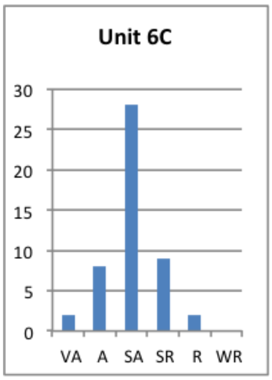

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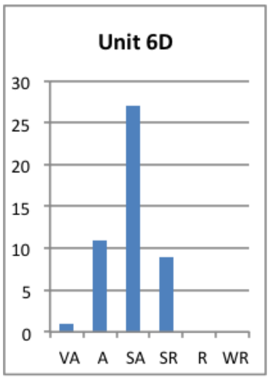

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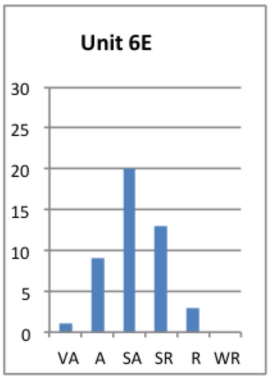

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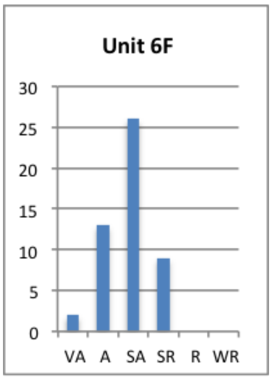

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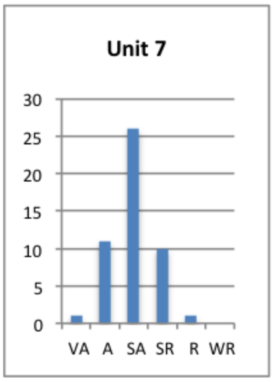

Fig. A.2.19. Unit 7

Appendix III

Table. A.3.1. Lithofacies codes for the section drawings (Krüger & Kjær 1999)

Lithofacies code

Diamict sediments

	D	Diamict
General appearance:		
	m	Massive, homogeneous
	h	Heterogeneous
	b/s	Banded/stratified
Granulometric composition of matrix:		
	C	Coarse grained, sandy-gravelly
	M	Medium-grained, silty-sandy
	F	Fine-grained, clayey-silty
Clast/matrix relationship:		
	c	Clast-supported
	m_1	Matrix-supported, clast poor
	m_2	Matrix-supported, moderate
	m_3	Matrix-supported, clast rich
Consistence when moist:		
	1	Loose, not compacted
	2	Friable, easy to excavate
	3	Firm, difficult to excavate
	4	Extremely firm

Sorted sediments

B	Boulders
Bh	Boulders, horizontally laminated
Gm	Gravel, massive
Gh	Gravel, horizontally laminated
Sm	Sand, massive
Sh	Sand, horizontally laminated
Fm	Fines, massive
Fl	Fines, laminated

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