Glacial morphology and dynamics with till geochemical exploration in the ribbed moraine area of Peräpohjola, Finnish Lapland

by

Pertti Sarala

ACADEMIC DISSERTATION

To be presented with the permission of the Faculty of Science of
the University of Oulu, for public criticism in the Auditorium GO 101,
Linnanmaa, on 14th October, 2005, at 12 o'clock noon

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Cover: Gravelly till with sandy layers in test pit M64 in the Sihtuuna village, Tervola. Photo by Pertti Sarala

Back: Sihtuuna moraine ridges in the Sihtuuna village, Tervola. Glacial flow has been from the west (left to right in photograph). Photo by Risto Aario

Pertti Sarala, 2005. Glacial morphology and dynamics with till geochemical exploration in the ribbed moraine area of Peräpohjola, Finnish Lapland. Geological Survey of Finland, Espoo. 17 pages with 6 original papers.

An aerial-photo and elevation model interpretation with detailed field surveys were used to study glacial morphology and stratigraphy in the Peräpohjola area, in southern Finnish Lapland. Test pit surveys with earlier and present till sampling were carried out in the seven test sites for investigating the glacial dispersal of elements and mineralized material in till. The results were presented in six papers dealing with the geochemical prospecting for Au, ribbed moraine formation and the glacial stratigraphy in the study area.

The till stratigraphy of the Peräpohjola area consists of three till beds, of which the oldest is an age of Saalian glaciation and the others of an age of the Weichselian glaciation. The glacial morphology depicts only two Weichselian glacial phases demonstrated by an assemblage of active-ice morainic landforms including ribbed moraines, drumlins and flutings. These forms are dominating landform types in the area of Kuusamo ice lobe. The Ranua interlobate area with the north-northwest to south-southeast oriented drumlin field, instead, is a relic of the older glacial phase and has preserved under cold-based, central area of the last glaciation. The glacial phase, when the old drumlin field was formed was the first one to cover the southern Lapland area during the Weichselian glaciation, probably at the beginning of the Middle Weichselian.

The characteristics of ribbed moraines were studied carefully to found out the composition, structure and stratigraphy of the ridges, and also to estimate glacial dispersal of till and surficial boulders. Ribbed moraines in the Peräpohjola area consist of three subtypes: hummocky ribbed moraines, Rogen moraines and minor ribbed moraines. The Sihtuuna moraine, a new morainic landform type, is introduced as a result of present study and can be classified as a minor ribbed moraine.

The formation of ribbed moraines is re-examined and a new hypothesis has been presented. The formation of the ridges was a two-step process where at the first stage fractured ice-sediment blocks were moved under ice sheet to form rib-like morphology. At the second stage, the sediments and the bedrock surface in the areas between the ribs were intensively quarried due to freeze-thaw process to become re-deposited to the next ridges. Thus, the transport distance of local bedrock fragments in the uppermost part of the ribbed moraine ridges is only a few tens or hundreds of metres. The most suitable conditions for ribbed moraine formation existed during the Late Weichselian deglaciation, after the Younger Dryas, when the climate warmed very quickly leading to an imbalance between warm glacier's surface and cold bottom.

The characteristics of ribbed moraines have been utilized in prospecting for Au and its pathfinder elements in the test areas. The short glacial transportation of mineralized material has become emphasised in many areas, especially in the Petäjävaara area, where Au-Cu-bearing, hydrothermally altered contact zone between diabase and quartzite in the bedrock was found. Also in other test sites, where ribbed moraine ridges occurred, the promising source areas were pointed out, although needing for future studies. The observations in the study area proved that the study of glacial flow directions and transport distances of till with distinguishing moraine formations and their genetic background is essential to succeed in ore prospecting.

Key words (GeoRef Thesaurus, AGI): glacial geology, ribbed moraine, till, geochemistry, ore prospecting, stratigraphy, subglacial environment, glaciation, deglaciation, Weichselian, Quaternary, Peräpohjola, Finland

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ISBN 951-690-934-5

Vammalan Kirjapaino Oy 2005

Preface

The doctoral thesis comprises the following papers:

I Aario, R., Peuraniemi, V. & Sarala, P. 1997. The Sihtuuna moraine at Tervola, southern Lapland. Sedimentary Geology 111, 135–145.

II Sarala, P., Peuraniemi, V. & Aario, R. 1998. Glacial geology and till geochemistry in ore exploration studies in the Tervola area, southern Finnish Lapland. Bulletin of the Geological Society of Finland 70, 19–41.

III Sarala, P. & Rossi, S. 2000. The application of till geochemistry in exploration in the Rogen moraine area at Petäjävaara, northern Finland. Journal of Geochemical Exploration 68, 87–104.

IV Sarala, P. 2005. Till geochemistry in the ribbed moraine area of Peräpohjola, Finland. Applied Geochemistry 20, 1714–1736.

V Sarala, P. 2005. Ribbed moraine stratigraphy and formation in southern Finnish Lapland. Journal of Quaternary Science. (submitted)

VI Sarala, P. 2005. Weichselian stratigraphy, geomorphology and glacial dynamics in southern Finnish Lapland. Bulletin of the Geological Society of Finland 77, Part 2, xxx–yyy. (accepted)

Introduction

This doctoral thesis summarizes data collected during the exploration studies in 1990's in the Rovaniemi-Tervola area, southern Finnish Lapland. The area was glaciated several times during the Quaternary period and was affected by glacial erosion frequently. Due to glacial deposition processes, eroded material is covering bedrock as a till sheet composed of different moraine formations. The till and moraine formations act as a medium reflecting glacial conditions and dynamics during the glacial erosion, transportation and deposition. By examining all of the features together the transportation of mineralized material in till can be estimated.

The bedrock of the study area is mainly composed of an association of sedimentary and volcanic rocks of the Peräpohja Schist Belt (Perttunen and Hanski, 2003). The rocks have proven to be potential for ore prospecting, because of many observed Au-Cu- and Fe-mineralization (Eilu, 1999 and the references within) and of numerous mineralized boulder observations (Papers II, III, IV and V). High metal anomalies in till are also a sign of the existence of mineralized sources in the bedrock. Those observations were done mostly during the earlier prospecting studies but also in the course of the present field works. However, the Quaternary geology of the area was poorly known before the present study and that is why the results to clear out the bedrock sources for the mineralized material in till were minor.

The glacial morphology of northern Finland is a composition of moraine and glaciofluvial formations of active and passive glaciers. Several works (e.g. Kujansuu, 1967; Glückert, 1974; Aario 1977, 1990; Kurimo, 1974, 1977; Aario and Forsström, 1979; Hamborg, 1986; Sutinen, 1992; Johansson et al., 2000; Johansson and Kujansuu, 2005) were done to classify the formation types and their existence in the area. The active-ice formations composed of an assemblage of hummocky moraines, ribbed moraines, drumlins and flutings (e.g. Lundqvist, 1969; Aario, 1977; Paper II), were formed under the ice lobes. In places, between the active ice lobes existed passive, cold-based interlobate areas, which were not able to erode or deform underlying bedrock and sediments (cf. Kleman, 1994; Kleman and Borgström, 1996, Punkari, 1997). The interpretation of those subglacial environments and moraine formations can be used to reconstruct glacial cycles and dynamics of former glaciations (e.g. Kleman et al., 1997; Clark et al., 2000; Jansson, 2002; Paper VI).

In the present study, attention was paid to the characteristics of special glacial morphology called ribbed moraine. It is a group of moraine ridges perpendicular to the last glacial flow direction in the central areas of the former glaciations in Northern Hemisphere. The term Rogen moraine has been commonly used as a synonym for these forms in Finland. In Fennoscandia ribbed moraines are common particularly in the central or northern areas of Finland and Sweden and also in Norway, in interior part of the Late Weichselian glaciation (cf. Hättestrand and Kleman, 1999). A lot of studies concerning their existence, composition, structure and formation hypothesis were published during their hundred-year study history (Papers III, IV and V). Especially the works of Lundqvist (1969, 1989, 1997) and Aario (1977, 1990), where they depicted the formation processes of those moraine ridges relating to special subglacial conditions, can be mentioned.

In the latest hypothesis presented by Hättestrand (1997), many of those earlier theories were concluded. Hättestrand presented on the basis of literature and mappings in Sweden that the formation of ribbed moraines was occurred at the retreating boundary between frozen- and thawed-bed conditions under extensional, moving ice sheet, which caused the fracturing of pre-existing till sheet. He also presented a classification for ribbed moraines including four subtypes: Rogen moraine, hummocky ribbed moraine, minor ribbed moraine and Blattnick moraine. This classification is also used in present study (Papers IV and V) and is proposed to use in Finland in future (cf. Sarala, 2003).

The deposition processes of moraine formations and till within were studied in seven test sites on the study area for estimating transport distances of mineralized boulders and debris (Papers I, II, III, IV). Because the ribbed moraine morphology was dominant in the area, the characteristics of their formation processes were essential to study for succeed in prospecting. The use of ribbed moraines in ore prospecting is only a little investigated earlier and only a few surveys have been published (Peuraniemi, 1982; Aario, 1990; Aario and Peuraniemi, 1992). In those studies, the uppermost part of the ridges was proven to be indicative of local bedrock composition and also the existence of surficial mineralized occurrences in the bedrock. Short transport distances came out as the anomalous metal contents of fine fraction of till on the distal side of mineralized occurrences in bedrock. Also, local rock fragments and boulders in the surficial part of ridges were indicative of short glacial dispersal. An average transport distance of surface boulders was the shortest in the case of ribbed moraines when comparing different moraine formations (cf. Salonen, 1986; Bouchard and Salonen, 1989).

The development of glacial morphology and stratigraphy during the Weichselian glaciation has been a long studied and debated in Finland. The works of Kujansuu (1967), Korpela (1969), Aario and Forsström (1979) and Hirvas (1991) have been bases for the construction of general till stratigraphy with glacial flow patterns in northern Finland. A chronology of different glacial phases has been based on the correlation of microfossil contents and radiocarbon ages of organic intermediate layers. An interpretation of the results has lead to the thought that all interstadial phases were dated to the Early Weichselian period. Because the determination limit for radiocarbon ages is about 40–50 ka, the reliability of age estimations is debatable. Since the implementation of thermoluminescense (TL) and optically stimulated luminescence (OSL) methods in dating the variation of ages has been increased and many determinations have given much younger ages than the Early Weichselian. For example, lately studies in the northwest Russia have pointed out that after the Middle Weichselian glaciation, quite warm and almost ice-free stage was occurred in Fennoscandia (e.g. Nenonen and Eriksson, 2004; Saarnisto and Lunkka, 2004; Svenden et al., 2004). Same type of age estimations has been presented also from northern Finland (e.g. Mäkinen, 1999; Helmens et al., 2001), leading to a re-examination of the timing of the Weichselian glaciation (Paper VI).

The aims of this thesis, in the first place, were to study glacial morphology and till stratigraphy in the Peräpohjola area with an estimation of transport distances of mineralized material in till at seven test sites. Special attention was paid on occurrence, structural features and the till geochemistry of ribbed moraines. On the basis of observations the formation hypothesis of ridges was re-examined. In the second place, the development of glacial morphology and stratigraphy was used to reconstruct glacial dynamics of the glaciers in the study area during the Weichselian glaciation. Furthermore, the observations made during present study were used as a reference for the examination of regional glacial morphology and dynamics in southern Finnish Lapland. As a comparison of the results with literature and present knowledge of dating, the glacial evolution of the Weichselian glacial phases was modelled.

Presentation of papers

Paper I: Aario, R., Peuraniemi, V. & Sarala, P. 1997. The Sihtuuna moraine at Tervola, southern Lapland. Sedimentary Geology 111, 135–145.

In this paper we review a new moraine type, Sihtuuna moraine found northwest of the village of Tervola, southern Finnish Lapland. The area of this moraine type covers about 10 km^2. Sihtuuna moraines are formed of ridges perpendicular to the latest west-east oriented glacial flow. Ridges are quite small in scale; commonly several hundreds of meters long, some tens of metres wide and from three to five metres high. They are formed of two till beds with stratified sands and gravels in between. The surface of ridges is covered with large and angular boulders transported only a very short distance.

As a conclusion, we presented that the origin of the Sihtuuna moraine was a two-step process. Initially plenty of streaming water together with subglacial mass-flowage existed. The second stage was related to bouldery surface of the ridges and represents strong quarrying activity of the glacier during the formation process.

Till geochemistry proves that till in the upper part of ridges is consisted of high contents of Au, Cu, Ni and Co particularly in a fine fraction of till (< 0.06 mm). Especially the distribution of Au is highly anomalous in the fine fraction but also in a heavy mineral concentrate of till in many test pits. Because the high Au contents occur in the uppermost till unit, characteristically depicting short glacial transportation and local phenomenon in bedrock, the possibility for an occurrence of Au mineralization(s) in the bedrock is great. Clear indication of local bedrock composition in the surficial part of ridges is also the feature that makes ore prospecting quite easy in the Sihtuuna area.

Paper II: Sarala, P., Peuraniemi, V. & Aario, R. 1998. Glacial geology and till geochemistry in ore exploration studies in the Tervola area, southern Finnish Lapland. Bulletin of the Geological Society of Finland 70, 19–41.

The general glacial morphology of northern part of the study area and the detailed exploration surveys in the test sites of Petäjävaara and Vammavaara was presented in this paper. Furthermore, some characteristics of ribbed moraines for ore exploration were pointed out.

The glacial morphology is mainly composed of the landforms deposited subglacially under the active ice sheet. An assemblage of active-ice landforms like ribbed moraines and drumlins is dominant. Ground moraine areas having no indication of glacial flow direction are also common in lowland areas, in the Kemijoki basin. Instead, only two esker chains as a mark of glacial meltwater streams are found, but no marginal formations. The later is due to glacier ending to the proglacial Ancylus Lake, the pre-existing phase of the Baltic Sea during the deglaciation. That is why the material released from the ice has mainly deposited as waterlain till or washed sediments above the pre-existing till sheet.

The test sites of Petäjävaara and Vammavaara were two of the most interesting and detailed studied areas during the present investigation in the Tervola area. Many Au-Cu mineralized boulders of which source(s) was unknown were found at the surface of the moraine ridges in the sites. The ridges perpendicular to the latest glacial flow direction were formed of two till units in Petäjävaara and of three till units in Vammavaara. Geochemistry of different till fractions (< 0.06, 0.06–0.5 and > 2 mm) and heavy mineral concentrate with boulder observations reflected short glacial dispersal of elements in ribbed moraine ridges. Particularly, the uppermost till unit is useful in tracing potential sources in the bedrock.

The study of glacial flow directions, till structures and stratigraphy of moraine formations with till geochemistry proved to be a powerful means in locating source rock of glacially transported, mineralized boulders and metal anomalies in till in the area. For prospecting Au, the most useful indicator elements in till geochemistry were among Au itself Cu, Te and Co. As a result of the study, Cu-Au mineralization was found at the Petäjävaara site.

Paper III: Sarala, P. & Rossi, S. 2000. The application of till geochemistry in exploration in the Rogen moraine area at Petäjävaara, northern Finland. Journal of Geochemical Exploration 68, 87–104.

Detailed studies for prospecting Au and Cu were done in the Petäjävaara test site. The studies were concentrated on tracing the transport distance of rock fragments in till and defining structural and geochemical features of ribbed moraines. The methods used were the test pit surveys with till sampling, geophysical ground surveys and bedrock mapping with deep drillings. For examining the distribution of Au and its pathfinder elements earlier percussion drilling samples were also used.

Glacial morphology is composed of Rogen moraine-like ridges in the main study area. Cover moraine with quite thin till sheet is common in northern parts. In the east, the slope of Petäjävaara hill is covered with shore deposits of Ancylus Lake.

The study shows that the uppermost unit of the two existing till units is indicative of local bedrock composition. Glacial dispersal of Au and other metals like for example Cu, Co and Te, the best pathfinder elements, are short due to strong quarrying during the deposition of ribbed moraine ridges. Particularly, Au contents are high on a distal side of mineralized zone in the bedrock, but steeply decreasing to the glacial flow direction. High Au contents exist in every till size fraction (< 0.06, 0.06–0.5 and > 2 mm), but the coarsest fractions have the clearest indication of close vicinity of the mineralized bedrock. This is also seen in fresh pyrite and chalcopyrite grains in heavy mineral concentrate. These minerals are typical for hydrothermally altered Au-Cu mineralizations in the Peräpohja Schist Belt.

In this paper we have also presented Au-Cu mineralized zone with quartz veins in the contact of diabase and quartzite in the bedrock as a result of present exploration studies. As a conclusion we have stated that in the Petäjävaara area several Au-Cu mineralized zones must be existed in the bedrock because of the high Au and Cu concentrations in till also on eastern side of the localized mineralization.

Paper IV: Sarala, P. 2005. Till geochemistry in the ribbed moraine area of Peräpohjola, Finland. Applied Geochemistry 20, 1714–1736.

Ribbed moraines have many features that make prospecting for Au and other metals easy. The best feature is their good indication of local bedrock composition in the uppermost part of ridges, which comes out as high metal contents in every till size fractions (< 0.06, 0.06–0.5 and > 2 mm), in heavy mineral concentrate and in the composition of surface boulders on the distal side of mineralization in the bedrock. Glacial dispersal for the elements is very sharp in a close vicinity to the mineralization with small outcrop, which is at the same time the benefit because the source(s) is easy to find out but also the restriction due to need of dense grid during sampling. In the case of large mineralized occurrence in the bedrock, high metal contents can be traced in a wide area by taking samples from the uppermost till unit but also from the lower, commonly distantly derived till units.

The use of lightweight percussion drill was estimated in the test sites of Petäjävaara, Vammavaara and Kivimaa. The examination was done both in horizontal and vertical dimensions. In Petäjävaara and Vammavaara, main study areas were composed of ribbed moraines and in Kivimaa of cover moraine. In the case of ribbed moraine ridges the penetration of percussion drill was low due to the surface and the uppermost till unit rich of boulders. In Kivimaa and Vammavaara the stony, brecciated weathered bedrock at the bottommost or intermediate layer in till stratigraphy was also the limit for percussion drilling.

All of the cases clearly prove that till composition and stratigraphy with the deposition processes of different moraine formations must be known before examining the distribution of metals and their pathfinder elements. These things should be also noticed when interpreting the results of different sampling scales (e.g. regional, local and prospect scales). An interpretation of glacial morphology together with test pit surveys are in this context a key to choose best equipment for sampling, to estimate sampling effectiveness and also to compare the results between different formation types.

Paper V: Sarala, P. 2005. Ribbed moraine stratigraphy and formation in southern Finnish Lapland. Journal of Quaternary Science. (submitted)

In this paper, the formation process of ribbed moraine ridges was re-examined. The observations made from the study area proved that the formation process was two-step. During the early stage of deglaciation, on the retreating zone of subglacial frozen- and thawed-bed, pre-existing sediments and the bottommost part of the ice sheet formed a stagnant, stacked mass. Due to pressure and tension caused by the moving ice sheet, featherlike cracks were formed and the stagnant mass was fractured. When the zero-degree boundary was crossed the surface of bedrock or other weakness zone (e.g. till unit boundary, stratified layer, boulder pavement), fractured blocks were moved along the ice sheet forming rib-like morphology. Because of the prevailing cold conditions, followed freeze-thaw process was caused the quarrying in between the newborn ribs and a bit later, after the pressure increased on the proximal contact, the deposition of material (released from the ice bottom) on the surface of the ribs.

Quick and strong decrease of the air temperature and the subsequent imbalance between the surface and the basis of the ice sheet might be the most suitable moment for the beginning of ribbed moraine formation at the end of Younger Dryas, on the early stage of deglaciation. The climate change during that time has been a global phenomenon and thus, explains the occurrence of ribbed moraines in the central areas of the former glaciated areas.

Paper VI: Sarala, P. 2005. Weichselian stratigraphy, geomorphology and glacial dynamics in southern Finnish Lapland. Bulletin of the Geological Society of Finland 77, Part 2, xxx–yyy. (accepted)

A detailed description of the glacial morphology, till composition and stratigraphy in each of the seven test sites with earlier published observations was used to compile the glacial stratigraphy in the study area. It includes four to five separate till units reflecting three different till beds deposited during the different glacial advances. The whole sequence is proposed to call as the Peräpohja Group. The lowest, Saarenkylä Till is an age of the Saalian glaciation and other two, the Kemijoki Till and the Tervola Till, are an age of the Weichselian glaciation. The uppermost till bed particularly in ribbed moraine ridges are composed of two till units named as till members of the Vammavaara Till and Korttelivaara Till representing both advancing and melting phases of the single glaciation period. Between them is situated the Petäjävaara Till Member formed on early stage of deglaciation, during the ribbed moraine formation in the contact zone of cold- and thawed-bed glacier.

Based on the glacial morphology, stratigraphy and the present knowledge of dating the comparison with literature have been done. The evidences indicate only of two separate glacial advance of the Weichselian age in southern Finnish Lapland. The first one depicted as drumlin field, was deposited during the glacial flow towards the south-southeast and was dated to the Early or the Middle Weichselian glaciation. The second advance, when the ribbed moraine-drumlin-flutings association deposited, existed during the glacial flow mainly from the west to the east at the end of the Late Weichselian glaciation. As a result, two models of stadial-interstadial cycles of the Weichselian glaciation in southern Finnish Lapland were presented.

Ribbed moraine formation

The composition and structure of ribbed moraines in the study area led to a re-examination for the formation processes of the ridges. Short transportation of till and rock fragments in the surface of ridges and in surficial boulders (on Papers I, II, III, IV and V), were the features of which deposition process is explained in a new way. Based on the observations, two-step formation of ribbed moraines was presented (Fig. 1).

At the first phase, under cold-based conditions during the early deglaciation stage, subglacial sediments together with the base of ice sheet formed a stagnant mass, while the upper part of the glacier moved. Due to movement, pressure and tension elevated at the base of the ice sheet causing featherlike fracturing of stagnant mass. By this way, the blocks/fragments of subglacial sediment and ice formed. Contemporary, an elevation of zero-degree boundary, i.e. the pressure-melting isotherm (cf. Hättestrand, 1997) from the bedrock to a boundary between the bedrock surface and the sediments, or within the sediments, together with moving glacier intensified the block transportation and finally, the forming of rib morphology.

At the second phase, after the tension was relaxed due to collapse of the featherlike cracks and the movement of ice-sediment blocks, the freeze-thaw process begun at the base of the moving glacier. This led to a quarrying activity in the areas between the ridges and the deposition of quarried material on the surface of newborn ribs. As movement of the ice sheet continued, bedrock surface was also quarried and the

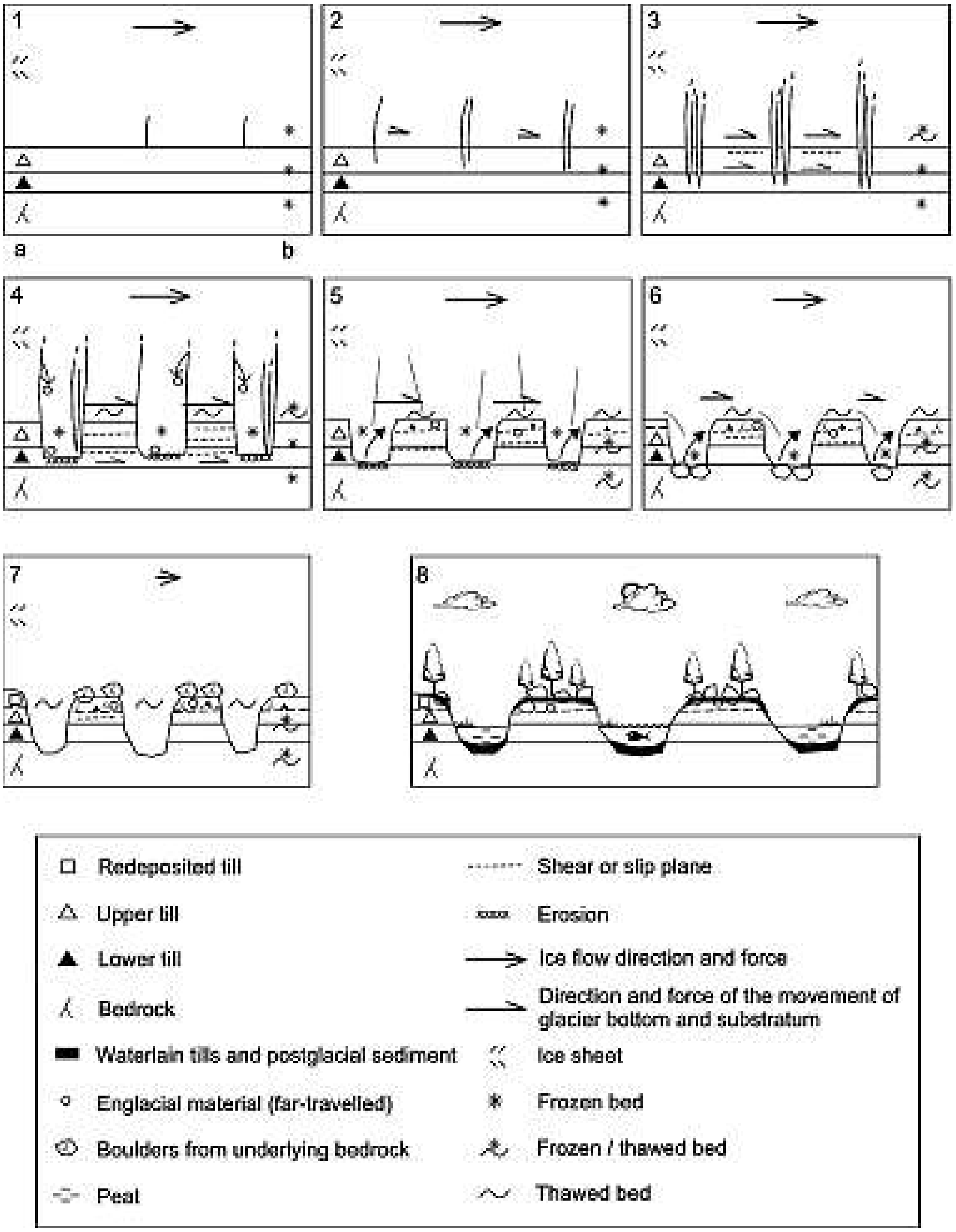

Fig. 1. A two-step model of ribbed moraine formation in the boundary between the frozen and thawed bed glacier. After the development of featherlike cracks and movement of ice-substrate blocks under tensional glacial flow, the followed quarrying and redeposition due to freeze-thaw process under prevailing frozen conditions have caused the formation of rip-like morphology and the deposition of localized, short-transported till material and boulders on the surficial part of ribbed moraine ridges. From Paper V.

boulders with good indication of local bedrock were deposited on the surface of ribbed moraine ridges. When the glacier's movement stopped, the passive ice sheet just melted away leaving the morphology as it was, but when the movement continued and the subglacial condition changed to thawed-bed, drumlinized and fluted morphology formed superimposing the ridges.

Even if the bouldery surface is a characteristic feature for ribbed moraines in Finland, it can be missed in places. If pre-existing till and sediment sheet is thick enough, the quarrying process do not reach the bedrock surface. In those cases, the benefit of short glacial dispersal of the upper till in ribbed moraines is also lost in ore prospecting.

In this thesis, the beginning of the ribbed moraine formation is presented to be a consequence of rapid climatic change during the last deglaciation. The increase of mean temperature of about 10°C over a few hundred years at the end of Younger Dryas (about 11.8–11.5 ka ago) could have been caused the temperature (and followed mass) imbalance between the glaciers bottom and top. Followed increase of melting at the glacier's margin and surface together with the separation of margin to fast flowing ice lobes and interlobate areas was the major effect causing the increase of tension and finally, the fragmentation of cold-based glacier's bottom.

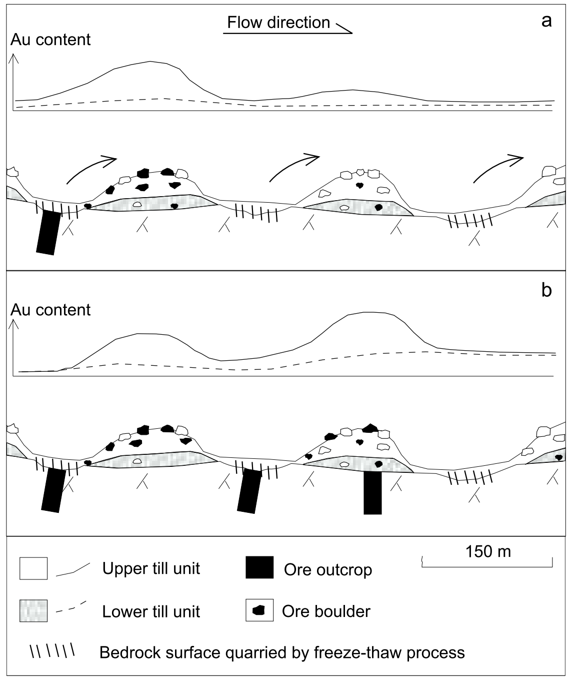

Fig. 2. Generalized model of the distribution of Au in till in the ribbed moraine ridges, where two till units are present and: a) one Au-rich vein; or, b) larger Au-rich shear zone with several veins. (cf. Paper III)

Ribbed moraines in ore prospecting

Ribbed moraines have many features that are useful in ore prospecting. The examples of prospecting for Au and its pathfinder elements in Peräpohjola emphasize the phenomenon:

1. Ribbed moraines are common morainic landform type on the large areas in northern and western Finland. An identification of this moraine type is easy if aerial photo interpretation or elevation models with high resolution are used. Prospecting strategy and sampling methods can be the same even if the ribbed moraine subtypes change.
2. The features of the upper till unit and the surficial boulders indicate strongly the variation of local, underlying bedrock. Short glacial transport distance of the till is seen in a sharp and anomalous dispersal of Au and its pathfinder elements in both horizontal and vertical dimensions. Boulders on the surface and in the upper till represent the local, quarrying activity of the ice during the formation of ribbed moraines (Fig. 2).
3. Different till size fractions indicate short glacial dispersal. Quarrying activity during the formation of ridges lift fresh mineralized material from the bedrock surface to the surficial parts of the ridges. Thus, ore indicators – mineralized boulders, heavy or other ore minerals and metal-rich till size fractions (< 0.06, 0.06–0.5 and > 2 mm) are useful indicators of the mineralized bedrock.
4. Till sampling in the ribbed moraine areas can be easy, fast and cost-effective, because the samples can be taken only from the upper till unit. However, in the Peräpohjola area, it is important to dis-

tinguish the till from the shore deposits to succeed in sampling.

Local bedrock indication of the surface boulders can also be usable in other purposes than ore prospecting. Especially in the areas, where glacial drift sheet is uniform and the bedrock outcrops are minor surface boulders can be used for bedrock mapping.

Glacial morphology and stratigraphy as an indicator for the timing of Weichselian glacial phases

The Quaternary lithostratigraphy of southern Finnish Lapland is composed of three till beds and two inter-till, stratified minerogenic sediment layers containing sometimes organic material, and is proposed to call as the Peräpohja Group. The descriptions, formal names and type sections of the units are also presented (Table 1).

The bottommost till unit, Saarenkylä Till, is interpreted to be an age of Saalian glaciation and can be correlated with Till Bed IV after the nomenclature of Hirvas (1991) (Table 2). Above that exists the Saarenkylä Gytja, which has deposited during the Eemian Interglacial (Sutinen 1992) and maybe also during the Early Weichselian Interstadial. The second, Kemijoki Till unit is known as dark till in literature and is correlative with Till Bed III. It has deposited during the first Weichselian glaciation that covered the southern Finnish Lapland area. The Sihtuuna Sands follows it in stratigraphy and represents the ice-free Interstadial stage of the Middle Weichselian. The Tervola Till Formation including members of Vammavaara Till, Petäjävaara Till and Korttelivaara Till represents the Late Weichselian glaciation including the till units from advancing phase to melting phase with the redeposited unit related to ribbed moraine formation in between. The Korttelivaara Till is rare and has seldom preserved, because the upper parts of morainic landforms were washed during the later Ancylus Lake and Litorina Sea stages and changed to shore deposits of the Suolijoki Formation.

Table 1. Quaternary lithostratigraphy, unit descriptions and formal names in Rovaniemi-Tervola area. A whole stratigraphic sequence is proposed to name as the Peräpohja Group. From Paper VI.

Formation	Member	Depth	Description	Interpretation	Chrono-stratigraphy	Type section
Suolijoki Formation		0.5 - 2 m	Stratified sand and gravel	Shore deposit	Holocene	N7345.5 I2561.5 M118, Vammavaara
Tervola Till Formation	Korttelivaara Till Member	0.1 - 1.5 m	Brownish grey sandy diamict	Melt-out, flow or waterlain till	Late Weichselian	N7334.0 I3444.6 M90, Korttelivaara
	Petäjävaara Till Member	1 - 3 m	Brownish grey or grey gravelly diamict	Lodgement or basal melt-out till		N7358.5 I2564.1 M1, Petäjävaara
	Vammavaara Till Member	1 - 4 m	Grey sandy diamict	Lodgement till		N7346.2 I2561.2 M25, Vammavaara
Sihtuuna Sands		1 - 2.5 m	Horizontally or cross bedded sand	Subaquatic fan	?	N7344.6 I2529.6 M124, Sihtuuna
Kemijoki Till Formation		1 - 2 m	Bluish grey, compact sandy/silty diamict	Lodgement till	Early or Middle Weichselian	N7345.9 I2562.2 M21, Vammavaara
Saarenkylä Gytja		2 - 3 m	Organic gytja, silt and sand	Lacustrine or marine deposit	Eem Interglacial or Early Weichselian	N7382.5 I4447.6 Saarenkylä (Sutinen 1992)
Saarenkylä Till Formation		> 1 m	Grey, compact sandy diamict	Lodgement till	Saalian	N7382.5 I3447.6 Saarenkylä (Sutinen 1992)

Table 2. The correlation of Quaternary lithostratigraphy with earlier studies in the area of southern Finnish Lapland. From Paper VI.

Formation	**Member**	**Correlation**				
		Korpela (1969)	Aario & Forsström (1979)	Mäkinen (1979)	Hirvas (1991)	Sutinen (1992)
Suolijoki Formation				Shore deposit		
	Korttelivaara Till Member				Surficial Till S	
Tervola Till Formation	Petäjävaara Till Member	Upper Till	Ranua Till	Upper Till Bed	Till Bed I	Rovaniemi Till
	Vammavaara Till Member				Till Bed II	
Sihtuuna Sands		Peräpohjola Interstadial		Kauvonkangas Interstadial	Maaselkä Interstadial	Katosharju Interstadial
Kemijoki Till Formation		Lower Till	Pudasjärvi Till	Middle Till Bed	Till Bed III	Kemijoki Till
Saarenkylä Gytja				Lower glaciofluvial deposit		Saarenkylä Interglacial
Saarenkylä Till Formation				Lower Till Bed	Till Bed IV	Saarenkylä Till

The development of glacial morphology and till stratigraphy over the two Weichselian glacial phases was reconstructed by modelling different scenarios. Two models were presented:

1. In the first model, the initial phase occurred during the Early Weichselian (Fig. 3a), in oxygen isotope stage (OIS) 5b and the second one from the beginning of the Middle Weichselian to the end of Late Weichselian (OIS 4–2) (Fig. 3b). The interstadial phase occurred at the end of the Early Weichselian (OIS 5a).
2. In the second model, the first Weichselian glacial advance was quite modest in extent and covered only the area of northernmost Finland (Fig. 4a). The glacier reached southern Finnish Lapland for the first time during the Middle Weichselian (Fig. 4b). Furthermore, the glacier may have also covered southern Finland. The marginal formations in the Pudasjärvi area and from there to northeast deposited during the melting phase. An interstadial phase was followed the first glacial phase in OIS 3, meaning that most of the radiocarbon ages clustering to 40–55 ka are correct and supported with the latest TL and OSL age determinations including age estimations of the Sihtuuna Sand (Paper VI). Finally, the interstadial was followed by the relatively short but very intensive and large Late Weichselian glaciation.

Conclusions

The glacial morphology of the Peräpohjola area, in southern Finnish Lapland, is dominantly composed of ribbed moraines, drumlins and flutings, the assemblage of active-ice morainic landforms of an age of the Late Weichselian glaciation. The Ranua interlobate area with the north-northwest to south-southeast oriented drumlin field is a relic from the older, probably Middle Weichselian glacial phase and has preserved under cold-based, central area of the last glaciation. The glacial phase during the Middle Weichselian was obviously the first one to cover the southern Finnish Lapland area.

Ribbed moraines are the most detailed studied

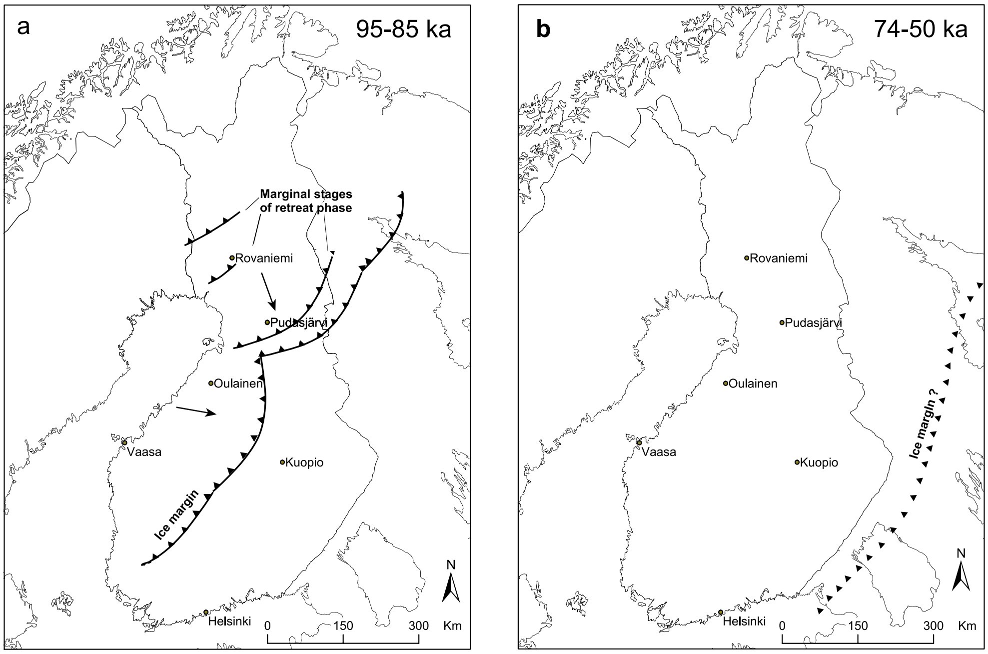

Fig. 3. Model 1: The glacial morphological and stratigraphical development during the Weichselian in southern Finnish Lapland, when a) the first extensive glaciation phase occurred during the Early Weichselian, and b) the second during the Middle Weichselian, probably continuing without a break to the end of Late Weichselian. From Paper VI.

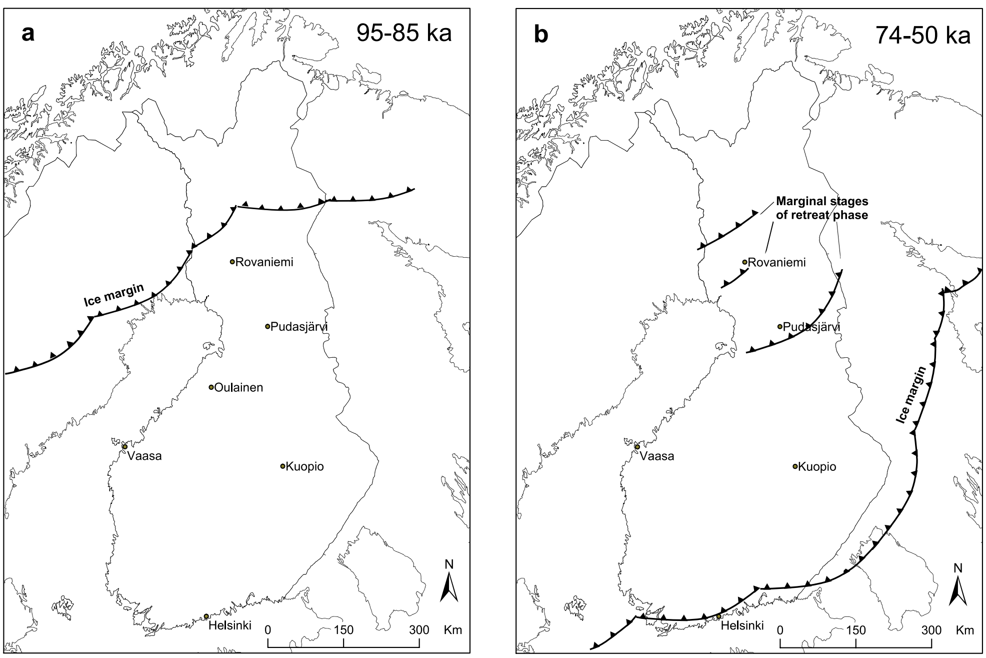

Fig. 4. Model 2: The second interpretation where a) southern Finnish Lapland stayed ice-free during the Early Weichselian glaciation phase and was b) initially glaciated not until the Middle Weichselian. Ice margin reached at least to the level of southern Finland (cf. Svendsen et al., 2004) and marginal formations in northern Finland were formed during the melting phase of that glacier, before the following interstadial stage at the end of Middle Weichselian. From Paper VI.

landform types in the area. They consist of three subtypes: hummocky ribbed moraines, Rogen moraines and minor ribbed moraines. The Sihtuuna moraine, a new morainic landform type in northern Finland, is introduced as a result of present study and can be classified as a minor ribbed moraine.

The formation of ribbed moraines was a two-step process where at the first stage, fractured ice-sediment blocks were moved under ice sheet to form rib-like morphology and at the second stage, the sediments and the bedrock surface in the areas between the ribs were intensively quarried as a consequence of freeze-thaw process. Quarried material was re-deposited to the next ridges. Thus, the transport distances of local bedrock fragments (from boulders to fine fraction of till) in the uppermost part of the ribbed moraine ridges are only a few tens or hundreds of metres. The most suitable conditions for the ribbed moraine formation existed during the Late Weichselian deglaciation, after the Younger Dryas, when the climate warmed very quickly leading to an imbalance between warm glacier's surface and cold bottom.

The characteristics of ribbed moraines have been utilized in prospecting for Au and its pathfinder elements in the test areas. The short transportation of mineralized material has become emphasised in many areas, especially in the Petäjävaara area, where Au-Cu-bearing, hydrothermally altered contact zone between diabase and quartzite in the bedrock was found after short tracing of mineralized boulders. Also in other test sites, if not counting the Korttelivaara site, the promising source areas were pointed out, although requiring future studies.

The observations in the area of Peräpohjola, in southern Finnish Lapland, underlie the importance of the investigations of moraine formations and their genetic background to succeed in ore prospecting. An interpretation of glacial morphology together with test pit surveys are the keys to choose the best equipment for sampling, to estimate the possibility to succeed in sampling and also to give a basis for the comparison of results between different formation types.

Acknowledgements

First of all I would like to express my gratitude to Professor Risto Aario and Professor Vesa Peuraniemi, my supervisors during the work. Their encouragement and guidance were necessary to accompany young researcher to right way during the study. I am especially grateful to Risto for making me familiar with numerous morainic landform types here in Finland and introducing me the world of aerial photo interpretation. The experience of which Vesa has in exploring the sources of metals and minerals in till, analysing till geochemistry and preparing and studying heavy mineral samples were helpful during the work. Also, many discussions on various geomorphological and till geochemical topics in office and in the field with them and constructive criticism to my writings inspired me in the course of years.

This work was impossible without the support that I got from the Geological Survey of Finland (GTK). The financial support was of course necessary, but most of all the mental support and guidance that I got from the Mr. Seppo Rossi during the study. He was a representative of GTK in this project, but above all a colleague in a journey to amazing world of ribbed moraines in the Tervola area. I never forgotten his patience during the numerous discussions we have while I was searching the answers – and maybe the questions, too. Seppo was also the person, who encouraged me all the time and believed my ambitious target to finalize this thesis. Also, the support I got from Dr. Peter Johansson during the late stage of work with fruitful discussions and comments on the manuscripts were helpful when finalizing thesis. Also, many advices and discussions during the fieldwork and writing phase with for example Mr. Jari Nenonen and Mr. Vesa Perttunen were encouraging.

I also acknowledge with gratitude Research Director, Dr. Keijo Nenonen for criticism and comments for the last manuscripts and for accepting this thesis for publication in a special publications of GTK. Also, I thank the head of the Regional Office of the Geological Survey for Northern Finland, professor Ahti Silvennoinen and his successor Mr. Risto Pietilä, the head of the Land Use and Environment Mr. Pasi Lehmuspelto, the early head of the Bedrock and Mineral Resources Dr. Erkki Vanhanen and his successors, the head of the IT and Information Services Mr. Hannu Kairakari, for giving me to opportunity to carry out this project.

Many people like Mr. Mikko Kvist, Mr. Antti Pakonen, Mr. Kalevi Tolppi, Mr. Lasse Rauhala, Mr. Mauri Vitikka and Mr. Matti Kantola have contributed to the fieldwork. Mrs. Anne Petäjä-Ronkainen, Mrs. Seija Roman and Mr. Kauko Holappa give me an introduction to laboratory work. Dr. Teuvo Pernu and Mr. Pekka Puhakka helped during the geophysical measurements. Professor Högne Jungner and Mr. Kari O. Eskola from the Dating Laboratory of University of Helsinki supported this work with the analysis of dating samples. I would express my most grateful thanks to all these people.

I would also like to thank the official referees of the manuscript Professor Raimo Kujansuu and Dr. Keijo Nenonen for suggesting valuable improvements to the synopsis, Mrs. Carrie Turunen for checking the English of the manuscript, Mr. Mika Palosaari for giving linguistic advices and Mrs. Terttu Aaltonen and Mrs. Helena Murtovaara for helping on literature retrieve.

Finally, my warmest thanks go to my wife Anna-Maija and to my wonderful daughter Hanna and sons Jouni and Olli. You have suffered much in the course of years and particularly, during the final stage of finalizing this thesis, when I spend a lot of holidays and evenings over my computer. I am also deeply indebted to my parents Anneli and Risto and my siblings of the interest and encouragement during the work.

This work was supported by the Geological Survey of Finland, the University of Oulu and the Foundation of Research of Natural Resources in Finland.

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