

# **De Geer moraine genesis and sedimentology in Perniö, SW Finland**

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Quaternary Geology / Maaperägeologia

Pro gradu

30 ECTS

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26.3.2025

Turku

The originality of this thesis has been checked in accordance with the University of Turku quality assurance system using the Turnitin OriginalityCheck service.

Pro gradu -tutkielma

**Pääaine:** maaperägeologia

**Tekijä:** Camilla Holmroos

**Otsikko:** Perniön De Geer -moreenien muodostumisprosessit ja sedimentologia

**Sivumäärä:** 44

Tämä pro gradu -tutkielma käsittelee Perniössä sijaitsevalla Uimarannantiellä olevia De Geer -moreenimuodostumia. Tutkielman pyrkimyksenä on tuottaa uutta tutkimustietoa Suomen De Geer -moreeneista, niiden syntyprosessista ja luoda sedimentologinen malli tutkielmassa nimellä UT1 kutsuttavasta muodostumasta. Tavoitteena oli muodostaa oman tutkimuksen pohjalta selkeä kuva siitä, ovatko moreenit vuosittain muodostuvia vai eivät.

De Geer -moreenit ovat jo 1800-luvulta tutkittuja viimeisen jääkauden aikana muodostuneita moreenivalleja, jotka ovat tyypillisesti suoria tai loivasti kaartuvia, 1-3 metriä korkeita, <20 metriä leveitä ja <200 metriä pitkiä, tosin pituudessa on vaihtelua. Vaikka Gerard De Geer, jonka mukaan muodostumat on nimetty, mielsi moreenivallit itse vuosittain muodostuviksi, on muodostumisprosessista ristiriitaisia tutkimuksia.

Ensisijaisena tutkimusmenetelmänä oli Uimarannantiellä sijaitsevan UT1 -moreenivallin tarkka sedimentologinen tutkimus, mukaan lukien raekoko- ja kivianalyysit, litofasieskuvauksen ja seinämäpiirroksset sekä kivien suuntauslaskut. Näitä tuotettuja aineistoja verrattiin edeltävään kirjallisuuteen ja tutkimuksiin. Tutkielmassa hyödynnettiin erityisesti Rivers et al. (2024) tutkimusta, sillä tämä kyseinen tutkimusryhmä tutki samaa De Geer -moreenivyöhykettä.

Kenttätutkimukset ja niiden sedimentologiset tulokset sekä niiden vertailu aiempiin tutkimuksiin viittaavat vahvasti De Geer -moreenivallien vuosittaiseen muodostumiseen. Muodostuminen jaetaan kahteen tapaan: kesällä tapahtuvan mannerjäätikön poikimisen aikana pohjakosketusrajalle kerrostuva sedimentti muodostaa välivalleja, kuten Rivers et al. (2024) mainittu UT2, ja talvella muodostuu yksittäinen suurempi valli, kuten UT1, jäätikön etenemisen aiheuttaman ylityönnön seurauksena. Enemmän tutkimusta tarvitaan selvittämään, voidaanko moreeneja käyttää etenemisen nopeuden määrittämiseen.

**Avainsanat:** De Geer -moreenit, sedimentologia, syntyprosessi, vuosimoreeniteoria, Suomi, De Geer -maasto, jäänreunarekonstruktio

MSc Thesis

**Major:** Quaternary Geology

**Author:** Camilla Holmroos

**Title:** De Geer moraine genesis and sedimentology in Perniö, SW Finland

**Page count:** 44

This master's thesis examines De Geer moraine formations located by Uimarannantie in Perniö. The aim of the study is to provide new research data on Finnish De Geer moraines, their formation process, and to create a sedimentological model for the formation referred to as UT1 in the study. The goal was to determine whether the moraines are formed annually or not.

De Geer moraines are moraine ridges formed during the last glaciation, first studied in the 19<sup>th</sup> century. They are typically straight or gently curving, 1–3 meters high, <20 meters wide, and <200 meters in length, although the length varies. Research literature reveals that although Gerard De Geer, after whom the formations are named, considered the moraine ridges to form annually, there are conflicting opinions on the formation process.

The primary research method was a detailed sedimentological study of the UT1 moraine ridge at Uimarannantie, including grain size analysis, logs, a vertical cross section, and petrographic analysis. The data collected was compared to previous literature and studies. The study particularly utilized the research by Rivers et al. (2024), as this research group has studied the same De Geer moraine field.

Based on field studies, sedimentological research, and comparison with literature, the thesis concludes that evidence strongly supports annual formation. The formation process is divided into two mechanisms: during the summer, when sediment deposited at the grounding line during ice calving creates intermediate ridges, such as UT2 mentioned by Rivers et al. (2024); during the winter, when a single larger ridge, such as UT1, forms due to bulldozing caused by glacier advance. Further research is needed to determine whether these moraines can be used in ice-marginal reconstruction.

**Keywords:** De Geer moraines, sedimentology, genesis, annual moraine theory, Finland, De Geer Terrain, ice-marginal reconstruction

# Index

1 Introduction .....	1
2 Background on De Geer moraines .....	3
3 Theories on the genesis of De Geer moraines .....	5
3.1. Crevasse infilling theory.....	5
3.2. Grounding line stabilizations and calving .....	7
3.3. Readvance theory .....	8
3.4. Comparing theories.....	8
4 Study area.....	10
4.1. Geological settings .....	13
4.1.1. Bedrock .....	13
4.1.2. Quaternary .....	14
4.2. DGM at Uimarannantie .....	16
5 Methodology.....	19
5.1. Field day and sample collecting.....	19
5.2. Grain-size analysis.....	21
6 Results .....	22
7 Discussion .....	32
8 Conclusions .....	39
Notes .....	40
References:.....	41

# 1 Introduction

This paper is written to further investigate the formation processes of De Geer moraines in Southwestern Finland. The information gathered for this thesis is from field course material, till samples from the field and grain size analysis. The goal is to present a comprehensive sedimentology of the ridges, to contribute to the theory on the genesis of the moraines.

Although the De Geer moraine formation has been studied for years (De Geer, 1889) it is still poorly understood due to lacking sedimentological studies and knowledge. Sedimentology is not well known, since digging up entire ridges is costly and requires much work. There are also competing perspectives, which create a schism in research. Studying the sedimentology of these structures offers much-needed insight into the formation of De Geer moraines. Since there have not been many studies into the sedimentology of De Geer moraines in Finland by using machine-dug excavation, this study provides new information and insight into the still relatively unknown formation processes.

In April of 2023, I participated in a field course in Perniö whose purpose was to study De Geer moraine formation and the structure. There haven't been many studies on the structures of these deposits, so the formation processes have remained relatively poorly understood. However, there is a general understanding of the depositional environments and related processes on De Geer formation, which I will describe in the chapter *Background on De Geer moraines*. During the course we created log drawings and cross-section drawings, and studied foliation, and the directionality of rocks. With these I attempt to create an up-to-date theory of De Geer moraine genesis and ideally, add to current understanding of their formation.

My aim is to investigate whether De Geer moraines are annually forming moraines, as suggested by many of the newer studies (e.g., Bouvier, 2018; Ojala, 2016; Rivers, 2024), based on new information provided by studying the Perniö formation. I will investigate the previous studies that have been completed on the subject, further discussing the current hypotheses and the facts that support those.

This thesis has been made in conjunction with the making of the Rivers et al. (2024) study.

## 2 Background on De Geer moraines

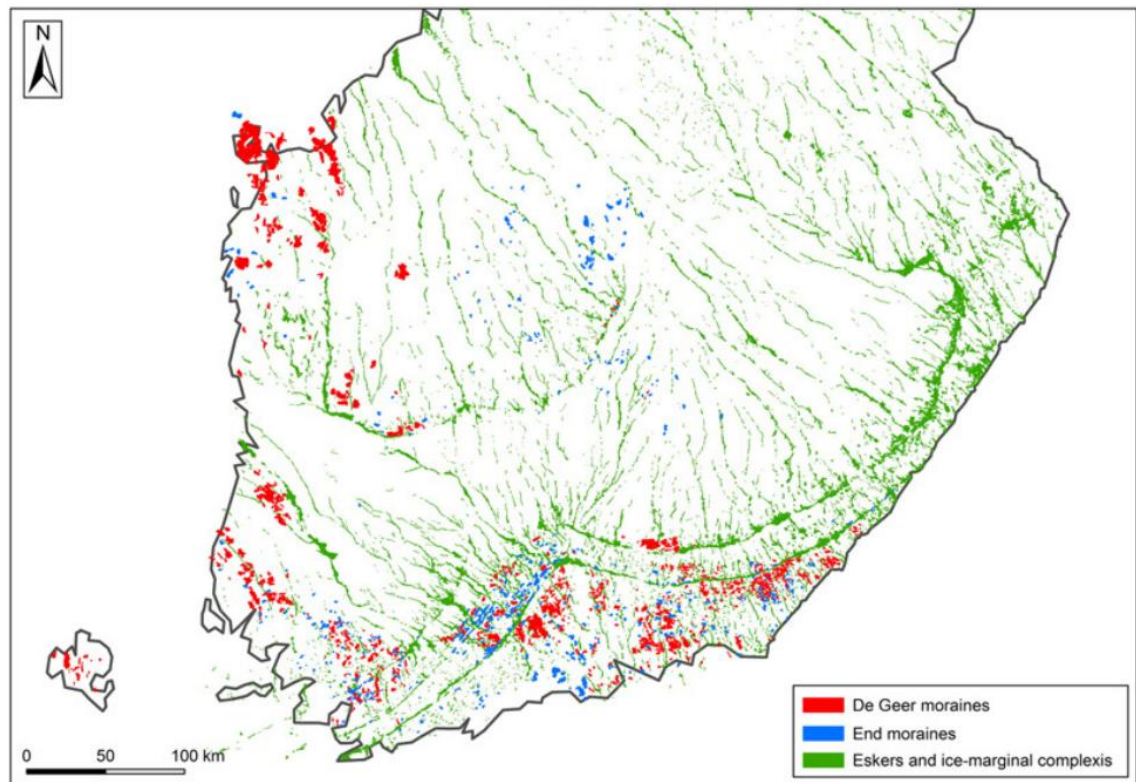


Figure 1. Regional distribution of De Geer moraines in Finland. AEK Ojala (2016).

De Geer moraines (later DGMs) are named after Gerard De Geer, who first observed and studied them (De Geer, 1889). They are distinctive as diamicton-dominated ice-marginal deposits (Palmu et al. 2021), which have been proposed to have formed during the last ice age. It is currently still unclear whether they formed annually, as end moraines, or during individual surge cycles (Zilliacus, 1989; Breilin et al., 2005). De Geer himself has hypothesized that they are annual moraines (De Geer, 1889).

Ojala et al. (2016) define De Geer moraines as follows: “a type of moraine comprised of successions of small parallel to subparallel, subequally spaced, often sharp-crested, narrow, subangular surface boulders, sandy to silty till ridges up to 12m high.” In the paper, moraines were defined as De Geers if there are more than five consecutive ridges. The ridges are typically straight and/or slightly concave, 1-3 m high, <20 m wide and <200 m long. The size, however, does vary, and it is notable that even if the length increases, height and width typically does not (Zilliacus, 1989). The formations have a

steeper distal, or down-glacier, side, with a typical composition of till, looser sediment and occasional sandy lenses (Hoppe, 1959).

De Geer moraines are typically found in the Younger Dryas ice-marginal zone (Ojala et al. 2016) and appear to have formed directionally similarly to the Salpausselkä formations in the Northeast-Southwest direction. The ridges appear mostly in limited areas below the highest shoreline and occur in swarms, being noticeably absent outside of these groups. This would indicate that they were not formed continuously during ice-margin retreat but were seen early on as registration of the glacier margin (Bouvier et al. 2015).

Even though numerous theories have been presented on the origin of De Geer moraines, many agree that De Geer moraines have a common origin at or near the grounding line of calving glaciers (Blake, 2000; Lindén and Möller, 2005; Bouvier et al., 2015). Sporadic appearances of De Geer moraines have been observed in Northern Finland, but the great majority of them have been found in the Salpausselkä region, Southwestern Finland and the Vaasa archipelago (Ojala et al. 2016). In the Ojala et al. (2016) study, two different end moraine types are discussed: terminal and recessional moraines. Terminal moraines are defined as the farthest extent of the ice sheet, while recessional moraines relate to temporal standstills or readvances of the ice sheet. Recessional moraines are further divided into two categories, which are De Geer moraines and end moraines. Large end moraine formations include those such as the Salpausselkäs.

There are several theories on the formation of the DGMs, which vary significantly on multiple aspects (e.g. De Geer, 1889 & 1940; Hoppe, 1959; Zilliacus, 1987 & 1989; Hoppe, 1959; Lindén and Möller, 2005). Notably there is much debate on the possible annual formation origin. I will compare the theories suggested so far. These theories include hypotheses that: 1) De Geer moraines have formed as annual moraines, 2) that they have formed at random, and 3) crevasse infilling.

### 3 Theories on the genesis of De Geer moraines

The prominent theories of De Geer moraines are winter readvance, subglacial crevasse infilling and grounding line stabilisation.

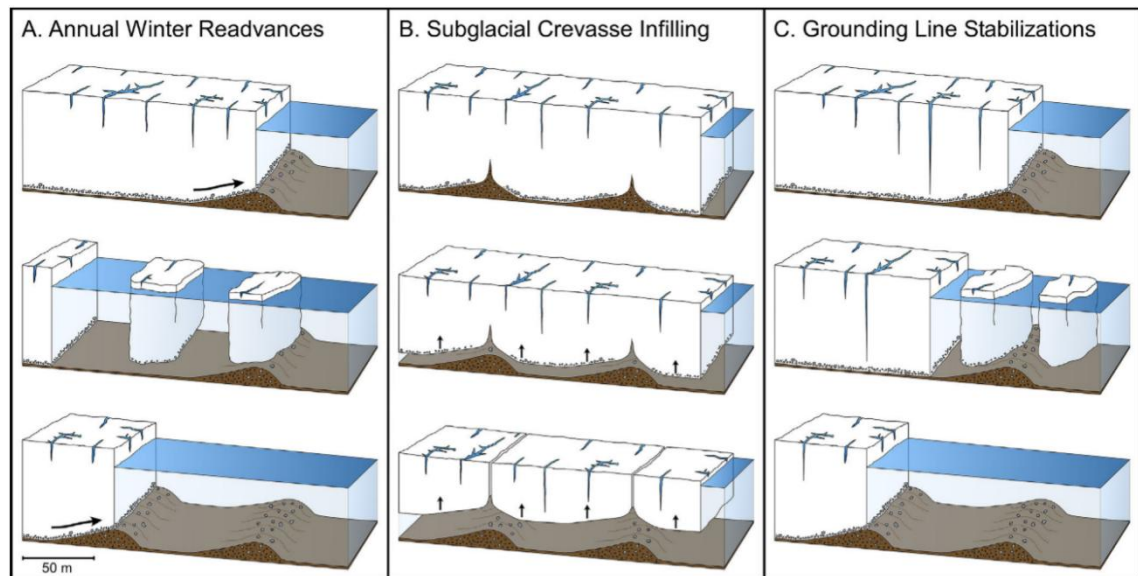


Figure 2. The proposed formation types, as described by Sinclair *et al.* (2018). Annual Winter Readvance creates moraine structures by pushing them during glacial readvances in subaqueous or terrestrial settings (Evans, 2013). The Crevasse Infilling genesis is thought to be due to crevasses forming during active flow phases or ice retreat, which in turn caused the subglacial till to be squeezed into the crevasse in the quiescent phase (Zilliacus, 1989). The Grounding Line Stabilization –model is thought to be due to subglacial sediment forming at the grounding-line during temporary halts in the retreat (Lindén & Möller, 2005).

#### 3.1. Crevasse infilling theory

Harry Zilliacus is perhaps the most prominent supporter of the crevasse infill theory in literature. Zilliacus conducted a significant amount of research into the De Geer moraine formations in Finland back in the 1980s and 1990s, so his work is by no means insignificant. In my thesis I will frequently reference his 1987 and 1989 studies. In the 1989 study, he bases his theory on certain features of the DGM structure, which can be observed elsewhere, too. Firstly, he argues that because the regular morphology and dimensions can be described in ridges from other countries such as Sweden and the USA,

this doesn't support the end moraine theory. Secondly, a rhythmic pattern of ridges can be observed very occasionally in Finland, which, in theory, makes identification of annual moraines "almost impossible" (Zilliacus, 1989).

Zilliacus is not the only notable supporter of the squeeze-up theory. Gunnar Hoppe, in his 1959 paper, wrote about this theory, in which the till is squeezed up into the crevasse. Hoppe also, ironically, refuses De Geer's theory while proposing to rename the formations as De Geer Moraines. According to the paper (Hoppe, 1959), there are several indicators that signify a squeeze-up genesis, notably orientation of pebbles perpendicular to the ridge direction, paired with their upright positioning (also in Zilliacus, 1987), and varve-dating of glacial striae compared to the DGMs. Zilliacus argues, that since the DGMs don't align with Sauramo's (1923) studies on varve sediments and ice retreat in southern Finland, they cannot be annually formed. It is envisioned that during summer, when meltwater velocity is high, water-saturated till is squeezed up and into the basal crevasse near the ice front (Hoppe, 1959; Zilliacus, 1989), which would explain the pebbles' orientation. This formation would require a rapid ice lift-off accompanied by widespread ice recession in order to preserve the ridges (Sinclair et al. 2018).

The crevasse infill theory has been proposed by people such as Hoppe (1959), and Zilliacus (1989, 1987). The most notable arguments against the annual model are made in Zilliacus' article "De Geer moraines in Finland and the annual moraine problem" (1987). In this study, Zilliacus plainly states, "Finnish De Geer moraines cannot be termed annual moraines" (p. 228). He bases this on a few distinct arguments. Firstly, in his study, the interdistance values are 100-120 m in Southern Finland and around 260 m in other parts. He argues that since the varve clay chronology (Sauramo, 1923) signifies a retreat rate faster than these distances would imply, the ridges only exceptionally correspond with the data. Secondly, Zilliacus also states that there is no evidence of interannual moraines and that the moraines are deposited in a way that indicates they are roughly the same age. Thirdly, he states they are not end moraines, asserting that there are no signs of pushing, considering DGMs to be closer to Rogen moraines in formation type.

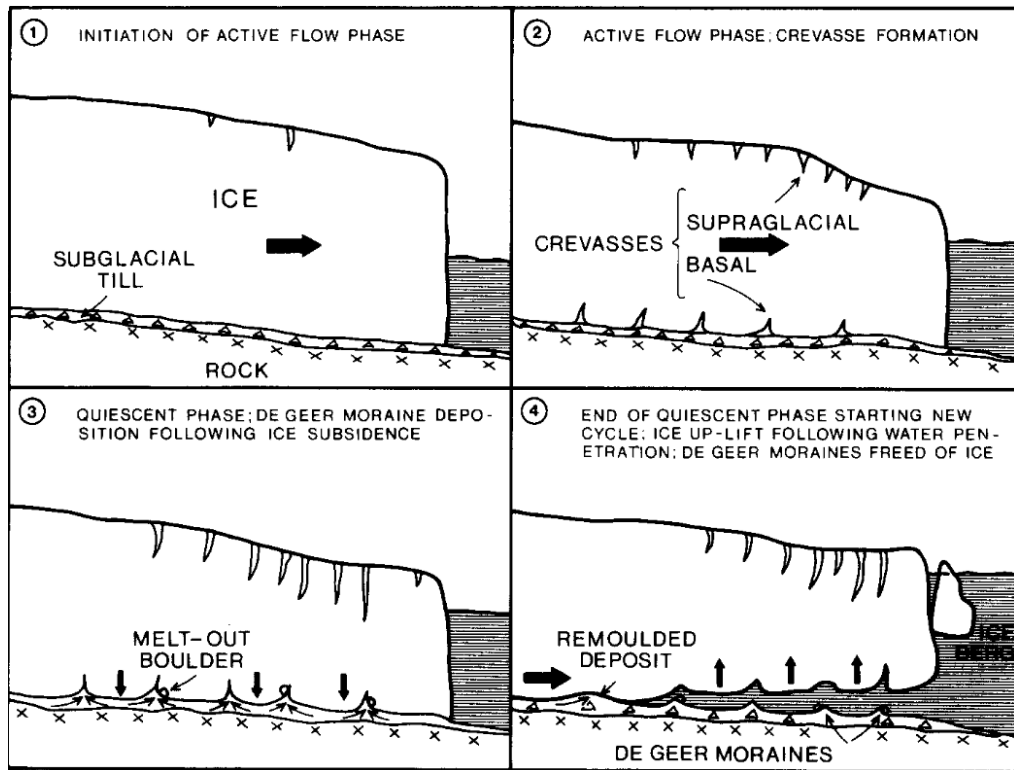


Figure 3. Zilliacus's theory on the formation of DGMs by squeeze-up into supraglacial crevasses. (Zilliacus, 1987)

### 3.2. Grounding line stabilizations and calving

The second theory of DGM formation was suggested in early studies that considered the moraine formations to be a result of a calving process. These include researchers such as Frödin (1916, as cited in Bouvier et al. 2015), who considered them “calving-moraines”. This theory is covered in the Sinclair et al. (2018) paper, as shown in Figure 2.

This conceptual model proposes that the De Geer moraine formation is driven by calving events, during which sediment accumulates at the grounding line through advection (Sinclair et al. 2018; Lindén and Möller, 2005). It is thought that the grounding line then relocates up-glacier after these calving events, forming a De Geer moraine. The sediment accumulation then continues at the newly formed grounding line. Lindén and Möller (2005) note that multiple moraine ridges could be formed over a summer, but that a winter readvance could essentially bulldoze many of those ridges, possibly causing a “winter moraine”. This model does not strictly exclude the possibility of “De Geer moraines as annual markers in some localities” (Sinclair et al. 2018).

### 3.3. Readvance theory

Newer studies have indicated possible other types of geneses. Some more modern methods of study such as LiDAR digital elevation models (DEMs) have given detailed looks into the formation of these moraines (Ojala et al. 2015; Bouvier, 2015; Rivers et al. 2024).

The readvance theory suggests that the ridges formed at ice margin during standstills or minor re-advances of the ice sheet (Ojala et al. 2015). It is thought that during the winters of the deglaciation period, the ice sheet goes through standstills, during which lodgement or basal till is collected at the edge of the ice sheet, forming these De Geer moraines (Sinclair et al. 2018). This till might be pushed by the advancing ice margin, forming a steeper proximal side against the edge of the ice sheet. Winter conditions include an overlying ice sheet and less meltwater, thus having a more suitable environment for readvance and reduced calving, which promotes the collection of till at the margin (Sinclair et al. 2018).

Gerard De Geer himself interpreted DGMs as annual moraine ridges formed by pushing at the grounding line during winter advances (1889, 1940). Others have suggested that more than one may form annually (Hoppe, 1959). Lindén and Möller (2005) suggested formation during stillstands of the ice-margin retreat that are not necessarily annual.

### 3.4. Comparing theories

The primary differences between the major theories are 1) the timing of formation and 2) location of formation. In the annual moraine theory, it is thought that the sediment collects at the ice margin during winter readvance and standstills, while in the crevasse infill theory the formation location is underneath the ice sheet, where meltwater carries the till. This could indicate a warmer period, and it is thought that this could occur during summer when discharge is high. The calving model, as described by Sinclair et al. (2018), mainly proposes a summertime formation, but also leaves the possibility of winter readvances forming DGMs open.

In the 1959 paper by Hoppe, he describes the moraine formations in detail in terms of structure and location, which are corroborated by newer studies. De Geer has described them as push moraines formed by the advance of the icefront during the winter and later started calling them annual moraines due to their even spacing indicative of the pace of ice sheet retreat (De Geer 1940, as cited in Hoppe 1959, Sinclair et al. 2018).

Other theories, like the basal crevasse infilling, have been questioned by newer research. While it has been argued that the formation is linked to subglacial crevasses and seasonal variations (e.g. Hoppe 1959, Zilliacus 1989), others are skeptical of the formation of such crevasses themselves due to the plastic behaviour of ice (Sollid and Carlsson, 1984). There are numerous issues raised with the crevasse infill theory in terms of physical conditions required for this genesis to occur. According to Blake (2000) it would require either tremendous water pressure or a very thin overlying ice, 22 m thick at most, and special conditions for the formations to be preserved. The number of ridges in Finland, for example, is high enough where these conditions occurring are probably unrealistic. The crevasse-infill model lacks sedimentological evidence and the existence of subglacial crevasse systems beneath grounded tidewater margins is questioned (Lindén and Möller, 2005).

## 4 Study area

The area in which we studied the De Geer moraines is in Perniö, Finland, at coordinates N 60° 14,923', E 23° 17,008'. Perniö is in the province of Western Finland, which is a part of the Southwest Finland region, about 23 kilometres south of Salo. A geographically notable feature of the area is the Kiskonjoki-Perniönjoki river system, which has a combined drainage basin area of about 1000 km<sup>2</sup>. The entire study area is roughly 10 kilometres across.

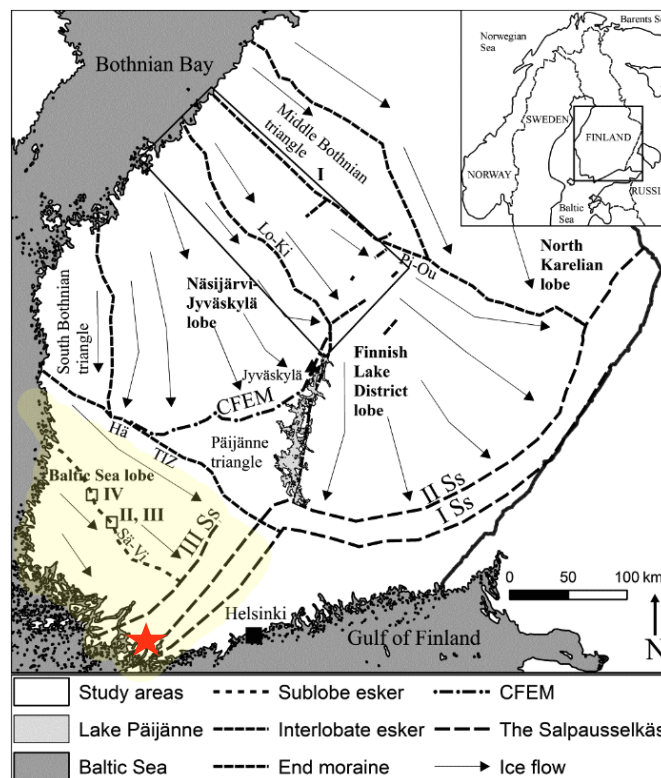


Figure 4. Map showing BSIL, highlighted in yellow. Star marks approximate location of study area. Ahokangas (2019).

The study area is located within the Baltic Sea Ice Lobe, later BSIL (see Figure 4). The BSIL retreated without experiencing any significant re-advancements. The Salpausselkä ridges were deposited as a result of prolonged standstills in deglaciation, marking the furthest extent of the Scandinavian Ice Sheet at the Younger Dryas. (Lunkka et al. 2021; Lunkka, 2023). It is suspected that the Finnish Lake District Ice Lobe (LDIL) underwent a major readvance of up to 60 km, while the BSIL did not exhibit any major oscillations

(Lunkka et al. 2021). This relative stability may have contributed to better preservation of the DGMs.

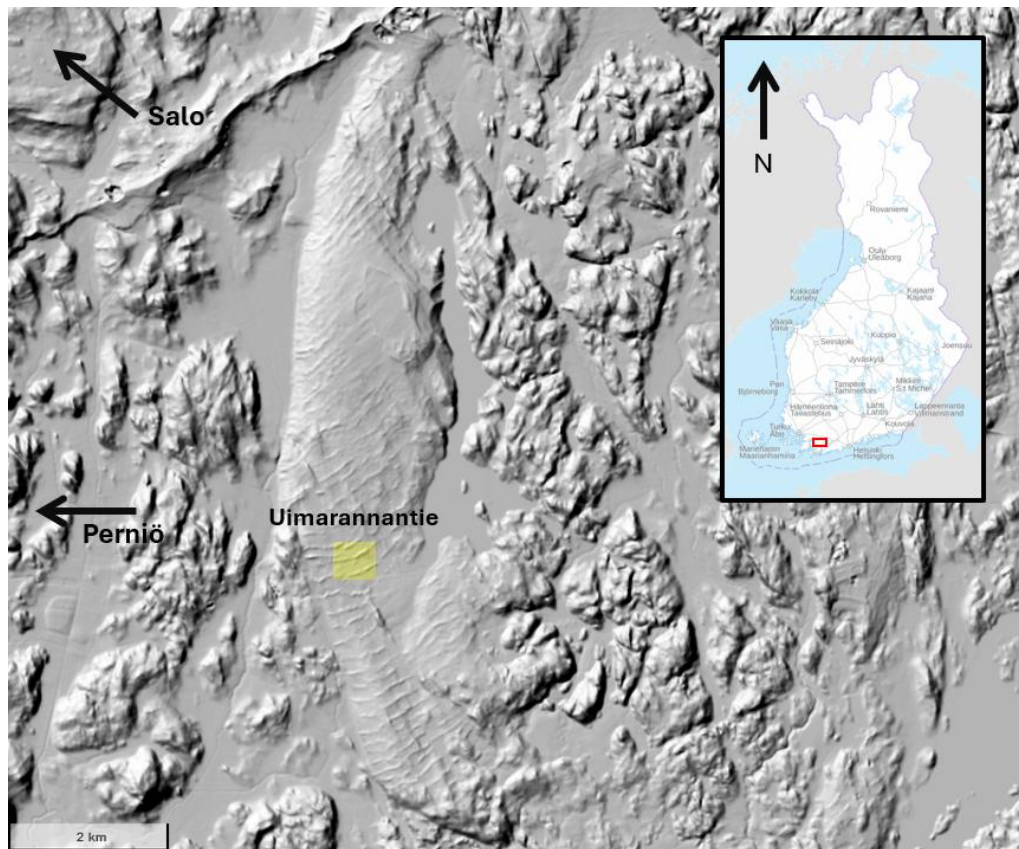


Figure 5. Location of study area on a map. Source: Maankamara.

Estimates suggest that the second Salpausselkä (SsII) formed around 11 600 to 11 800 years ago during a standstill event (Saarnisto and Saarinen, 2001). Since the study site lies immediately south of the third Salpausselkä (SsIII) and north of SsII, it is estimated that these formations developed between 11 600 and 11 400 years ago. This estimate is based on research indicating that SsIII was formed around 300 years after the onset of the Holocene, approximately 11 300 BP (Donner, 2010; Walker et al., 2009).

Presence of DGMs would seem to correlate with topography. Most ridges form at below 60 m a.s.l (Figure 6). Above 60 m a.s.l., the ridges are noticeably absent or very faint compared to those below 60 m a.s.l., as seen in Figures 7B and 7C.

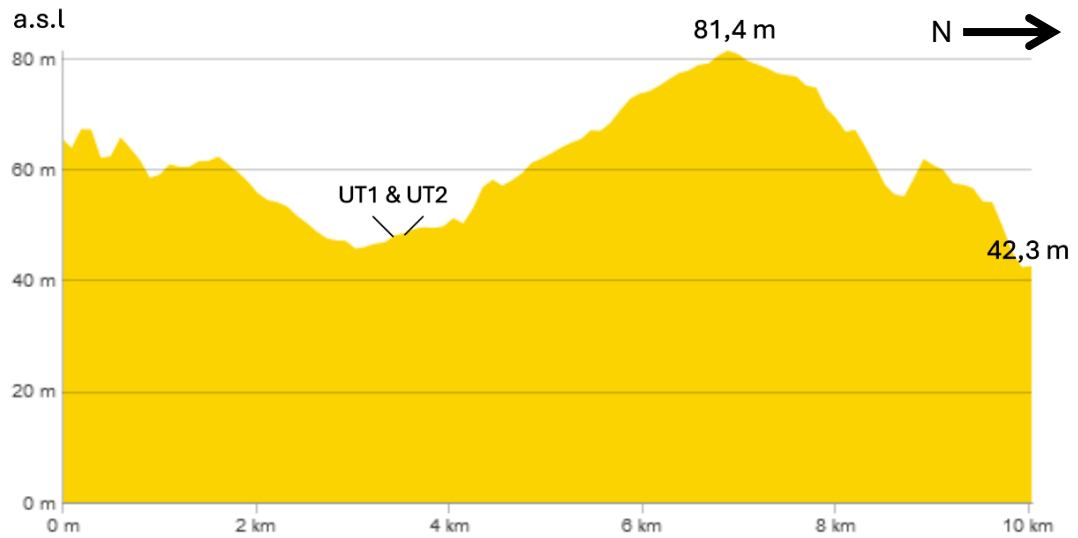


Figure 6. Topographical chart of the study area from Figure 7A, with excavations UT1 and UT2 marked. Source: Paikkatiетоikkuna.

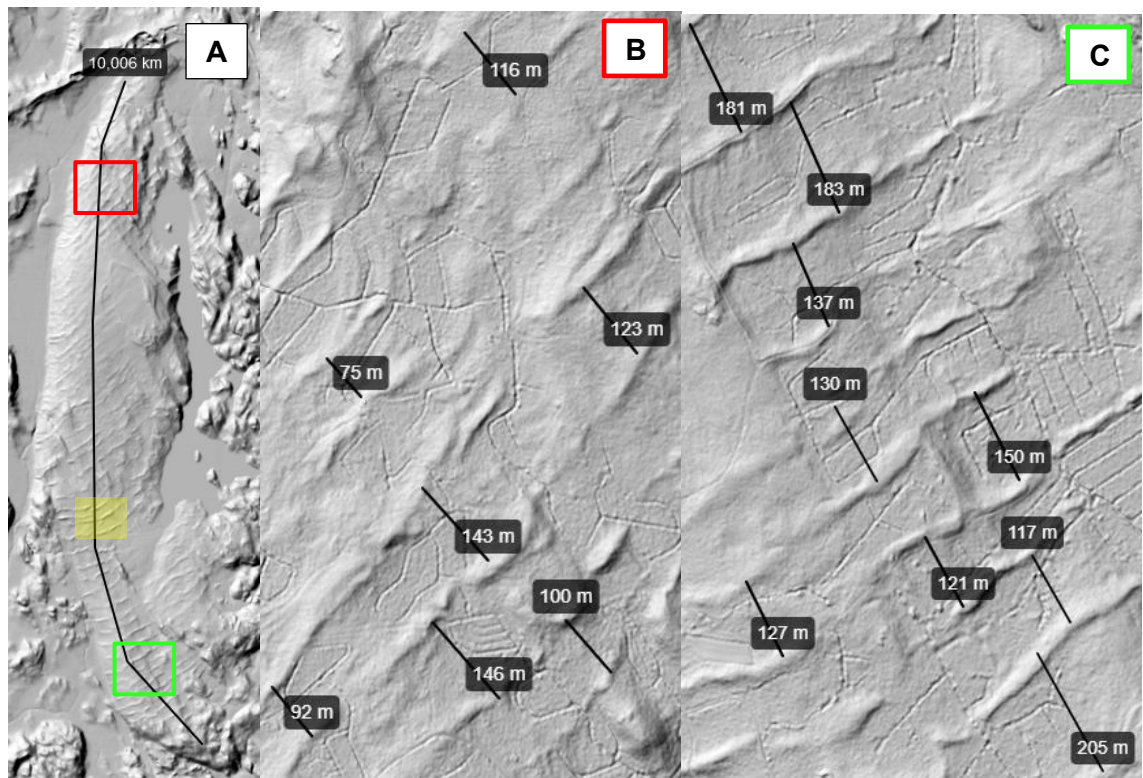


Figure 7. A) Entire De Geer moraine field in Perniö. B) Interdistances of DGMs ~4km north of UT1. C) Interdistances of moraines ~2km south of UT1. Most ridges form south of the study area and around the 8-kilometre mark, at below 60 m a.s.l. Source: Paikkatiетоikkuna.

The distances between the De Geer moraines in Perniö range from approximately 70 to 200 metres. The average distance among the used examples is 131 metres, but this does not account for all the ridges in the De Geer moraine field. The De Geer moraines further



is a porphyritic granite. It is typically greyish red or a pale red, with large microcline crystals in varieties lacking garnet. The rock is generally massive. (Eskola, 1914)

#### 4.1.2. Quaternary

The area is a uniform sandy moraine, forming part of the larger De Geer moraine field, which contains approximately 50 ridges. The ridges are more distinct further south, compared to those north of the study area. A possible explanation is the topography: there was likely less water on top of the northern parts of the study area, resulting in more rounded and less distinct ridges (see Figure 7).

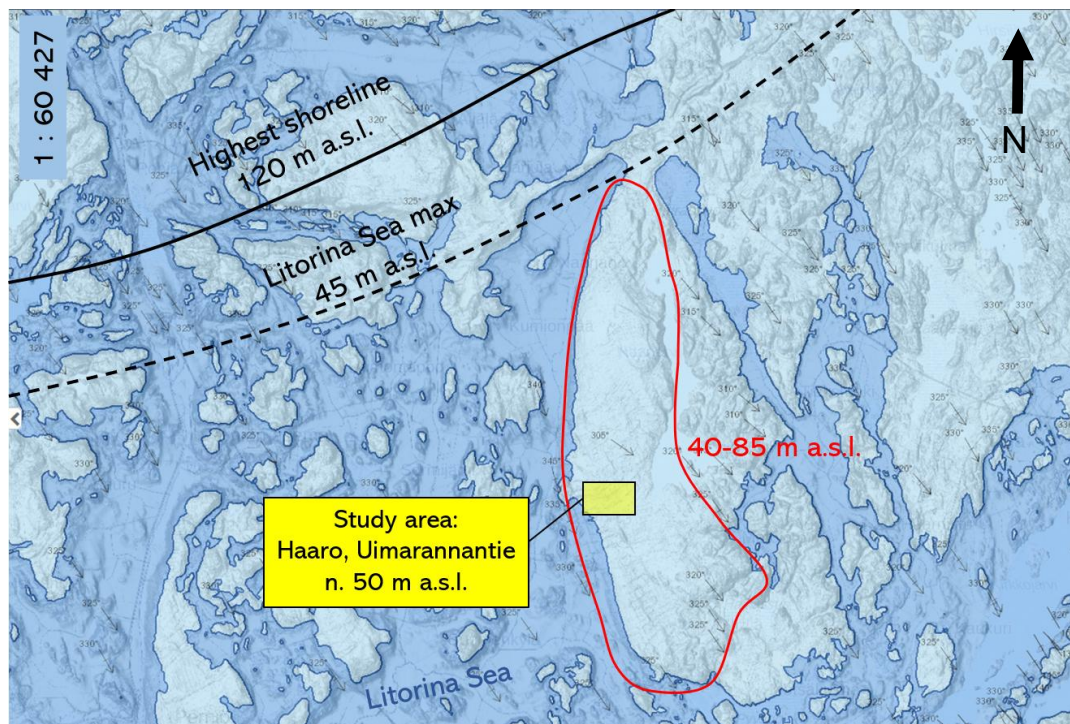


Figure 9. Proglacial water depth of study area in Perniö. Source: Ojala et al. (2013), Maankamara / GTK.

The study area has optimal conditions for the formation of De Geer moraines: the water depth is ideal, with the deepest parts being right around the Uimarannantie region (see Figures 6 and 9). DGMs typically form in water depths of more than 150 m but occur anywhere with proglacial water depths ranging from 15 to 270 m during deglaciation (Zilliacus 1989; Lindén and Möller 2005). With the study area being at approximately 50

m a.s.l. (see *Results*), the water depth would have been at roughly 70 metres, assuming a shoreline at 120 m a.s.l., as shown in Figure 9.

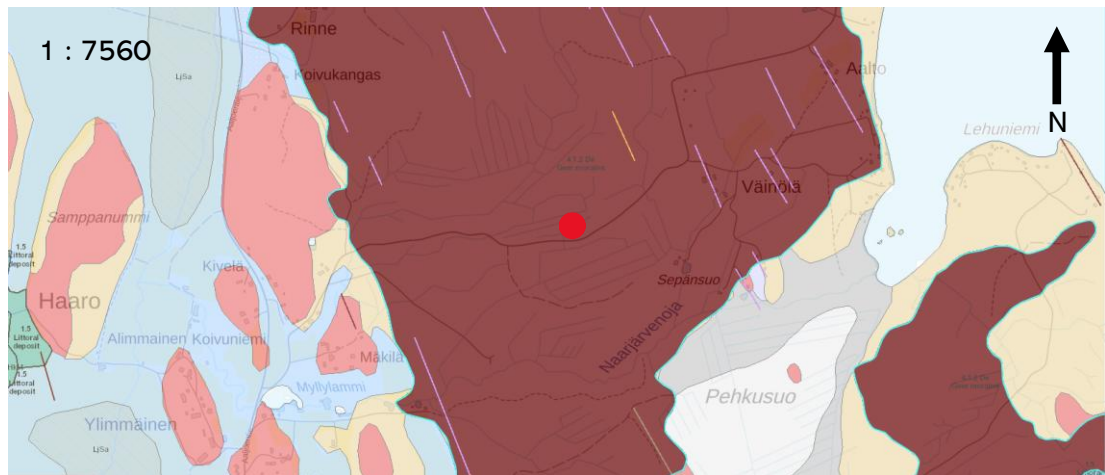


Figure 10. Glacialic formations. The large red area seen in the pictures is of the De Geer moraine area. Lines (purple, orange) are glacial lineations. Red dot signifies study area. Maankamara / GTK.

The study area is encompassed by a large De Geer moraine field, with glacial lineations oriented in the NW-SE direction below the DGMs, consistent with the ice flow direction. The ground cover consists largely of sandy moraine. The morpho-lithogenic unit of the De Geer moraines is a diamicton dominated, sandy end moraine. UT1 and UT2 are “framed” by Carex peat, which rests between the moraine ridge formations. In addition to these, silt and peat are present. Exposed bedrock occurs occasionally, though none is found immediately in the Uimarannantie area. The superficial deposits of the study area consists largely of sandy moraines, with small areas containing peat.

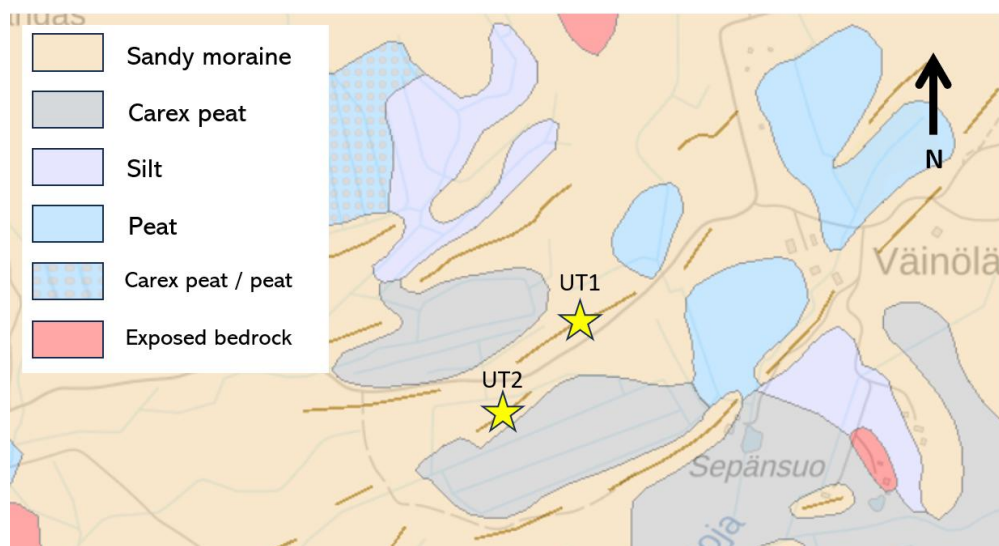


Figure 11. Superficial deposits of the study area. Maankamara /GTK.

## 4.2. DGM at Uimarannantie

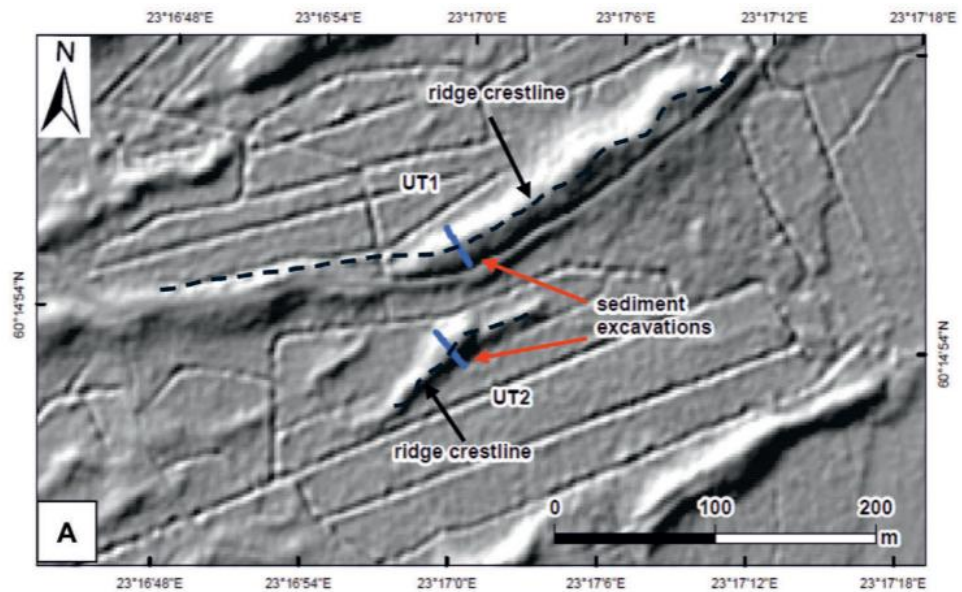


Figure 12. Locations of excavations at Uimarannantie. Rivers et al. 2024.



Figure 13. Oblique aerial photo of study site, facing southwest. Rivers et al. 2024.

The study area consisted of two ridges, UT1 and UT2. UT1 was the primary target of study. Most obvious differences were size and shape, with UT1 being longer and having a distinctly steeper proximal side. UT2 was more symmetrical and there wasn't an obvious dip direction.



*Figure 14. Cross section of moraine wall UT1. To the left of the picture is the proximal side of the formation, distal side is to the right.*



*Figure 15. Distal side of the UT1 moraine formation.*



*Figure 16. Mosaic image of UT1. Proximal side on the left, distal side on the right.*

The De Geer moraine ridge under study is UT1, located adjacent to the Uimarannantie road. The study site is situated within a DGM cluster, that extends approximately 2,4 km W-E and 9 km N-S.

The UT1 DGM ridge is approximately 485 metres long, 2 metres high and 40 metres wide (Rivers et al. 2024), with the length of the continuous moraine wall measuring around 1,4 kilometres. The minor ridge south of UT1, UT2, is about 100 metres long and 25 metres wide. The typical moraine ridge in this cluster is about 200 metres long and 30 metres wide. The minor ridges in between the major DGMs are noticeably smaller, at about 50-100 metres long and 10-20 metres wide.

The minor ridges seem to follow a clearer diagonal NE-SW orientation, whereas the major formations run slightly more in the W-E direction. On a larger scale, the major DGMs form distinct moraine walls, which are easily observable on a hill-shaded map, such as the one available via Paikkatietoikkuna.

## 5 Methodology

### 5.1. Field day and sample collecting

The observation day was a hot summer day, with temperatures approaching 30°C. As a result, the observable ridges were sufficiently dry for sampling and note-taking. Field conditions were significantly easier than during the initial observation round in early spring.

Before heading to the field, we examined the site using remote sensing and mapping data, including LiDAR DEMs and Quaternary maps. Upon arrival, we conducted an initial walk-around of the site and ridges to gain a general understanding of the area. UT1 was the primary focus of the course, while UT2 was examined in more detail during the summer field day.

The lithofacies descriptions in this thesis follow *A Practical Guide to the Study of Glacial Sediments* (Benn and Evans, 2004). The focus was on structures and components found in the sediment. The facies were classified into units based on their notable features, contacts, and continuity (or lack thereof).

During the field day, UT1 was cleared using shovels and trowels. After removing most of the obstructing sand and dust, the structures and layers were examined, and their dimensions were measured. A cross-section of UT1 was then drawn based on these observations. Various field data were recorded, including:

- Clast orientations
- Layer descriptions
- Dip directions and material composition
- General area description
- Cross-section and log drawings
- Coordinates
- Grain size, colour, and moisture content

The macro-fabric orientation of clasts was measured using a geological compass on rocks sized 10–50 mm, with an axis ratio of at least 1,5:1 (or 2:1). The direction of their longest A-axis was recorded. A paleoflow plate, in conjunction with a geological compass, was used to measure orientation of fissility.

In total, 77 rock samples were collected from the ridge, and their rock type and roundness were determined on the field. No soil samples were taken until the second field visit in the summer. UT2 was only reviewed visually, with key observations noted. UT2 is described in detail by Rivers et al. (2024) (see figure 26 also). Field observations and samples were collected on 14 June 2023. The primary objectives of the fieldwork were:

- Observing the excavations
- Creating cross-sections and sedimentology logs
- Collecting till samples for grain size analysis of the ridges
- Photographing UT1 and UT2

Cross-sections were dug by excavators.



*Figure 17. Fissile structures from moraine formation UT1.*

Till samples were collected both from UT1 and UT2. Samples were scratched or dug from the wall of the De Geer moraines and put into plastic bags for storage. Around 1,5-2

kilograms of samples were collected from each unit, though some were easier to acquire than others. Some units were difficult to break up, while others had a soft and crumbly consistency. Samples were then marked by order of collection 1-17.

## 5.2. Grain-size analysis

The till samples collected during the field day were dried at 100°C for 12 hours. All samples were dried simultaneously. It is important to note that, due to scheduling issues, the samples remained in the drying cabinet for some time, meaning that it is not entirely impossible that some moisture may have been reintroduced into the samples through exposure to air. However, the samples were deemed adequately dry, and it was decided that they could proceed to sieving. No issues related to potential moisture reabsorption were observed at the start of the sieving process or during sieving itself.

The till samples from the moraine formations UT1 and UT2 were analysed using a vibratory sieve shaker, model Fritsch Analysette 3 Pro. The sieves used were according to the Udden-Wentworth scale and of the following mesh sizes: 63, 125, 250, 500, 1000, 2000, 4000, 8000, 16000, and 31500 micrometres, with an amplitude of 2,5 millimetres. The sieving duration ranged from 20 to 30 minutes, depending on the sample. The time required varied according to the sample quality: some samples had a smaller particle size, so to separate clumps of fine-grain till, a longer sieving time was applied.

Each sample was manually sieved, which resulted in some sample loss when pouring between containers. These losses were unavoidable, as the vacuum in the sieving unit pulls small particles (mainly dust, <63 micrometres) into it when pouring samples into the sieves. A loss of 5–10 g was measured for each sample, and this was noted during the analysis of each sample. Any potential anomalies in the samples will be addressed in the Results section.

## 6 Results

The UT1 trench was initially divided into three lithological units: lodgement till, diamicton, and topsoil. However, this classification was soon abandoned, as Unit 3 exhibited such a clear fissile structure that it was decided to define it as a separate lithological unit. The diamicton was much more homogenous. The following classification is used:

**Unit 1** lodgement till (Dmm)

**Unit 2** diamicton (Dmm)

**Unit 3** laminated / fissile structure (Sld/Dms)

**Unit 4** diamicton (Sm/Gm)

Table 1. De Geer moraine ridge excavation, grain-size samples from UT1, Uimarannatie, Haaro, Perniö, 14.6.2023

Sample ID	position (m)	height (m)	Unit	Unit description	Other
UT1_2023_GS1	6,2	1,4	Unit 4	Loose beach deposit	
UT1_2023_GS2	5,5	0,3	Unit 2	Clay capture/stripe	
UT1_2023_GS3	9,9	0,6	Unit 2	Weakly stratified diamicton	
UT1_2023_GS4	10,5	1,6	Unit 3	Fissile diamicton	
UT1_2023_GS5	14,2	0,6	Unit 2	Weakly stratified diamicton	
UT1_2023_GS6	16,7	1,5	Unit 3	Fissile diamicton	
UT1_2023_GS7	17,6	1,8	Unit 4	Loose beach deposit	
UT1_2023_GS8	22,3	0,4	Unit 2	Homogenous diamicton	
UT1_2023_GS9	21,1	0,1	Unit 1/2	sand	Thin layer between Unit 1 and 2
UT1_2023_GS10	26	0,4	Unit 2	diamicton	very compact; log
UT1_2023_GS11	26	1	Unit 4	Loose beach deposit	log

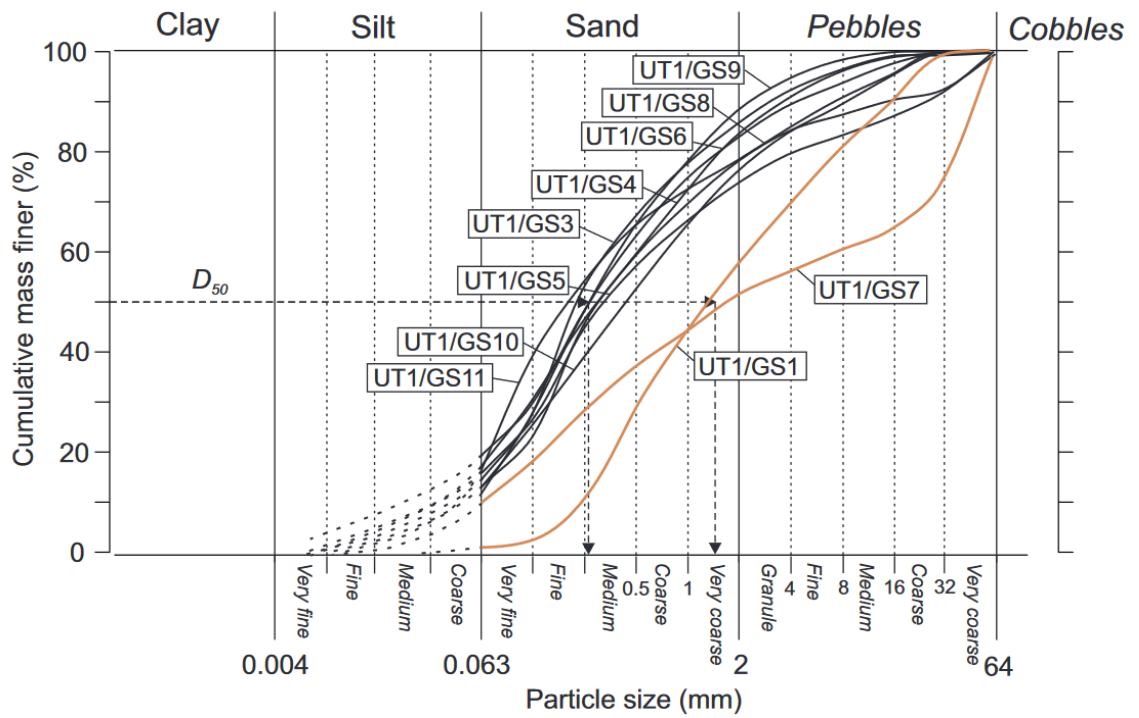


Figure 18. UT1 grain size curves. Rivers et al. 2024. Diamicton curves shown as black; sand/gravel as orange

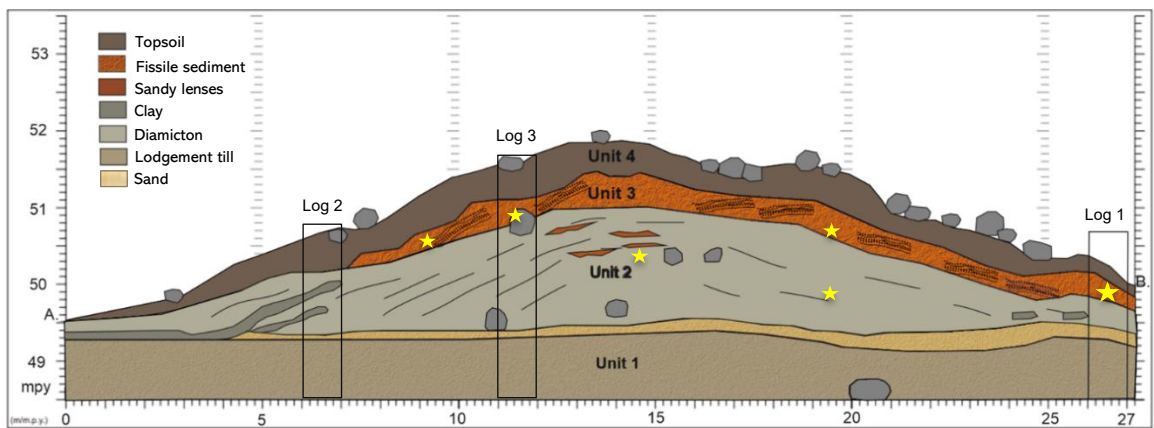


Figure 19. Cross section of UT1. Grey irregular rounded shapes are boulders. Stacked lines in Unit 3 are fissile structures. Lines in Unit 2 are shear structures that were more distinct in the proximal side. Yellow stars imply positions where clast orientations were calculated from (see Figure 23).

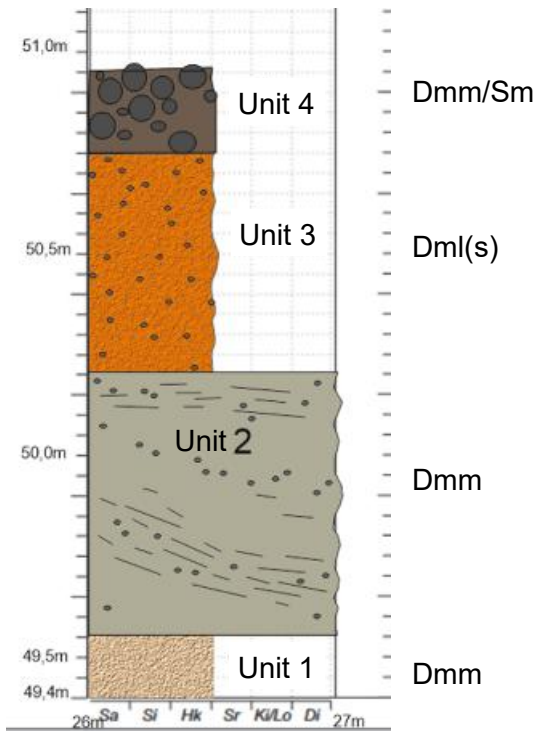


Figure 20. Log 1 from 26 metres & photograph from field

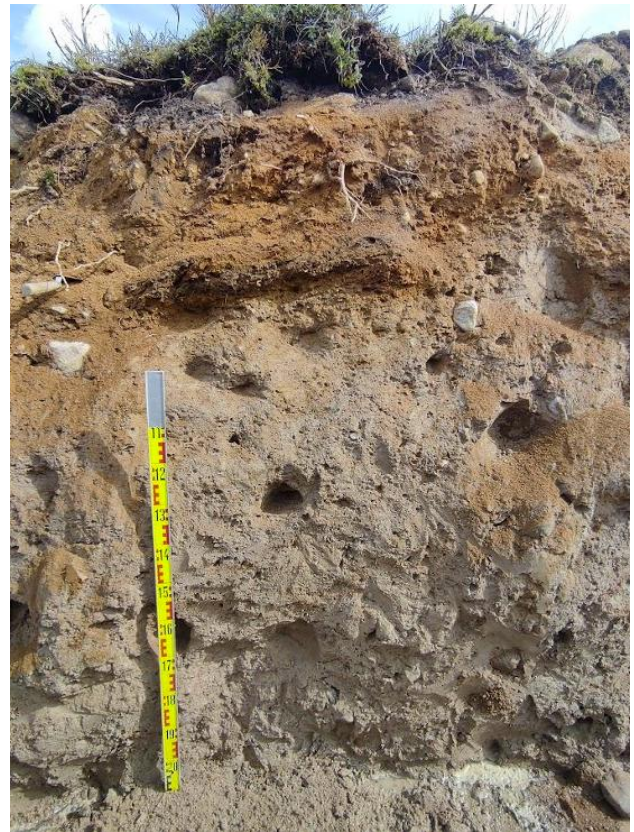
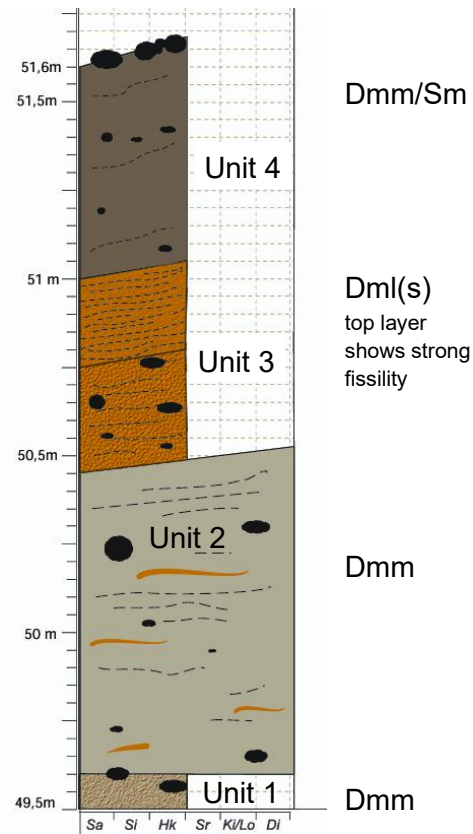


Figure 21. Log 2 at 9 metre mark on the left. Image from the field on the right.

The profile and log in Figure 20 are from UT1 at 9 metres. The log was taken from near the apex of the moraine structure and resembles the first log. However, since this log is from the proximal side, the layers are thicker, and the entire log is taller than Log 1. The cross-section at this 9-metre mark is 0,7 metres taller than Log 1, with the most noticeable difference being the significantly thicker diamicton (uppermost layer). This variation is partially due to differences in how the course attendants chose to separate the layers. For simplicity, interpretations have been left unchanged. Additionally, in this log, Unit 3 has been partially divided, as the upper part of the unit at this point exhibits a much stronger fissile structure compared to Log 1. Unit 2 in this log also differs slightly, with distinct sandy lenses present.

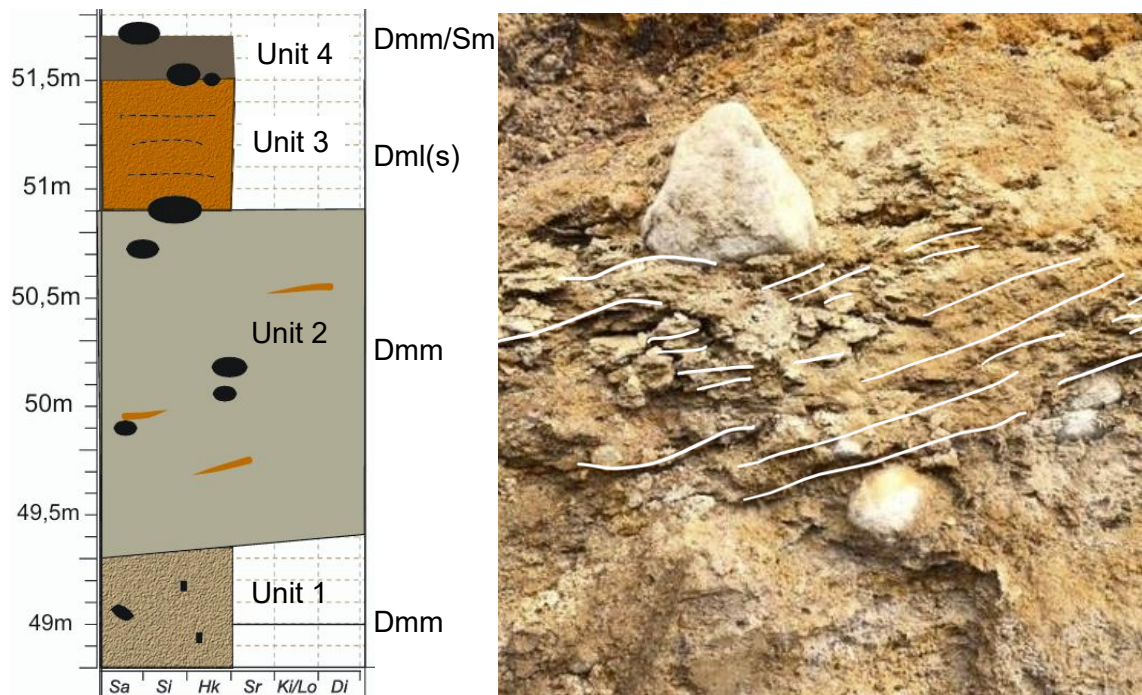


Figure 22. Log 3 from 11 m. Fissile structures on the right.

The third log was observed at the 11-metre point, right next to the apex of the ridge. The units visible in this log are similar to those in Log 1. Notable differences include the sandy lenses present in Unit 2, similar to Log 2, and the fact that Unit 1 is twice as thick as that in Log 1. In Unit 3, fissile structures are present, from which the layering and sedimentation can be observed. On the proximal side, there is a roughly 7 metre long and 10-centimetre-thick layer of clay, which can also be observed in the profile of the moraine structure (Figure 19).

Table 2. Unit descriptions

Unit	Lithofacies	Superficial deposits (GEO)	Size	Density	Stoniness	Roundness
Unit 4	Dmm/Sm	gravelly sand/sand moraine	1	2	3	3
Unit 3	Dml	sand/sand moraine	2	4	2	3
Unit 2	Dmm	sandy silt moraine	2	4	2	2
Unit 1	Dmm	silt moraine	4	4	-	-

Unit	% of rocks in unit	Rock max/ave (cm)	Texture	Structure	Contact
Unit 4	15	40/20 cm	matrix-supported	massive	gradational
Unit 3	5	40/6 cm	matrix-sp.	sheared	gradational /sharp
Unit 2	10	40/6 cm	matrix-sp.	massive	gradational
Unit 1	-	90/ - cm	matrix.sp	massive	gradational

Unit 1 consists mainly of silty diamicton and its lithofacies is matrix-supported. Unit 1 had the highest moisture content of all the layers due to the groundwater. The consistency was very dense. Stoniness, roundness and rock content wasn't measured on field, because the trench wasn't deep enough for any meaningful measurements to be made. The largest singular rock was 90 cm across, which was in the distal side at 20–21 m. We were unable to determine average rock size. Grain-size in Unit 1 was silt moraine and texture matrix-supported, as was with other layers. The contact was gradational.

Unit 2 had a lithofacies of matrix-supported sandy silt diamicton. It was not as humid as Unit 1, because the groundwater hadn't affected the layers further up. The density was packed. Stoniness was a low content, roundness also subangular and rock content 10 %. Largest rock was 40 cm across, and average size was 6 cm across. Matrix grain size was silt/medium coarse sand, so rougher than Unit 1. The unit also had some very dense points and reddish-brown sandy points (Figure 23), which have been noted in the cross section.

Unit 3 had a lithofacies of matrix-supported, laminated sandy diamicton. Moisture, density and stoniness were the same as those of Unit 2. Roundness was subrounded, rock content 5 % and the largest clast was 40 cm across, with an average size of 6 cm. Diamicton was sandy, with dominating grain size being sandy. The most notable features were the lamination in the unit, which had an upwards directionality towards the ridge. In Unit 3 there were some more pronounced layers, which separates it from the other Units.

Unit 4 had a lithofacies of matrix-supported massive gravelly, sandy diamicton. There was little to no moisture and the structure was noticeably looser. Roundness was subrounded and stoniness 15 %. Largest measured rock was 40 cm and on average they were 20 cm across, so much larger than in other layers. The diamicton matrix grain size was classified as sand. There were spots in the unit that looked like ash, which could indicate a forest fire at some point in time.

Noticeably, the grain size grew going up the structure. In Figures 20 and 21 with the log and picture, one can observe colour differences in the units. The lowest unit was a light sandy colour, after which the colour becomes duller and greyer in Unit 2 and Unit 3. Unit 3 is greyish and partially a reddish brown. Unit 4 is a darker tone, with the lower point looking more red due to probable iron oxidation. In the Unit 3 from the log, the lamination wasn't easily observable. Unit 1 in the log is well sorted, Unit 2 weakly sorted, Unit 3 moderately sorted and Unit 4 very weakly sorted. In general, the structures observed in the log drawing followed the rest of the structure consistently.

During the field trip in spring of 2023, we took clast orientation measurements from the point of our log 1, which is at the 26 to 27 metre mark. The results have been presented in Table 3 and in Figure 24. It was our goal to take measurements from Unit 3 of the log, since Unit 3 had clear lamination in the sediment. The fact that the distal side was not as rocky as the proximal side did make the calculations slightly more difficult, since finding appropriate rocks wasn't easy. The texture of the diamicton was also very tightly packed, which made breaking apart the rocks more difficult.



Figure 23. Red sandy lenses in Unit 2 at UT1 trench at 25 metres, height 49 m

Table 3. Rock orientation: slope direction and slope, from 25-26m/49 m height at UT1

210/10	280/20	300/00	305/10	310/00	310/05	315/00	320/15	320/00	335/05
230/05	285/10	300/10	305/20	310/00	315/25	315/05	320/20	325/15	335/10
240/05	290/05	300/10	305/05	310/05	315/10	315/00	320/15	330/30	340/15
240/20	295/10	300/15	310/20	310/25	315/10	315/15	320/05	330/20	340/20
280/05	295/10	300/00	310/00	310/15	315/20	320/20	320/15	330/15	340/20

Table 4. Rock quantity by count and percentage

Rock type	TOT	%
Biotite-paragneiss	20	26
Sandstone	4	5
Quartz biotite	1	1
Granite	51	66
Quartz diorite	1	1

A grand total of 77 rock samples were collected from UT1 at 25 to 26 metres, from which the rock type and the general roundness of the rocks was deciphered. The rock types and quantities can be observed in Table 4. The rocks were mostly subangular, and minority were subrounded. The roundness indicates that the rocks have somewhat abraded under the ice sheet but haven't been completely rounded. The dominant rock type granite is well represented in the samples. The other prominent rock types – biotite-paragneiss and sandstone – are present approximately 3 km south of the study site.

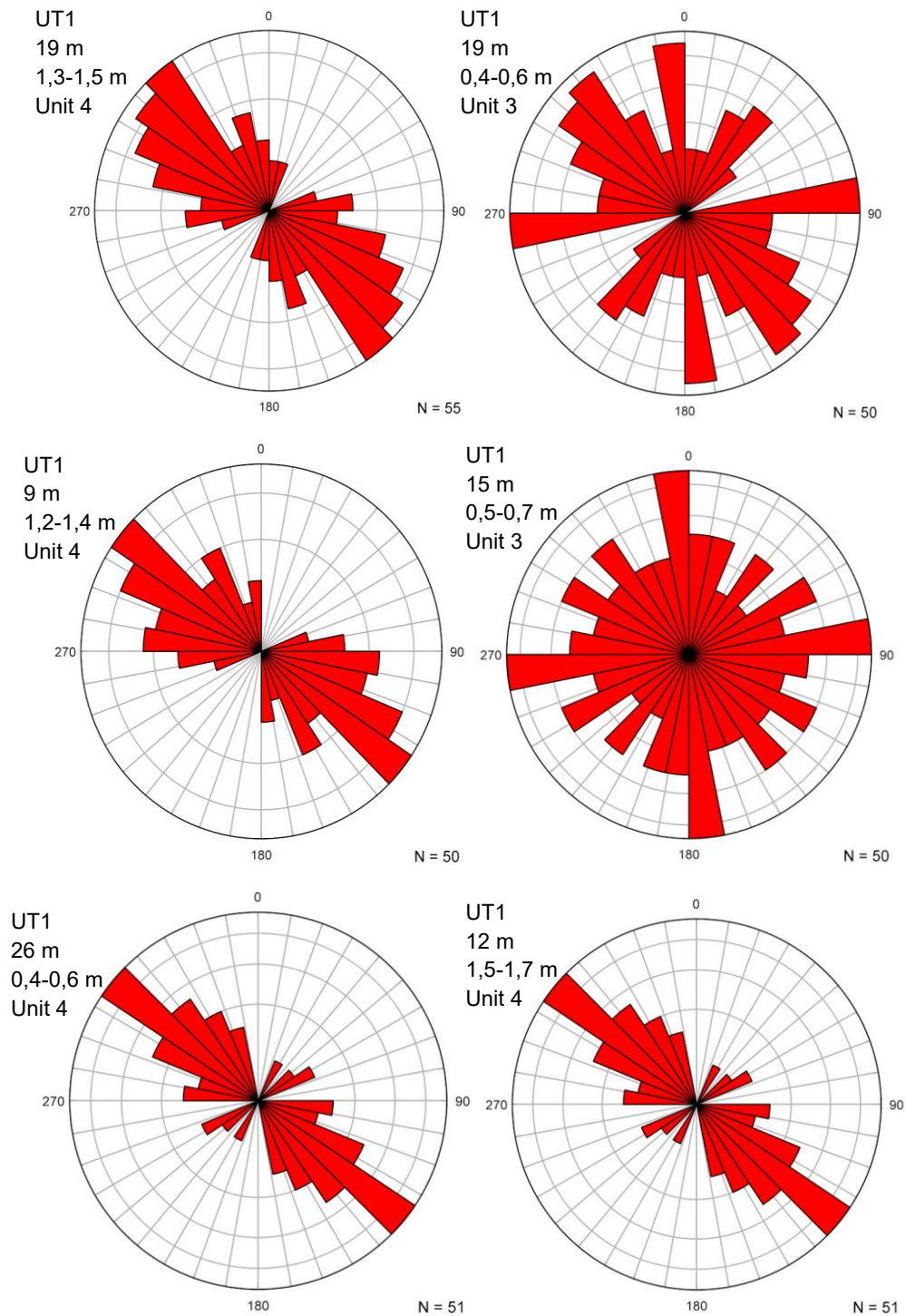


Figure 24. Orientation of rocks as rose diagrams.

The rocks' orientation in Unit 2 followed the glacial flow and ridge. The rocks in the diamicton were mainly in a NW-SE direction. The dip direction was 280-340 degrees and conformed to the ridge's distal side's slope. Other groups from the field course took measurements from Units 2 and 3, and there were clear similarities in orientation in Unit 3 between all observations. Unit 3 had no distinct orientation, which likely indicates a

stronger mixing of the material, inhibiting the rocks from settling into the sediment in a particular direction. The rocks in Unit 3 have been layered on top of the Unit 2, allowing them to form a clear directionality according to the overflow/thrust of the glacier's movement.

The clasts found in the ridge resemble the bedrock of the surrounding area (Figure 7 and Table 3), with biotite-paragneiss (26 %) and granite (66 %) being the most common types. The study area is dominated by the Perniö granite, with other undefined granites and granitoids present in the surrounding bedrock. Biotite paragneiss is not present in the study area, but is found to the north (see Figure 25), which explains its presence in the ridge.

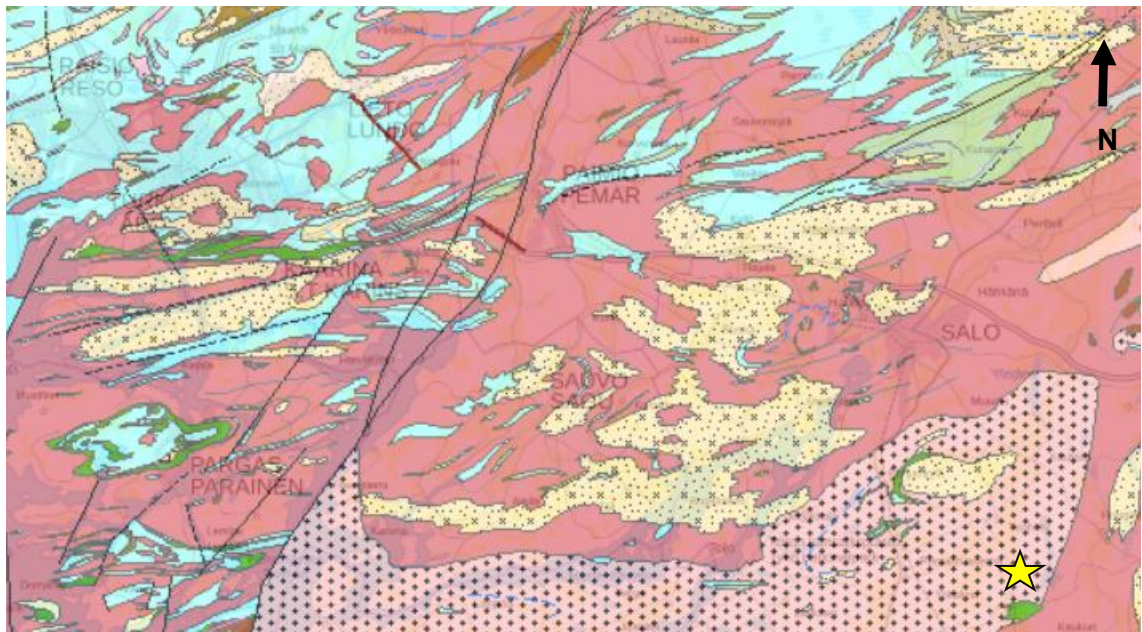


Figure 25. Study area noted by star. Turquoise areas are biotite-paragneiss. Maankamara / GTK.

In the UT1 ridge a notable structure is the lamination in Unit 3, which is formed due to friction. The lamination has been preserved well in the proximal side, from the flow direction of the glacier. The motion of the glacier and the sediment it has piled up has helped preserve the structure. There was no sorted sediment around the largest rocks/boulders, and they were stuck to the mass. The diamicton in general was very densely packed excluding the diamicton. Unit 2 contained very dense sandy lenses, which were pushed against the lamination structure. This is probably due to them having been frozen and getting picked up from the bed diamicton, which indicates that their original

position was at the bottom. On the proximal side there are overthrusts of clay that weren't there originally, but were pushed there by the ice, to their current position. The different layers of clay were separated by sandy layers. The large boulders were most likely pushed to the distal side.

UT2 is described by Rivers et al. (2024) in detail, thus it will not be expanded on here. However, understanding it is important, so it will be discussed. UT2 had a much stronger lamination structure with an abundance of large rocks and boulders and a generally more bowed shape. UT2 was slightly differently oriented, which can be seen in the hillshade elevation model (image 12). The distal side had defined littoral deposits and glacial sands under the diamicton, which transformed into a sandier texture towards the distal side. The formation had a sandy core in the middle, which can be due to a formation origin in a crevasse. The proximal side had no clay thrust, so the last push of the glacier observable in the UT1 formation is missing.

## 7 Discussion

As it has been previously noted, due to structural features, it is possible that the De Geer moraines observed are annual moraines. There are certain points raised by different researchers which I want to highlight to back up my results.

One of the most prominent proponents of the theory that De Geer moraines in Finland are not annual moraines, but something else, is Harry Zilliacus. He bases his theories mainly on external structure, morphometry and petrography of the moraines. Also, we must take into consideration that his text is made in 1987, before modern ranged technologies, such as ground penetrating radar (GPR) used by Rivers et al. (2024). His text also surprisingly lacks any significant portion on sedimentology, which is a crucial part of this thesis and looks closely into the physical characteristics related to the formation processes.

In his paper *Genesis of De Geer moraines in Finland* (1989), Zilliacus points out that in his field observations of the Hyvinkää ridges, there were “no finer lenses or any other conspicuous structural features – Thus, there are no signs of pushing by the ice.” This contrasts with the observations we made in the field in Perniö. Sandy lenses, lineations and the clay in the proximal side were observed, as notified in figures 19 to 22. Zilliacus also makes the argument in the same paper, that pebble orientations haven’t happened at random (upward directionality in the proximal side and downward directionality in the distal side), which would indicate that the formations couldn’t have been end moraines formed in thrust zones. I do not see how this could indicate in all certainty that the moraines are formed in basal crevasses. The pebbles in UT1 are positioned to the direction of the moraine formation, parallel to ice movement (see Figure 24).

As mentioned in earlier chapters, Zilliacus argues that DGMs have no geochronological value based on older varve chronology. There are clues in the terrain that give indications of the DGMs being annually formed. If you suppose that the Salpausselkä ridges have formed roughly 200 years apart, meaning that Salpausselkä II formed around 200 years before Salpausselkä III, the approximately 30 km separating the formations gives an average annual melting rate of roughly 150 years, which is consistent with the interdistances measured (see Figure 7 A, B and C). Considering that this is a simplistic

calculation based on Paikkatietoikkuna's hillshade image and the fact that the number is based on an average, these distances coincide with the calculated melting rate based on age of the Salpausselkäs.

Zilliacus also states that there are no signs of any DGMs forming interannually. However, Rivers et al. (2024) suggests no evidence of crevasse infilling as a DGM formation mechanism, but rather formation based on seasonal deposition stage, indicating annual deposition. The variations are subcategorized as "Summer calving retreat" (Fig. 27, A/B) and "Winter and Spring push advance" (Fig 27, C/D). During the summer subglacial sediments are deposited at the grounding line via subglacial meltwater or extrusion. During ice margin calving, the deposited sediments are preserved. The margin may remain stationary or advance. The amount of depositional material will likely be less than during winter, resulting in smaller ridges, and this entire process is likely to be repeated over the course of a summer or during early autumn. This would result in a series of intermediate DGM ridges such as UT2 (Rivers et al. 2023). Winter advances would, on the other hand, while depositing material similarly to during the summer retreat, also deposit additional material at the grounding line by bulldozing and deforming existing material (Unit 3a/3b in Rivers et al. [2024] cross-section, Unit 2 in Fig. 19). This would result in a larger, more uniform ridge once per season. Due to the possibility of differing processes linked to DGMs, the term "De Geer terrain" (DGT) is suggested by the author to refer to these formations, where "different interseasonal ridge forming processes may occur within the same environment" (Rivers et al. 2024, pp. 20). Based on this information, UT2 could be assumed to be a DGM with a summertime origin via calving, while UT1 has a terminal wintertime origin.

Lastly, he states they are not end moraines, as there are "no signs of pushing", considering DGMs to be closer to Rogen moraines in formation type. UT1 has multiple properties that indicate that it is an end moraine, mainly the homogenous nature of the stratigraphic units when compared to UT2, which has large boulders that break up the units. The orientation of the rocks is consistent with the flow direction of the ice. The distinct steeper proximal side with upwards fissility combined with the more gently sloped distal side with downhill fissility are strong indicators of it being a terminal moraine (see figure 26).

Zilliacus argued (1987) that there are no findings that support an annual formation model. However, Rivers et al. (2024) has proposed a model that strongly suggests that DGMs form annually. Largely it is accepted that they are formed at the grounding line of ice margin (e.g. Blake, 2000; Bouvier et al. 2015; Rivers et al. 2023) and multiple suggestions point to a ridge formation during winter re-advances and summer retreats (e.g. Rivers et al. 2024; Blake 2000; Lindén and Möller 2005; Bouvier et al. 2015). In the Rivers et al. (2024) study they aim to provide a comparative field investigation of the internal structure of winter and summer DGMs within the same environment.

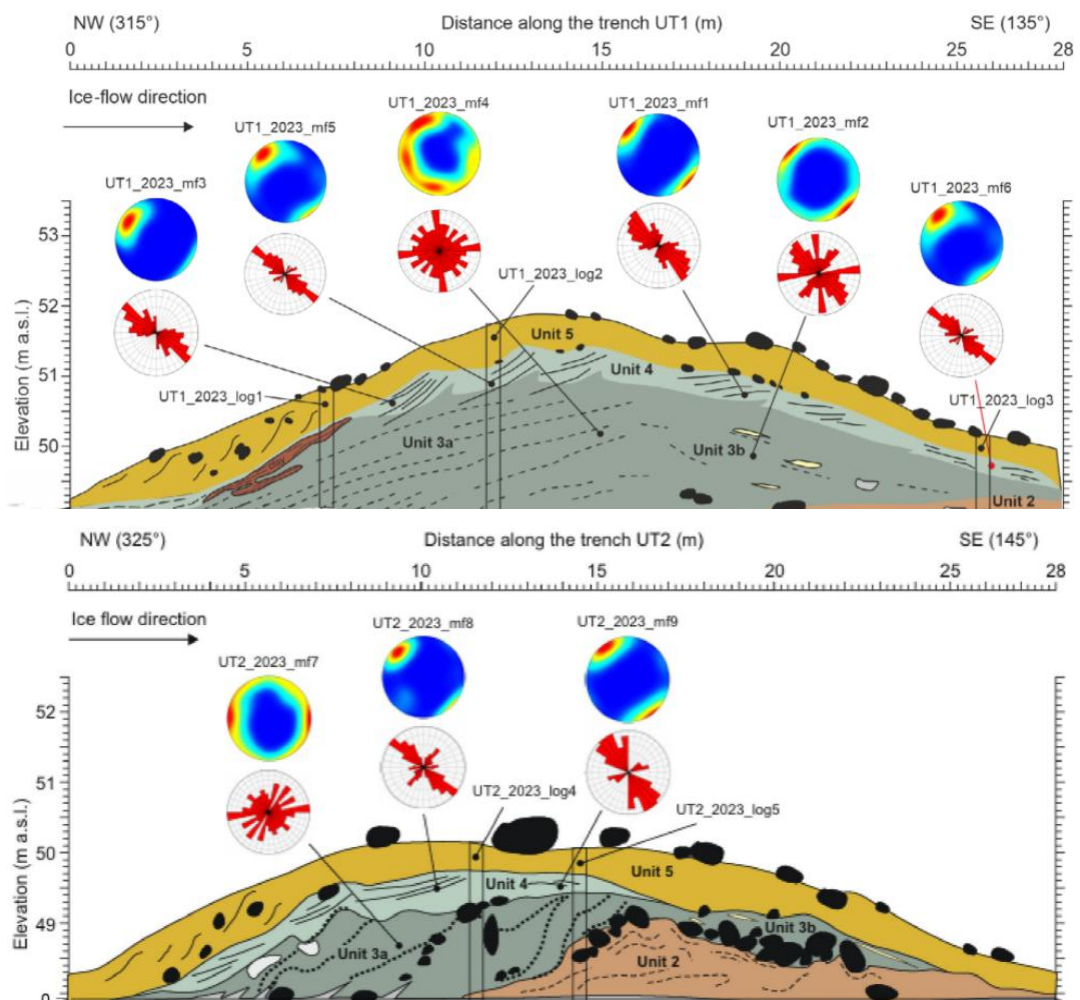


Figure 26. Cross sections of UT1 and UT2 by Rivers (Rivers et al. 2024).

Since DGMs are found near the Salpausselkäs, and Salpausselkäs formed during the major standstill events (Ojala, 2016; Lunkka et al. 2021 p. 11), it is feasible that DGMs have formed during similar environmental conditions. It is suspected that Southwestern Finland has a thicker overlying pre-LGM sediment overburden compared to the Finnish

Lake District Ice Lobe (Nenonen, 1995 as per Lunkka et al, 2021, pp. 11), which could indicate why the conditions are suitable for the formation of DGMs. BSIL probably also deglaciated slower than LDIL due to active ice streaming (Lunkka et al, 2021).

Comparisons between newer studies including sedimentology of these De Geer moraines and the sedimentology of this thesis indicate common features, that could be alluded to the annual moraine theory. Studies that support the annual model have similar sedimentological features including deforming diamictons, in-fill sediments and gravity flow deposits (Lindén and Möller, 2005).

UT2 was likely a sandy ridge with loose gravel on top, over which ice has pushed over and thus piled the large boulders on the distal side as the pushing force decreased. In UT2 the lineations are likely tied to the different phases of the glacier's thrust. The fissile structures in UT1 and UT2 framed larger stones, where they had been well preserved. They have been pushed upwards towards the ridge and a "jerking" movement can be deciphered in the structure. The fissile structures are more distinct up towards the ridge and indicate mechanical abrasion from the ice. There was no such distinct structure at the bottom of either formation.

From the structure of the entire ridge, we can decipher the different phases of UT1's genesis. Unit 1 has likely been formed from the material that has been brought in by meltwater and ice during the calving process. This would have taken place during late summer. Unit 2 has likely formed during early winter, as the ice had stabilized. The orientation of the diamicton is due to the thrust of the ice sheet, due to which there is a lineation pattern in the proximal side. Unit 3 has been likely formed by the overthrust of the ice sheet at the end of the winter, during which the lineations and rocks have aligned according to the orientation of the ridge. Unit 4 has formed last as the melting has layered the remaining material on top of Unit 3 as weather warmed, gaining its final form from the plants and ash covering it today.

The internal structure observed in the study ridge UT1 shows the typical features notified as proof of annual formation origin at or near the grounding line. There are sandy lenses, a lamellar structure, boulders down the distal side (as suggested by Blake [2000] to be unlikely in the scenario of a crevasse infill genesis) and morphology that supports the

assumption that the ridge formed at the glacier's edge during a standstill. These can be interpreted to be signs that the till in the DGM ridges is basal melt-out till (Blake, 2000). The large clay deposit on the proximal side of ridge UT1 (Figure 19) is perhaps the clearest indication of wintertime deposition, since its most likely formation environment is during winter, with deformation indicating the ice sheet's movement (grounding line readvancement.)

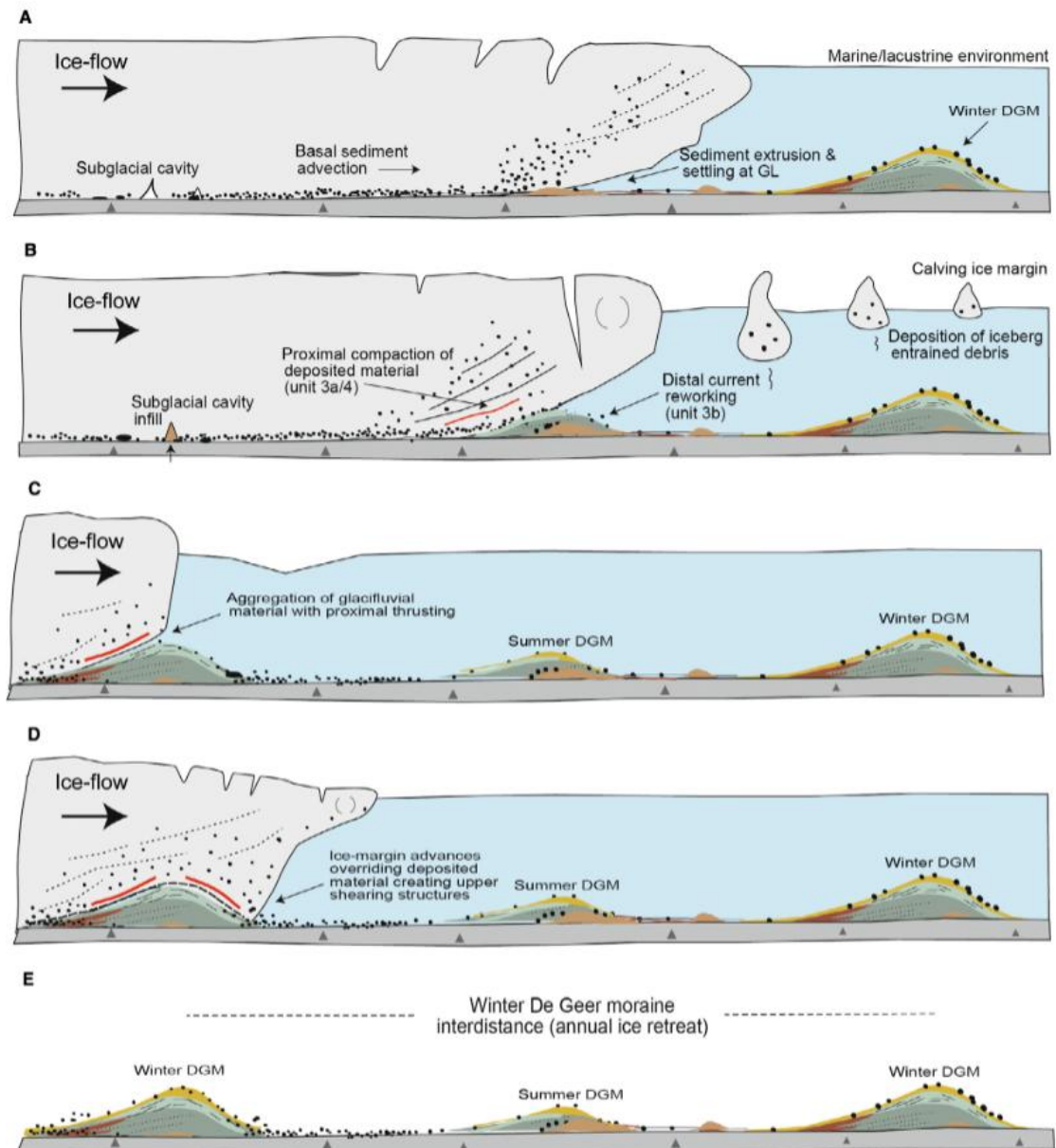


Figure 27. Proposed conceptual model for formation of De Geer moraines. Rivers et al. 2024.

Based on the literature, the study of Uimarannantie and newer research such as that by Rivers et al. (2024), it can be said that De Geer moraines are annual marginal moraine

formations with distinct winter ridges, such as UT1, and smaller intermediate summer ridges, such as UT2. The sedimentology, morphology, granulometry and other study methods used in this thesis support the hypothesis of an annual formation model and based on the internal structure it can be assumed that the formation is specifically at the margin and not in crevasse as claimed by some (e.g. Zilliacus 1987, Hoppe 1959).

Local topography also could affect how these ridges form, as in low lying areas they are more distinct than in areas with less ground cover (Figure 6 and 7). The ridges would thus form in areas with deeper proglacial waters, than in areas with insufficient cover, such as those at above 60 metres a.s.l in the study area (Figure 6). This could explain why distinct ridges occur only in certain areas.

Here is an outline of the process, using Figure 27 and the article by Rivers et al. as support:

- Summer calving retreat (A/B). Subglacial sediments are deposited at the grounding line via subglacial meltwater and extrusion during late summer or early autumn. Overriding ice may compact the accumulated sediment. The ice margin goes through calving and the grounding line retreats, preserving the deposited sediment. The process exerts multiple forces on the grounding line, causing smaller ridges that aren't as defined as the winter push ridge. This causes possibly multiple intermediary ridges, such as UT2.
- Winter and spring push advance (C/D). In late autumn and early winter, the ice margin has retreated to winter position, and glacial material has aggregated at the grounding line. The ice margin re-advances, bulldozing the material at grounding line and deforming pre-existing material, like observable in Figure 19 with the layer of clay. This process would cause one ridge such as UT1, termed a prominent DGM, to form per winter/spring season. The process, however, is more closely affected by factors such as ice-moraine contact and water depth.
- DGM interdistance (E). Winter DGMs, the major ridges, indicate annual retreat rate, while smaller summer DGMs are irregularly forming. These ridges form the De Geer terrain.

These formation processes would explain the difference between UT1 and UT2 (see Rivers et al. 2024 for description) and possible confusion about the genesis. The

formation is neither strict nor generic but tied to seasonal environmental factors, leading to some differences between ridges. Thus, Rivers et al. suggest the term DGT, De Geer Terrain, to be used to describe the moraine fields.

## 8 Conclusions

De Geer moraines are marginal moraine ridges formed during the Weichselian glaciation that follow the direction of the ice margin. They consist of layers of lodgement till, sandy diamicton, sandy lenses, fissile structures and rocks oriented to the direction of ice flow. They typically have a steeper proximal side with an elongated distal side. There is shearing and sandy lenses that are consistent signs of deglaciation. The general orientation of these structures is consistent with the flow and direction of the ice sheet.

Based on studies by Ojala (2016), Ojala et al. (e.g. 2015, 2021) and Rivers et al. (2023, 2024), in the light of modern study methods, one can reasonably assume De Geer moraines to be annually forming marginal ridge formations. Due to the varied formation processes observable in a singular area, the term De Geer Terrain was suggested by Rivers et al. (2024) to be more accurate in describing the formations at large. Regardless, DGMs observed in the thesis study area, when compared to older studies such as those by Zilliacus (e.g. 1987, 1989), would seem to be more comparable to those forming annually due to seasonal changes rather than temporally at random, such as in subglacial crevasses.

Based on this thesis De Geer moraines are, as speculated by Gerard De Geer, annually forming. This assumption cannot be made based on geomorphology alone, but combining this with facies analysis, sedimentology, the deglaciation history of the area and distances measured, there is evidence that can be associated with an annual model above others.

More studies are required to investigate whether DGMs/DGT can be used to determine ice margin retreat rates and reconstruct a temporally accurate ice-marginal model.

## Notes

1. During the sieving process, one sample was mistakenly poured into the sieving unit before weighing. Because of this, the sample had to be poured out and weighed again, before pouring back in. This might have reduced the sample's weight by some grams (marginal effect on results, <5 %) due to the smallest used grain-size in the sievette being dust-like (measured in microns).
2. Stratigraphic unit names in this thesis differ from those by Rivers in Rivers et al. (2024). This is due to stratigraphy in this thesis being done mainly visually on field. Rivers et al. (2024) includes GPR data, through which the bedrock can be observed. Unit 1 in the study is described as either bouldery diamicton or fractured bedrock.
3. ChatGPT was utilized to check for grammar mistakes after the final edits had been made.

## Acknowledgements

Thank you to Antti Ojala and Joni Mäkinen for their supervision and support during the making of my thesis. Thank you to the other attendees in the 2023 field course, whose insights were very informative. Thank you to Rivers et al. whose results gave important information for this thesis. Finally, thanks are also warranted to my course mates circa 2019, "Moose".

## References:

Ahokangas, E. (2019). New insights into the sedimentological-geophysical research of interlobate glaciofluvial complexes in western Finland. University of Finland, Department of Geography and Geology.

Blake, K. P. (2000). Common origin for De Geer moraines of variable composition in Raudvassdalen, northern Norway. *J. Quaternary Sci.*, Vol. 15, pp. 633–644. ISSN 0267-8179.

Boulton, G.S., Meer, J.J.M. van der, Beets, D.J., Hart, J.K., Ruegg, G.G.J. (1999): The sedimentary and structural evolution of a recent push moraine complex: Holmströmbreen, Spitsbergen. *Quaternary Science Reviews*, 18, 339-371. ISBN 0277-3971/9

Bouvier, V, Johnson, M.D., & Pässe, T. (2015): Distribution, genesis and annual-origin of De Geer moraines in Sweden: insights revealed by LiDAR. *GFF*, DOI:10.1080/11035897.2015.1089933

Breilin, O., Kotilainen, A., Nenonen, K., & Räsänen, M., (2005). The unique moraine morphology, stratotypes and ongoing geological processes at the Kvarken Archipelago on the land uplift area in the Western coast of Finland. *Geological Survey of Finland, Special Paper 40*, pp. 97–111

De Geer, G. (1889). Ändmoräner I trakten mellan Spånga och Sundbyberg. *Geologiska Föreningens i Stockholm Förhandlingar 11*, 395–397

Donner, J. (2010). The Younger Dryas age of the Salpausselkä moraines in Finland. *Bulletin of the Geological Society of Finland*, Vol. 82, pp. 69–80

Evans, D. J. A. (2013) Moraine Forms and Genesis. In *Encyclopedia of Quaternary Science*, Elias, S. A. and Mock, C. J. (ed) Second Edition, Elsevier, pp. 769-779 <https://doi.org/10.1016/B978-0-444-53643-3.00073-X>

Hoppe, G. (1959): Glacial Morphology and Inland Ice Recession in Northern Sweden *Geografiska annaler, 1959-01, Vol.41 (4)*, pp. 193-212

Lindén, M. and Möller, P. (2005). Marginal formation of De Geer moraines and their implications to the dynamics of grounding-line recession. *J. Quaternary Sci., Vol. 20* pp. 113–133. ISSN 0267-8179.

Lunkka, J. P., Palmu, J.-P. & Seppänen, A. (2021 April): Deglaciation dynamics of the Scandinavian Ice Sheet in the Salpausselkä zone, southern Finland. *Boreas, Vol. 50*, pp. 404–418. <https://doi.org/10.1111/bor.12502>. ISSN0300-9483.

Ojala, A. E. K., Palmu, J.-P., Åberg, A., Åberg S. & Virkki H. (2013). Development of an ancient shoreline database to reconstruct the Litorina Sea maximum extension and the highest shoreline of the Baltic Sea basin in Finland. *Bulletin of the Geological Society of Finland*, Vol. 85, 2013, pp. 127–144

Ojala, A. E. K., Putkinen, N., Palmu, J.-P. & Nenonen, K. (2015) Characterization of De Geer moraines in Finland based on LiDAR DEM mapping, *GFF, 137:4*, pp. 304-318, DOI:10.1080/11035897.2015.1050449

Ojala, A. E. K. (2016): Appearance of De Geer moraines in southern and western Finland — Implications for reconstructing glacier retreat dynamics, *Geomorphology 255*, pp. 16–25

Ojala, A. E. K., Mäkinen, J., Ahokangas, E., Kajuutti, K., Valkama, M., Tuunainen, A. & Palmu, J.-P. (2021) Diversity of murtoos and murtoo-related subglacial landforms in the Finnish area of the Fennoscandian Ice Sheet. *Boreas*. <https://doi.org/10.1111/bor.12526>. ISSN 0300-9483.

Palmu, J.-P., Ojala, A. E. K., Virtasalo, J., Putkinen, N., Kohonen, J. & Sarala, P. (2021). Classification system of Superficial (Quaternary) Geological Units in Finland. *Geological Survey of Finland, Bulletin 412*, pp. 115-169

Rivers, G. E., Storrar, R. D., Jones, A. H., Ojala, A.E.K. (2023): 3D morphometry of De Geer Moraines and Crevasse-Squeeze Ridges: Differentiating between pushing and squeezing mechanisms from remotely sensed data. *Quaternary science reviews*, 2023-12, Vol.321 108383.

Rivers, G. E., Storrar, R. D., Ojala, A. E. K., Mäkinen, J., Holmroos, C. & Holmes, N. (2024). De Geer moraine internal architecture based on sedimentological and geophysical investigations and implications for ice-marginal reconstructions. *Boreas*. <https://doi.org/10.1111/bor.12692>. ISSN 0300-9483.

Saarnisto, M. & Saarinen, T. (2001). Deglaciation chronology of the Scandinavian Ice Sheet from the Lake Onega Basin to the Salpausselka End Moraines. *Global and Planetary Change* 31, pp. 387–405.

Sauramo, M. (1923). Studies on the Quaternary varve sediment in southern Finland. *Fennia*, 44: 1-164.

Selonen, O., Ehlers, C. & Lindroos, A. (1996): Structural features and emplacement of the late Svecofennian Perniö granite sheet in southern Finland. *Bull. Geol. Soc. Finland* 68, Part 2, pp. 5-17.

Sinclair, S.N., Licciardi, J.M., Campbell, S.W., Madore, B.M. (2018). Character and origin of De Geer moraines in the Seacoast region of New Hampshire, USA. *Journal of quaternary science*, 2018-02, Vol.33 (2), pp. 225-237

Sollid, J.K., Carlsson, A.B. (1984). De Geer moraines and eskers in Pasvik, North Norway. In *Ten Years of Nordic Till Research*, Königsson L.K. (ed.). Striae 20: pp. 55–61.

Walker, M., Johnsen, S., Rasmussen, S. O., Popp, T., Steffensen, J.-P., Gibbard, P., Hoek, W., Lowe, J., Andrews, J., Björck, S., Cwynar, L. C., Hughen, K., Kershaw, P., Kromer, B., Litt, T., Lowe, D. J., Nakagawa, T., Newnham, R., and Schwander, J. (2009). Formal definition and dating of the GSSP (Global Stratotype Section and Point) for

the base of the Holocene using the Greenland NGRIP ice core, and selected auxiliary records. *J. Quaternary Sci.*, Vol. 24. pp. 3–17.

Zilliacus, H., (1987). De Geer moraines in Finland and the annual moraine problem *Fennia*, Vol.165 (2)

Zilliacus, H., (1989). Genesis of De Geer moraines in Finland. In: *J. Menzies and J. Rose (Editors), Subglacial Bedforms--Drumlins, Rogen Moraine and Associated Subglacial Bedforms. Sediment. Geol.*, 62: pp. 309-317.