

GLACIAL GEOLOGY AND TILL GEOCHEMISTRY IN ORE EXPLORATION IN THE TERVOLA AREA, SOUTHERN FINNISH LAPLAND

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Glacial geology and till geochemistry were studied in an ore exploration project in the Palaeoproterozoic Peräpohja Schist Belt in the Tervola area of southern Finnish Lapland. The starting point for the exploration were numerous Au-Cu-rich erratics, the source rock of which was unknown. The mapping of the glacial landforms was based on aerial photo interpretation. The structure, texture, lithology and geochemistry of the till were studied using test pits. Three sieved fractions together with a heavy mineral fraction of the till were analyzed chemically.

The glacial landforms of the area include cover and ground moraines, drumlins, flute ridges and Rogen moraines. The ridges of the Rogen moraine were found to be composed of three different till beds. The surficial parts of the Rogen ridges showed very short transport distance, whilst the lower till was of more distant derivation.

Gold and Cu contents in the till are above their regional background levels in every analyzed fraction in the two case study areas of Petäjävaara and Vammavaara. High metal contents in till are associated with basic volcanic rocks and their contact zones with quartzite in bedrock. Metal anomalies in till are usually very sharp-contrasted and dilute quickly with increasing distance from the source rock. The most useful indicator elements in till geochemistry, in addition to Au, are Cu, Te and Co. The combination of careful studies of glacial geology and till geochemistry proved to be a powerful means in locating source rock of glacially transported ore boulders in this area. As a result of the exploration, Cu-Au mineralization was localized at Petäjävaara.

Key words: mineral exploration, geochemical methods, till, stratigraphy, geochemistry, gold, copper, pathfinders, heavy minerals, glacial transport, erratics, Tervola, Finland

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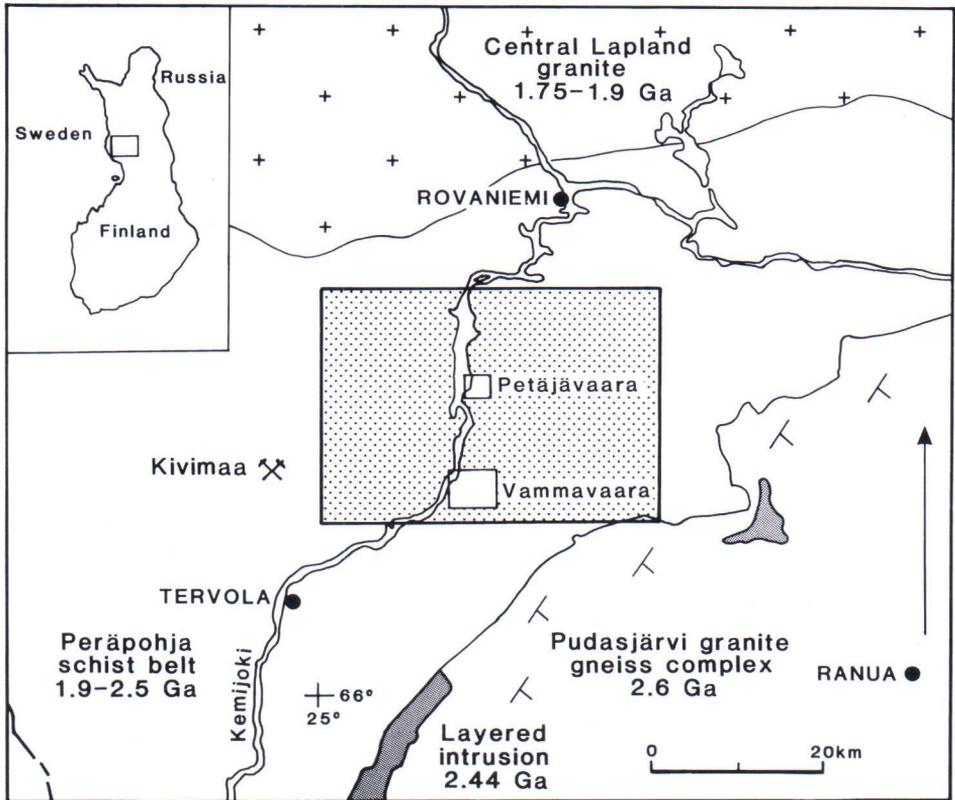


Fig. 1. The location of the study area in the Peräpohja Schist Belt.

INTRODUCTION

Ore exploration has been quite intensive in the area of the Peräpohja Schist Belt during the last decades. Many small mineralizations have been discovered (e.g. Mikkola 1947, Peuraniemi 1982, Äyräs 1991), but only one, a Cu-Au deposit in Kivimaa (Rouhunkoski & Isokangas 1974) has been mined so far (Fig. 1). Gold exploration in the greenstone and schist belts in Finland has intensified prospecting also in the Peräpohja Schist Belt.

Till geochemistry is an effective method in prospecting for metal mineralizations in glaciated areas. Different sampling densities, fractions and soil horizons have been used in Au exploration e.g. by Shilts (1984), Bloom and Steel (1989), Gleeson et al. (1989), McClenaghan (1992), Nichol et al. (1992), Hartikainen and Nurmi (1993), and Sibbick and Fletcher (1993). The importance

of knowledge on glacial history and till stratigraphy in prospecting has been stressed by Campbell and Schreiner (1989), Hirvas (1989), Hirvas and Nenonen (1990), Aario and Peuraniemi (1992), and McClenaghan et al. (1992).

Delineation of the geochemical provinces in Finland is possible on the basis of regional till geochemical maps (Koljonen 1992, Salminen 1995, Salminen & Tarvainen 1995). Maps of the regional till geochemistry of northern Finland (sampling density 1/30 km²) show that the study area is a part of a SW-NE trending Cu-anomalous zone (Fig. 2a). Gold, instead, has no anomalous values in the study area (Fig. 2b). Both maps are based on the work of the so-called Nordkalott Project (Bølviken et al. 1986). A more detailed (sampling density 1/4 km²) regional till geochemistry (Koivisto 1992) shows several Cu and Au anomalous samples in the study area (Fig. 3).

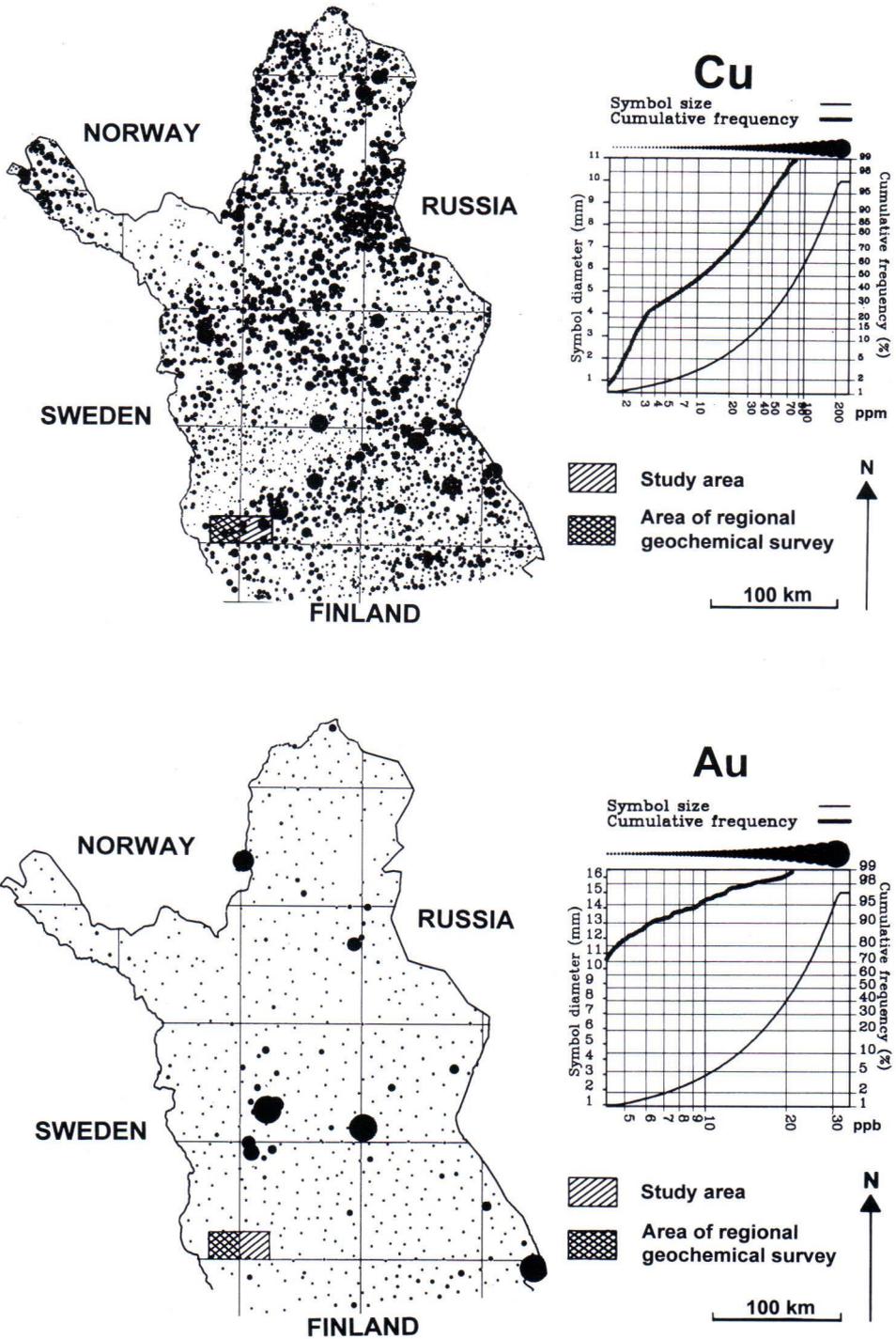


Fig. 2. The distribution of a) Cu and b) Au in till in northern Finland. Sampling density is one sample per 30 km². Number of samples is 5 400 in Cu map and 1036 in Au map. Modified from the maps of the Nordkalott Project (Bølviken et al. 1986).

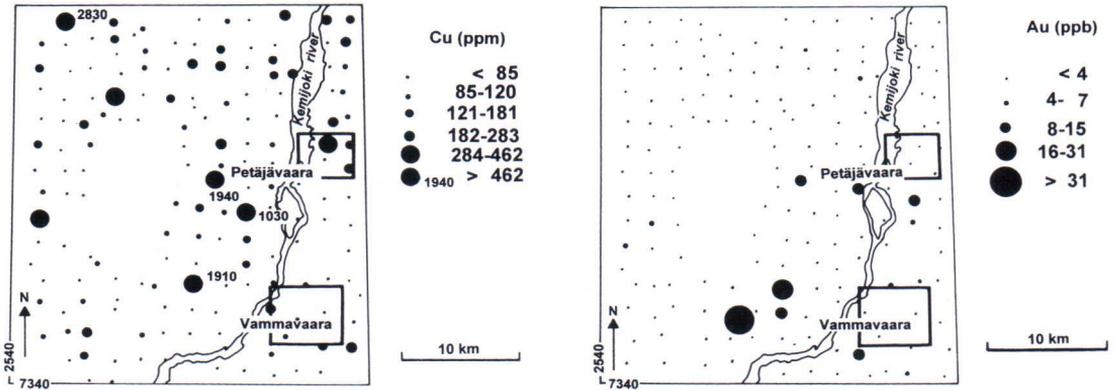


Fig. 3. The distribution of a) Cu and b) Au in till in the central part of the Peräpohja Schist Belt. Sampling density is one sample per 4 km². Slightly modified from the map of Koivisto (1992).

Numerous erratics (basic volcanic rock and/or quartzite) containing pyrite, chalcopyrite and Au have been the starting point for this study. The aim has been to decipher the glacial geology of the area in order to shed light on the ice transport directions and distances. The ultimate goal has been to locate the source rocks of the mineralized erratics. Detailed studies were concentrated in the Petäjävaara and Vammavaara areas (Fig. 1); field work was done during the years 1992–1995.

GEOLOGICAL SETTING

Bedrock geology

The study area is a part of the Palaeoproterozoic Peräpohja Schist Belt (Fig. 1). The schists are bordered in the south by the Archaean Pudasjärvi Granite Gneiss Complex and in the north by the Palaeoproterozoic Central Lapland Granite Complex. Layered mafic intrusions occur between the schist belt and granite gneiss complex. According to Perttunen (1989, 1991), the supracrustal schist belt contains three volcanic formations separated by quartzite-dominated sedimentary formations that typically consist of quartzite and dolomite beds. Volcanic rocks are composed of tholeiitic basalts or tuffitic rocks. Quartzites are usually cut by albite diabases. Other rock types are conglomerate, phyllite and mica schist. The schist belt has been folded along an E-W trending fold axis.

Quaternary geology

Quaternary geology in southern Finnish Lapland has been studied since Okko's (1941, 1944) work on grain size properties and lithology of till. The earliest study on till stratigraphy in the area was made by Korpela (1969). He found two different ice flow phases, the younger one from the west, and the older one from the northwest; and between the respective tills there were sorted sediments and organic matter suggested to belong to the Peräpohjola Interstadial. Hirvas et al. (1977) further studied the till stratigraphy in North and Central Finnish Lapland and had also some observations from southern Lapland. In his till stratigraphy, Hirvas (1990) suggested six different till units numbered I–VI from the youngest to oldest. Units I–III are of Weichselian age and the Peräpohjola Interstadial was interpreted as lying between units II and III. Units II and III are accordingly correlated with the upper and lower till beds of Korpela (1969). Units IV–VI are older and they have been found mainly in the former ice divide zone in Central Lapland, but not in the present study area. The latest stratigraphical studies have been made by the present authors on the northern side of the village of Tervola, where the Sihtuuna moraine ridges were described (Aario et al. 1997).

The final retreat of the ice sheet from northern Finland took place at about 9 000 B.P. (Hyyppä 1966, Ignatius et al. 1980). During deglaciation,

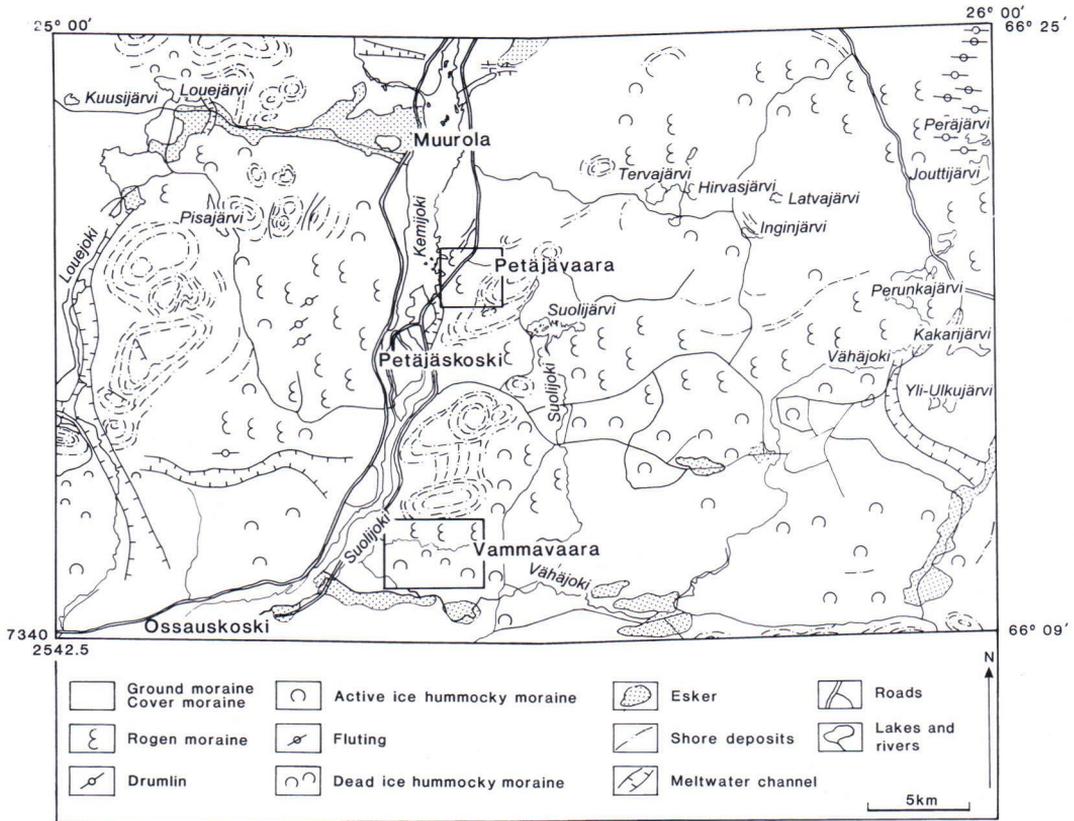


Fig. 4. Glacial geology of the study area. Youngest ice flow direction has been from west to east.

the proglacial Ancylus Ice Lake left its marks on the slopes of the highest hills in western and southern Lapland. The highest shore lines are now seen on the level of about 215 m a.s.l. (Eronen 1974). The shore deposits under the level of 100 m belong to the Litorina Sea phase.

An aerial photo interpretation of the study area (Fig. 4) shows that till is the most common surficial deposit occurring as various morainic landforms and their assemblages (Aario et al. 1996, Sarala et al. 1996). Ground moraine having only very gently undulating topography occurs mostly in the western and southern parts of the area. The thickness of till is 5–8 m in low-lying areas and 1–3 m on higher ground. In places, ground moraine passes laterally into active ice hummocks of low relief. Till is quite thin in the northern and southeastern parts and has been interpreted to be

cover moraine. It drapes the bedrock topography (Aario 1977).

Rogen moraine is the most dominant landscape type. It was formed during a younger ice flow from the west. The Rogen areas consist here both of hummocks and ridges (Fig 5), which commonly have a boulder-strewn surface. The dimensions of the ridges are variable: the length is 100–500 m, width 50–100 m and height 2–10 m. Three areas dominated by Rogen moraines have been delineated. The first is at Petäjäskoski, where the main area occurs on the west side of the Kemijoki river and continues to the east as far as the Petäjävaara case study area (Fig. 6). The second area begins from Suolijärvi and continues as a narrow chain up to Perunkajärvi. The third area is in the northeastern part of the study area (Peräjärvi-Jouttijärvi). Rogen moraine is common

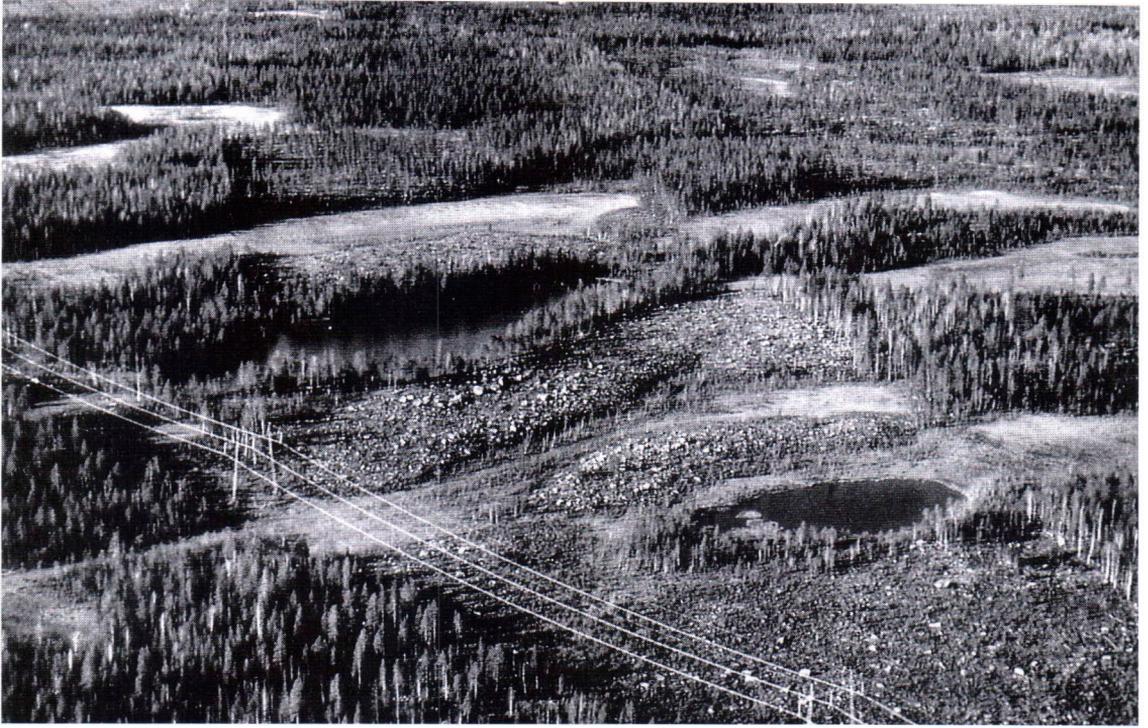


Fig. 5. An oblique aerial photograph of the Rogen moraine ridges at the western side of Petäjäsoski. Ridges are characteristically crescentic and covered by a bouldery surface. Ice flow has been from the upper left to lower right. Photo R. Aario.

also on the southern and eastern sides of Vammavaara hill (Fig. 12). At Petäjäsoski and in the northeastern part of the study area, one can find morphological series from Rogen moraines to drumlins, a phenomenon described frequently in the literature (cf Lundqvist 1969, 1989, 1997, Aario 1977, 1990, Hättestrand 1997). Transport distances of rock material in Rogen moraines are usually short and applicability for prospecting is therefore good (Aario & Peuraniemi 1992).

Dead-ice hummocky moraines with kettle holes occur in some places. These moraines have been deposited as ablation till on the margin of stagnant ice together with meltwater activity, which is seen as glaciofluvial sediments and meltwater channels near the hummocky moraines. Two larger esker chains have been observed: Muurola esker in the north and a branching esker chain from Ossauskoski to the east. Giant potholes in the

cordierite-antophyllite-gneiss bedrock hill occur northeast of the village of Muurola, at Hirvas. They belong to the Muurola esker chain. Because of the activity of Baltic Sea stages during the post-glacial emergence due to land uplift, the surface of till has often been washed or, in low areas, covered by gravelly and sandy sediments washed down from the hill slopes.

METHODS

Glacial morphology was mapped using aerial photo interpretation and subsequent field revision. Detailed till studies in the field including tractor excavations and surface boulder counting were done in the Petäjäsoski and Vammavaara case study sites. Textural and structural analyses from test pits were used to compose stratigraphical sections.

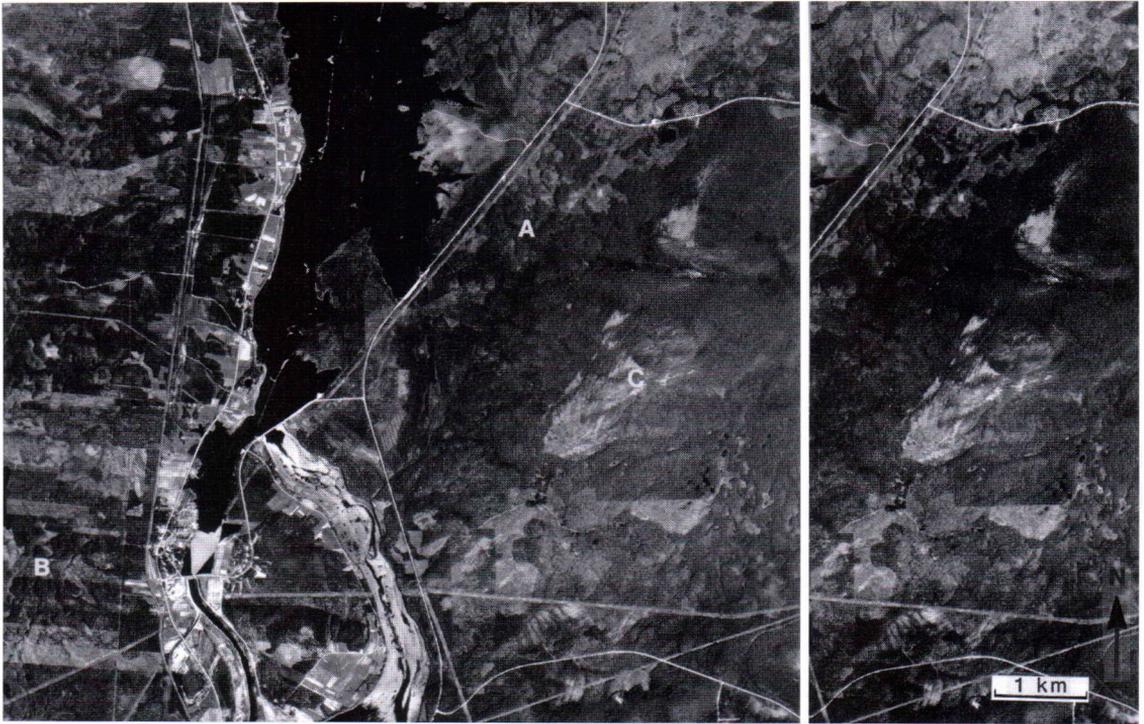


Fig. 6. Rogen moraine ridges at Petäjävaara (A) and the western side of Petäjäsoski (B) (aerial photos 7703/100 and 101). Petäjävaara hill with washed slopes and shore deposits is on the right margin (C). Youngest ice flow direction has been from west to east. By courtesy of Topografikunta (The Army Map Service).

Surface boulder counting has been used to estimate the glacial transport distances and to supplement bedrock data because the outcrops are few.

Samples have been taken from test pits for grain size, pebble lithology, chemical and heavy mineral analyses. Grain-size analyses were done by wet-sieving and areometry. A rock type of 100 pebbles was determined. The orientation and dip of 150 or 200 pebbles were measured in till fabric analyses. Three fractions (< 0.06 mm, 0.06–0.5 mm and > 2 mm) of till were analyzed chemically (cf Gustavsson et al. 1979, Salminen 1980). The fractions were extracted by hot aqua regia and 31 elements were analyzed by inductively coupled plasma atomic emission spectrometry (ICP-AES). Gold, Pd and Te were analyzed by graphite furnace atomic absorption spectrometry (GFAAS). All analyses were made in the laboratory of the Geological Survey of Finland at Rovaniemi. Sam-

ples taken earlier by percussion drilling were also used in till geochemistry. Samples for heavy mineral study (about 10 l each) were panned and magnetite was removed by hand magnetite. Mineralogical composition of the heavy mineral separates was determined by X-ray diffraction (XRD) and Scanning Electron Microscope (SEM).

DETAILED CASE STUDIES

Petäjävaara

The Petäjävaara site is situated between the Petäjävaara hill and the Kemijoki river (Fig. 7). The absolute height varies between 65 m and 140 m a.s.l. (top of hill is about 223 m a.s.l.). Overburden is thin and several bedrock outcrops occur in the northwestern and northeastern parts. Rogen moraines dominate in central parts of the area.

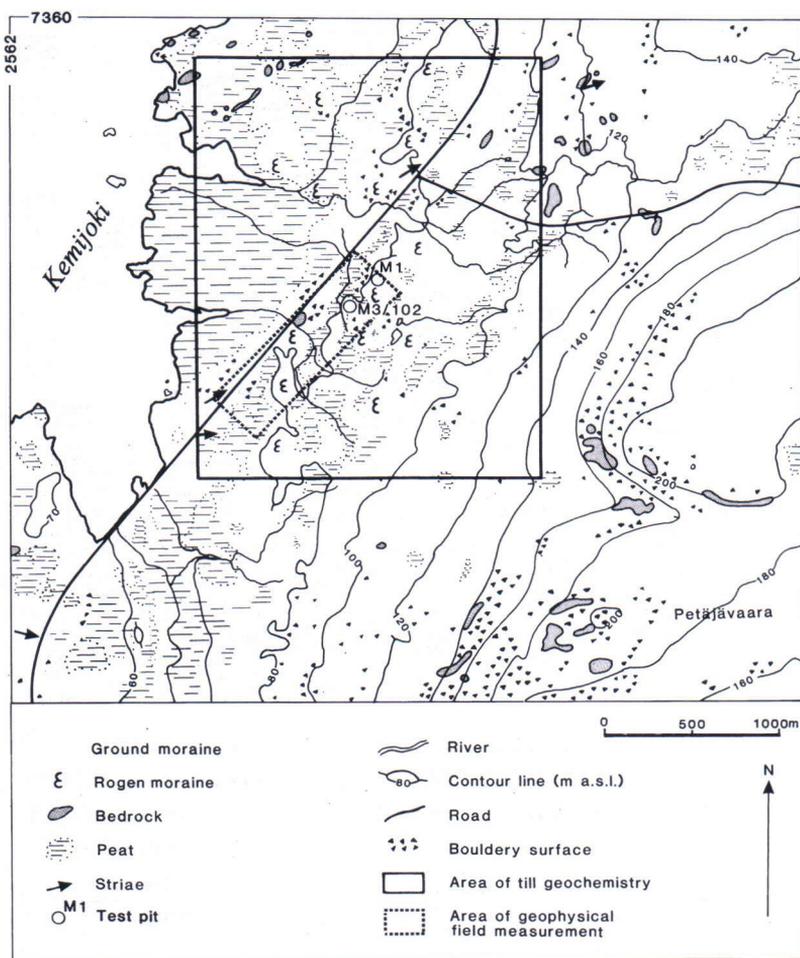


Fig. 7. Quaternary deposits and topography at Petäjävaara.

Bedrock is composed of quartzite and basic volcanic rocks (Fig. 8). Some diabase dykes are present in the southern parts of the area. Variation in the bedrock lithology is reflected in the boulder lithology on the ground surface. Two types of ore boulders have been found. Quartzite boulders are common 0.5 km to the NW from the test pit M1, and boulders of basic volcanic rock near the test pit M1. Both types are hydrothermally altered containing pyrite, chalcopyrite and magnetite. Boulders are quite large and angular.

A few striae observations were made at Petäjävaara. One cross striae set (336° and $275\text{--}280^\circ$) was found on the northern side of the case

study site. The older ice flow direction is north-westerly and the younger one westerly. Four observations (245° , 245° , 265° , 278°) of an age of the younger ice movement were found. A SW-NE direction is a sign of flow deflection of the glacier ice in front of the Petäjävaara hill.

Till stratigraphy

Rogen moraine ridges are composed of two till units (Fig. 9), which represent different ice flow phases. The lower unit is grey sandy till ($D_{50} = 0.5$ mm), which is mainly massive, but in places some fine-grained laminae can be found. The clay

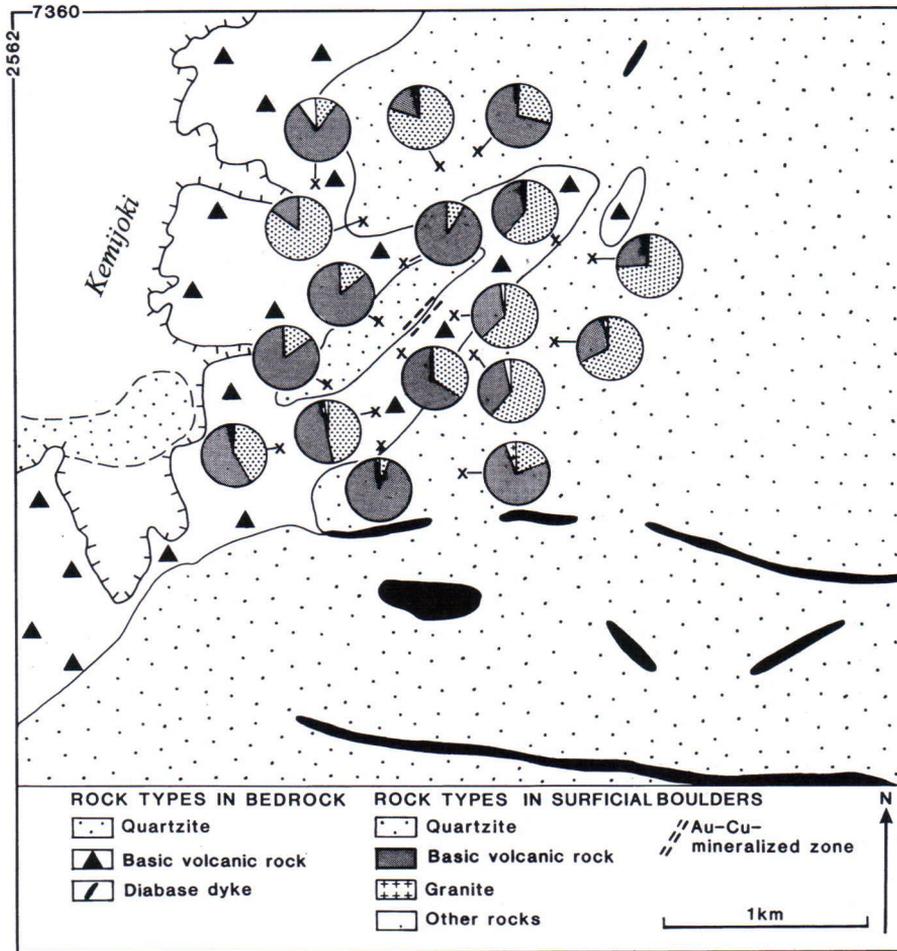


Fig. 8. Bedrock geology and surficial boulder lithology at Petäjävaaara. Local ice flow direction has been from southwest to northeast because the glacier flow was deflecting around the Petäjävaaara hill.

content is low. The clast lithology is: 37 % quartzite, 53 % basic volcanic rock, 5 % granite and 5 % other rock types (phyllite, vein quartz or chlorite schist). Granite clasts represent far-transported debris because their source rock is 30 km NW in the Central Lapland Granite Complex. Clasts are usually rounded with long-axes orientation NW-SE and inclination of 10–15° to the southeast. A clear transverse orientation is also seen in a composite rose diagram (Fig. 9). The poor pebble orientation was possibly caused by the disturbing effect of large boulders in till during deposition. Because of its compact structure and mature texture this grey till has been interpreted to be a

sal till (cf Dreimanis 1989), deposited during an active ice flow from northwest.

Between the two till units one can often find a sheared zone, layers of sand and sometimes a boulder pavement.

The upper unit is sandy or gravelly ($D_{50} = 5.25$ mm), brownish grey till, which is more heterogeneous than the lower one. Clay content is low (under 1%). Deformation, fine-grained layers and sandy lenses are typical features. The amount of very angular pebbles and boulders is high. Clast lithology varies according to variations of rock types in the underlying bedrock. The content of granitic pebbles is lower as compared to the low-

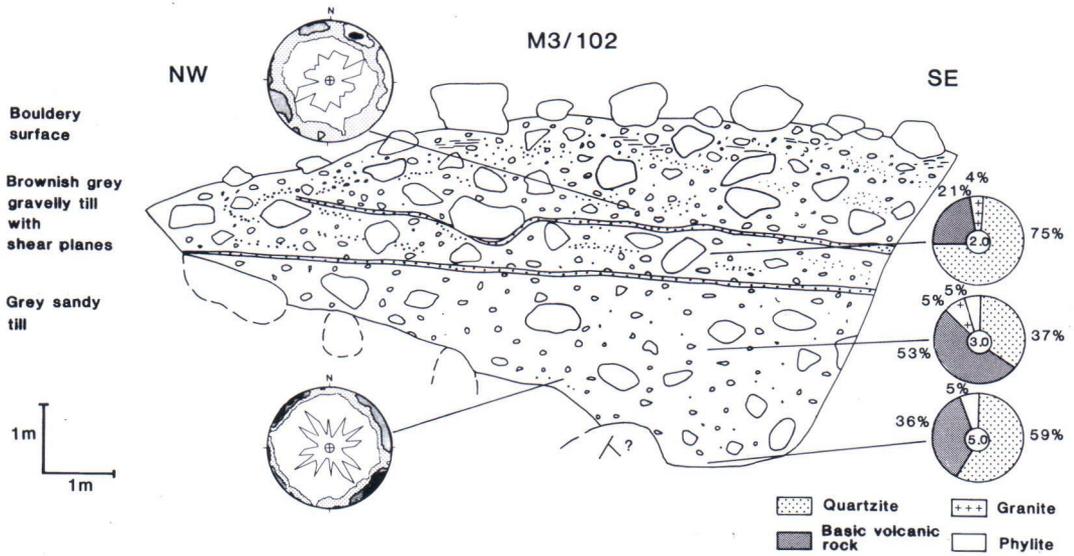


Fig. 9. Lithostratigraphy of section M3/102 at Petäjävaara.

er till unit. The presence of very easily crushable schist pebbles and pyrite crystals in till matrix are signs of the local provenance. Till fabric analyses show an orientation maximum in the direction of 240–270° with low (10–20°) inclination. A general ice flow direction has been W-E. The more southwesterly direction is caused by deviating movement of the ice sheet around the Petäjävaara hill. Gravelly and sandy shore deposits cover the upper till unit in some test pits. These deposits are usually 1–1.5 m thick and occur at 100 m a.s.l.

The coarse texture, sandy lenses and fine-grained sediment layers together with good till fabric are the typical features of a melt-out till (Boulton 1976, Dreimanis 1976, 1989, 1990). Steep inclination in some till fabric analyses may be caused by the deposition in subglacial or marginal conditions during flow processes. Also melt-water activity at the time of deposition is a noteworthy factor because a lot of fine-grained particles have been washed away from primary glacial debris.

Till geochemistry

Statistical parameters for the contents of the analyzed elements in the fine fraction of till are shown

in Table 1. The distributions of Au, Cu and Te are positively skewed, which can be seen in the high values of standard deviation and the coefficient of variation. Arsenic contents are low and have no correlation with Au ($r = 0.02$). This is significant because As is usually regarded as a good pathfinder for Au (Boyle 1979). Tellurium contents are low, too, but they correlate well with Au ($r = 0.81$). The correlation between Cu and Au is also good ($r = 0.70$).

The statistical parameters for the contents of the analyzed elements in the fine fraction of till from percussion drilling are presented in Table 2. Arsenic has not been analyzed. The mean contents of metals, especially that of Cu, are high. The standard deviation of Au contents is high and the coefficient of variation is even higher than in the test pit samples. This shows anomalous distribution and local derivation of Au in till. The correlation between Au and other metals is poor.

The areal distributions of Au, Cu and Co contents are shown in Fig. 10. Both test pit and percussion drilling samples have been taken into account. Only the highest contents (one sample/pit) from the test pit samples have been included. Gold and Co have anomalous values almost in the whole test area. The high Cu contents are concen-

Table 1. Statistical parameters of elements in the fine fraction of till from test pits at Petäjävaaara. *x* = arithmetic mean, *s* = standard deviation, *md* = median, *c* = coefficient of variation, *min* = minimum and *max* = maximum. *n* = number of samples.

	Au ppb	As ppm	Co ppm	Cu ppm	Ni ppm	Te ppb	n
<i>x</i>	13	5	23	366	46	41	90
<i>s</i>	39	3	11	423	31	42	
<i>md</i>	3	5	19	208	31	29	
<i>c</i>	2.9	0.6	0.5	1.2	0.7	1.0	
<i>min</i>	< 1	< 3	7	35	17	7	
<i>max</i>	245	11	54	3030	162	315	

Table 2. Statistical parameters of elements in the fine fraction of till from percussion drilling at Petäjävaaara. *x* = arithmetic mean, *s* = standard deviation, *md* = median, *c* = coefficient of variation, *min* = minimum and *max* = maximum. *n* = number of samples.

	Au ppb	Co ppm	Cu ppm	Ni ppm	Te ppb	n
<i>x</i>	5	23	203	49	38	166
<i>s</i>	32	15	198	88	67	63 (Te)
<i>md</i>	1	18	139	38	25	
<i>c</i>	6.1	0.7	1.0	1.8	1.8	
<i>min</i>	< 1	5	7	10	< 1	
<i>max</i>	417	88	1100	1120	533	

trated in the central part of the area. The highest contents of all three metals follow the NE-SW oriented contact zone of quartzite and basic volcanic rock (cf Fig. 8).

In order to study the distribution of metals between different size fractions, 30 samples from seven test pits were sieved. Twenty three samples were from brownish grey till (Fig. 11) and seven from grey till. The overall figure for Au, Cu and Te is almost the same with the highest contents in the fine fraction. The behaviour of S is different: the highest contents are in the sand fraction. One possible explanation is that pyrite is quite coarse-grained in the bedrock and therefore it has been enriched in the coarser fractions of the till. Gold and Cu have very high contents in every analyzed fraction above and/or near the mineralized zone. The test pit M1 is a very good example of that. Relatively high contents in test pit M4 are also a sign of the close relationship between the mineralized zone and the till. Some high Au contents in test pit M104 obviously derive from

a very local, unknown source rock.

As a result of the present exploration, Cu-Au mineralization in the shear zone was localized in the close vicinity of the ore boulders near the test pit M1 (Fig. 8). The transport distance of the boulders was only a few metres or some tens of metres at most.

Vammavaara

The Vammavaara site is located to south from the Vammavaara hill (Figs. 12 and 13). The absolute height varies between 60 m and 120 m a.s.l. (the top of the hill is about 228 m a.s.l.). The northern part of the area is dominated by Rogen moraine. Dead-ice hummocky moraines with kettle holes occur to the south of Suolijoki. In the southern part, till is thin and a lot of bedrock outcrops are present. No striae observations have been made at Vammavaara.

The bedrock is composed of quartzite, basic volcanic rocks, tuffite, dolomite and phyllite (Fig. 14).

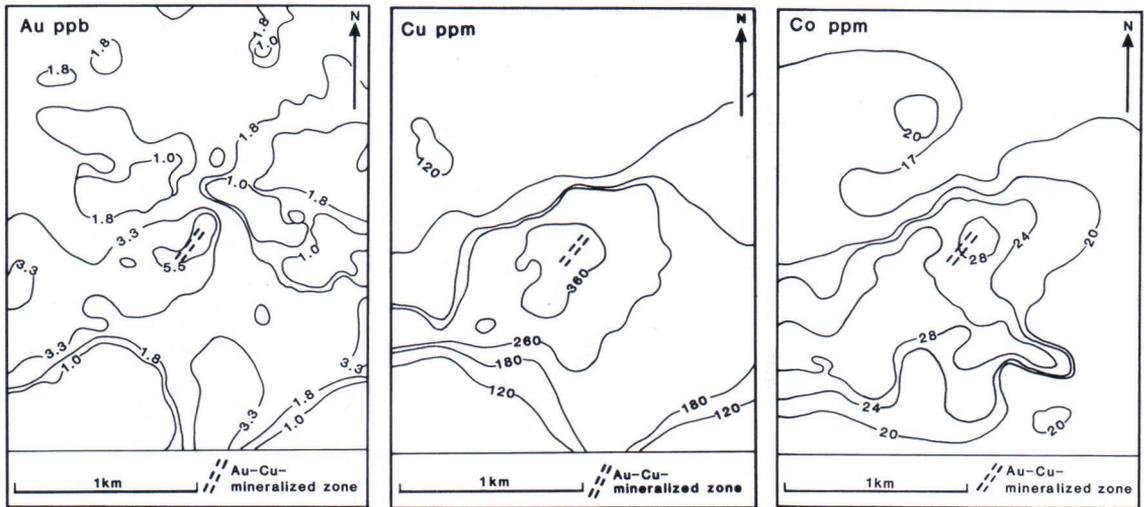


Fig. 10. Distribution of a) Au, b) Cu and c) Co in till at Petäjävaara.

The proportion of far-transported granites in the surface boulders is higher than at Petäjävaara, particularly in the western part. This reflects the relatively high amount of englacially or supraglacially transported material in the surficial till. Local derivation of boulders is clearly seen in the central and eastern part of the boulder counting area, both of which are dominated by Rogen moraine ridges. Two ore boulders of basic volcanic rock type have been found (Fig. 13 and 14).

Till stratigraphy

Three different till units representing different ice flow phases have been observed in the Rogen moraines at Vammavaara (Fig. 15). The lowermost unit is a dark, bluish grey till, which has been found as a layer in the bottom of two test pits (M21/113, M28) and as lenses in upper till in some test pits. The till is fine-grained ($D_{50} = 0.2$ mm) and its clay content is relatively high (7%). Only one fabric analysis with NW-SE orientation and low inclination of pebbles ($5-10^\circ$) was done. Pebbles are well-abraded and rounded. Pebble lithology is as follows: 40% quartzite, 20% basic volcanic rock, 20% granite and 20% other rock types (phyllite, dolomite and vein quartz). The dark till has been preserved in low-lying areas on

proximal sides of the hills. Because of the high clay content, the till has probably been deposited as the first till bed after the Eemian interglacial period during Early Weichselian (cf Rainio & Lahermo 1976, 1984, Hirvas 1991, Lintinen 1995) and so it includes material from the old weathering crust and pre-existing fine-grained sediments. The very compact structure might be due to the clayey matrix and the high pressure of the ice sheet during Middle Weichselian glaciation.

A two metres thick unit consisting of layers of sorted sand and gravel or stony flow sediments occurs above the dark till in the section of M28. The test pit is situated on the western slope of the Vammavaara hill. Clasts of the unit seem to be very local: almost 75% are quartzites derived from the underlying bedrock. The unit could have been deposited in certain subglacial conditions, where pressure melting under the ice has produced a lot of meltwater. The second till unit occurs directly on the dark till in test pit M21/113.

The second unit is grey sandy till ($D_{50} = 0.4$ mm), massive in its structure. Sand lenses and laminae of fine-grained sorted sediments occur. Its clay content is low (about 1%). The clast lithology is: 30% quartzite, 40% basic volcanic rock, 15% granite and 15% other rock types (phyllite, dolomite, mica schist or vein quartz). The pebbles are rounded and

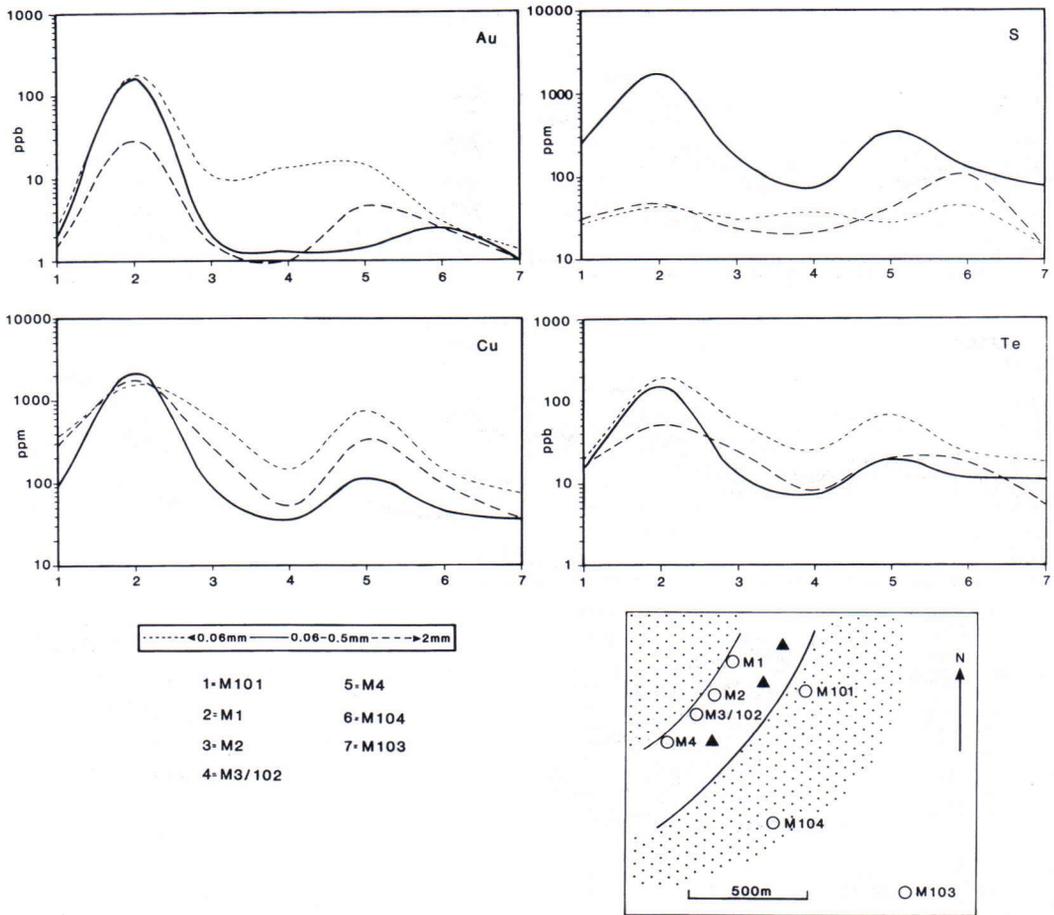


Fig. 11. Gold, Cu, S and Te contents in three till fractions of brownish grey till at Petäjävaaara. Total number of samples is 23 and arithmetic means have been used. Bedrock geology and location of test pits are shown in the map (symbols as in Fig. 8).

the inclination of their long axes is about 10–20° to variable directions. Pebble orientation is mainly W-E. Strong transverse orientation is also present in places. The compact structure with a minor stratified component suggests that the till has been deposited as lodgement till in subglacial conditions during an active ice flow from the west.

Sorted and sheared sandy or silty layers, some tens of centimetres thick, are observed above the grey till. There is also one observation of 60 cm thick gravelly flow sediment in the section of test pit M27 under a 15–20 cm thick silty layer. A gravelly ($D_{50} = 30$ mm) and dark grey diamict unit, one metre thick, occurs in two test pits (pit M33

shown in Fig. 16). It is rich in very angular boulders and pebbles (composed nearly 100 % of basic volcanic rocks). It is supposed to be a slice of deformed weathering crust with quarried fresh boulders carried two hundred metres along the ice bottom. There are usually no interlayers between the lower grey and the upper till beds.

The upper till unit is variable in its characteristics in the Rogén moraine ridges. It is divided into western and eastern types. On the western part this unit is composed of sandy or gravelly brownish grey till, which is more heterogeneous and coarse ($D_{50} = 3.2$ mm) than the lower tills. The clay content is very low. The mean thickness of

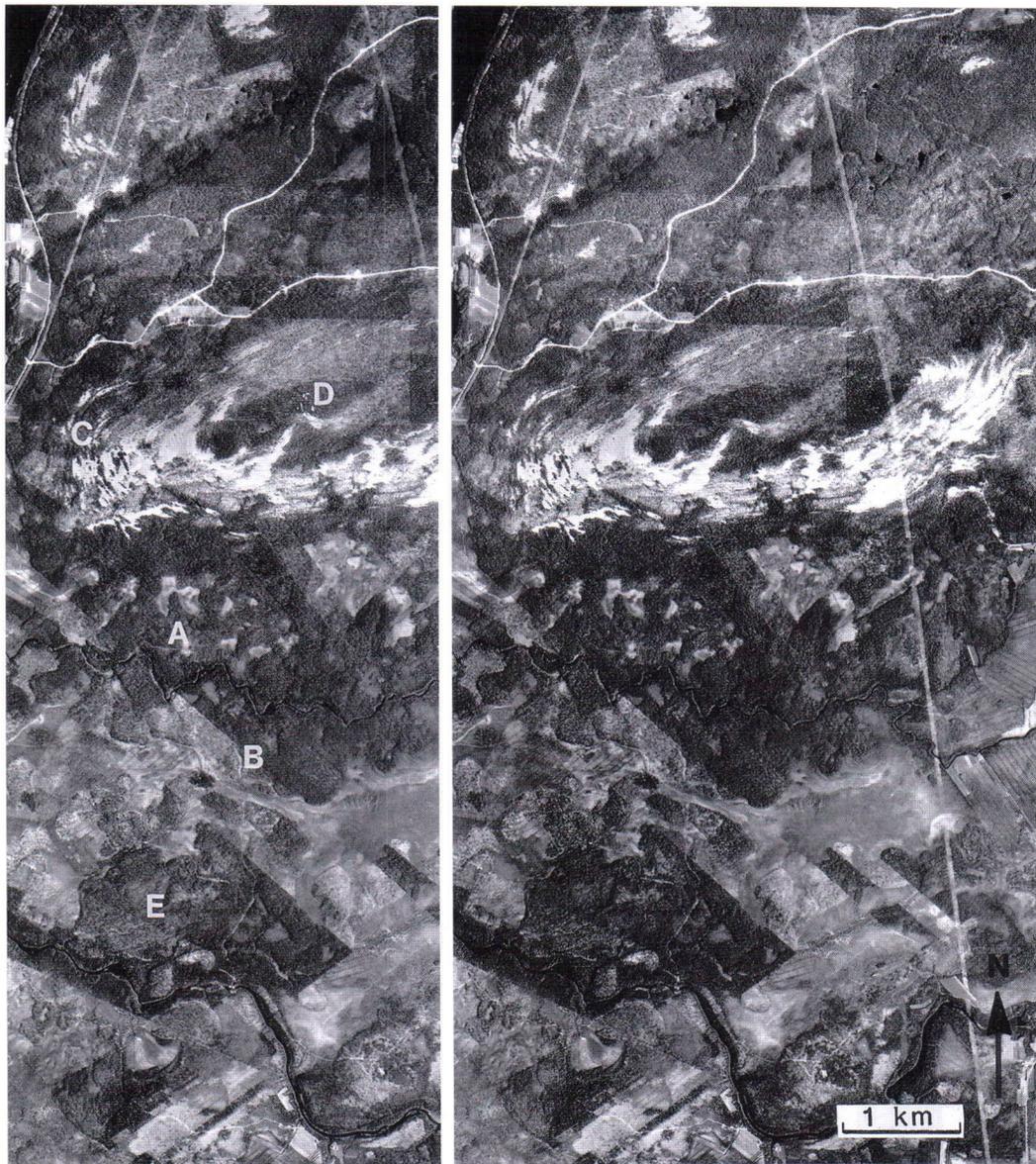


Fig. 12. Rogen moraine ridges (A), dead ice hummocks (B) and beach gravels of Ancylus Ice Lake (C) at Vammavaara (aerial photos 7703/15 and 16). Vammavaara hill in the north has a supra-aquatic top (D) and in the southern parts of the figure there occurs cover moraine with plenty of outcrops (E). Youngest ice flow direction has been from west to east. By courtesy of Topografikunta (The Army Map Service).

that unit is about 2.6 m. Sandy or silty layers and lenses with deformation structures are the main features. The till contains a lot of angular pebbles and boulders whose lithological composition varies with the underlying bedrock. The amount of granite pebbles is low. Till fabric analyses show

an orientation maximum in the direction 240–270° with inclinations 10–20°. The structures indicate that the till in the western parts has been deposited as a melt-out till.

In the eastern parts of the Rogen moraine area, the mean thickness of the sandy ($D_{50} = 0.5$ mm)

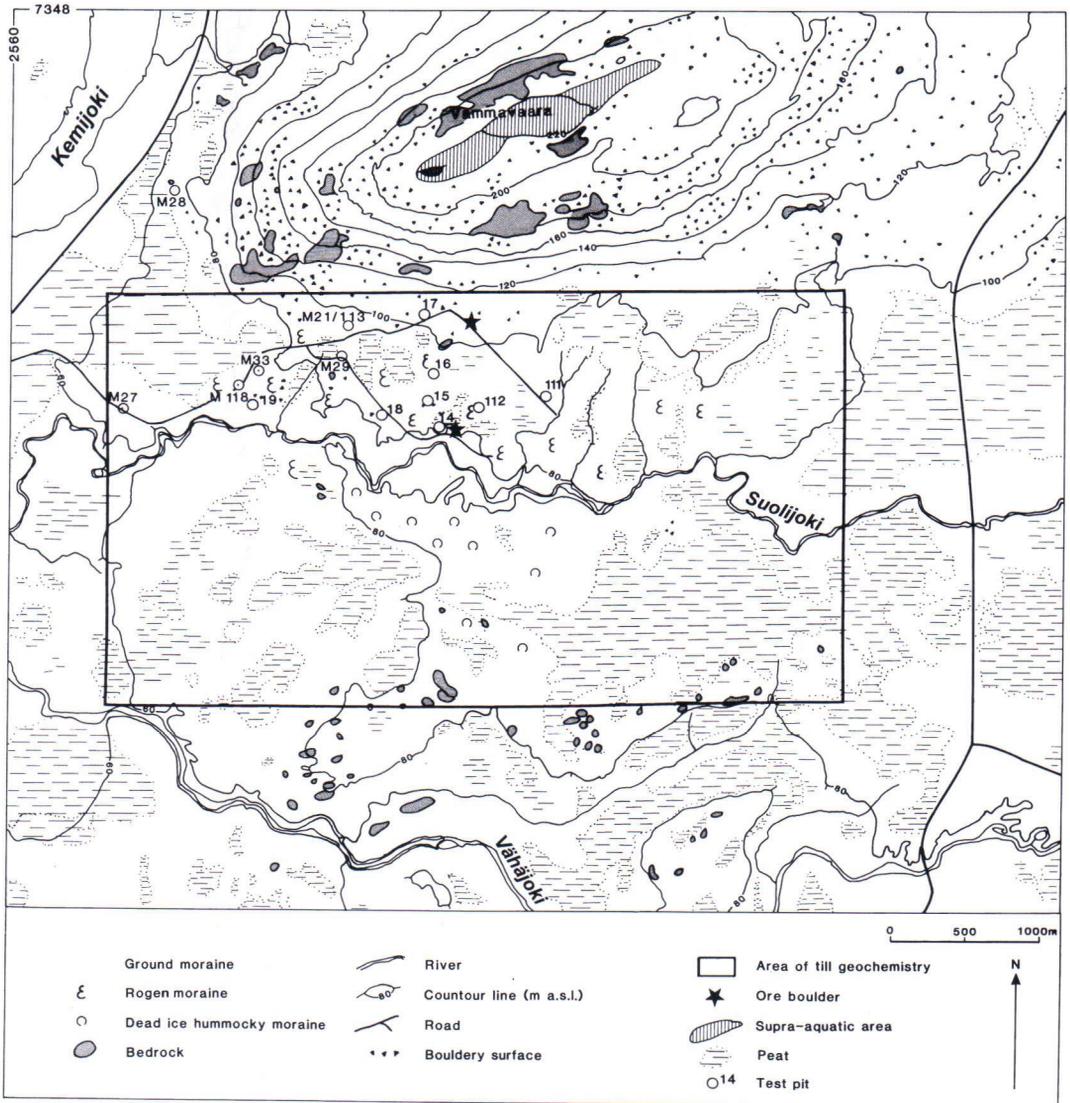


Fig. 13. Quaternary deposits and topography of Vammavaara.

till bed is 4.5 m. The amount of boulders is lower than in the western area and a lot of sandy-rich layers and lenses have been found. These properties refer to high meltwater activity during deposition and are typical features of melt-out till. Pebbles are usually more rounded and far-travelled than in the west. Steep inclination and poor orientation of the pebbles might also be a sign of secondary flow processes during deposition.

The upper till is covered by a one metre thick silty, laminated (varved) and dropstone-rich sediment in some western test pits. It is interpreted to be a glaciolacustrine deposit. These sediments have been deposited obviously in quite a deep water, while floating icebergs have been present. At a later stage, when the water depth decreased, the upper parts of morainic ridges have been washed and covered by sandy and gravelly shore deposits.

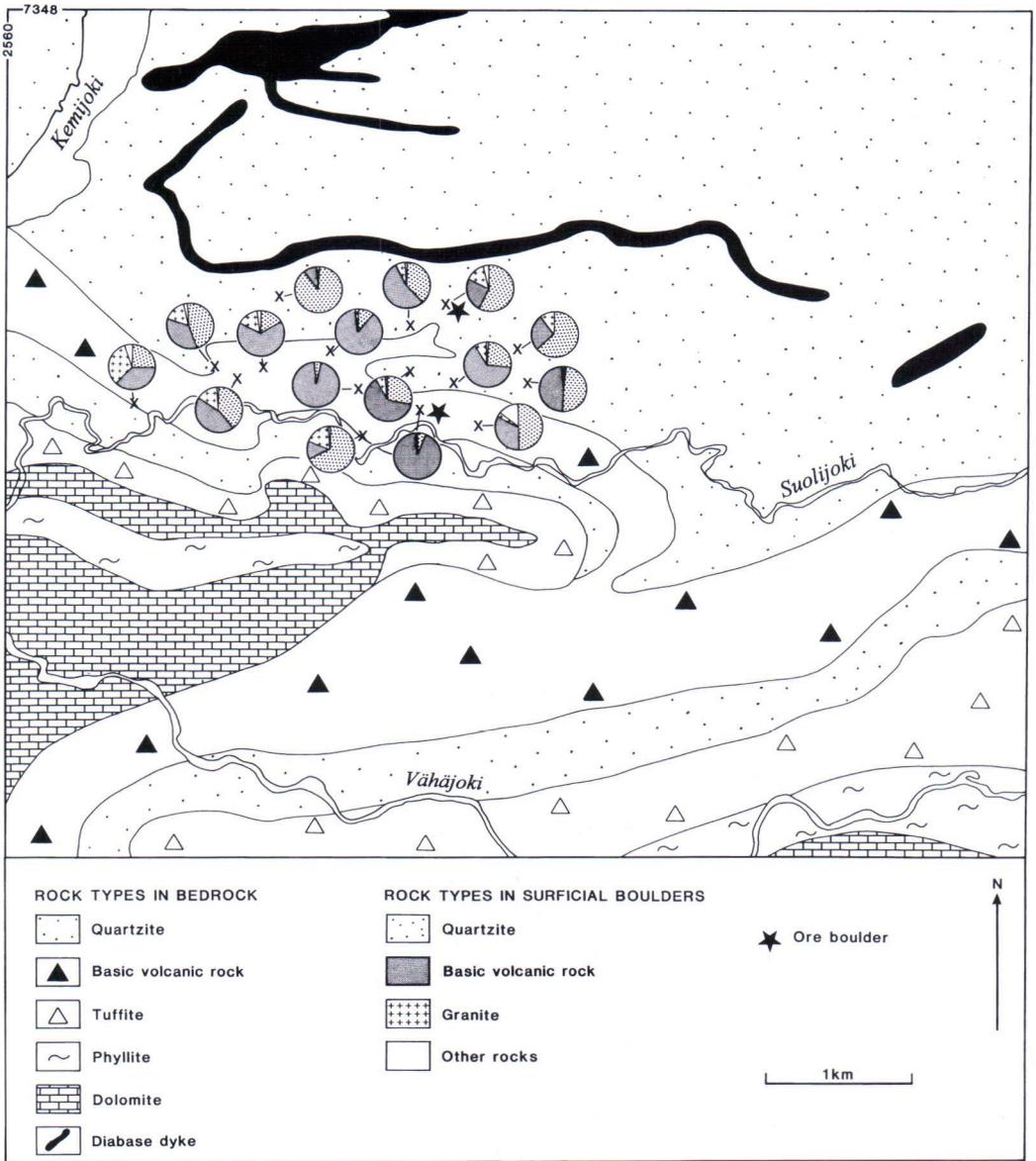


Fig. 14. Bedrock geology and the surficial boulder lithology of Vammavaara. Youngest ice flow direction has been from west to east. Sites of the two ore boulders are also marked.

Till geochemistry

Metal contents in the fine fraction of till are lower at Vammavaara as compared to those at Petäjävaara (Table 3). Copper shows anomalous distribution, but Au contents are only a little higher than normal in Finnish till (cf Koljonen

1992). Arsenic and Co contents are at the same level as at Petäjävaara.

The statistical parameters for the contents of the analyzed metals in the fine fraction of till of percussion drilling are presented in Table 4. Gold, Ni and Te contents are higher than in the test pit samples. Gold has a very high value of coefficient of

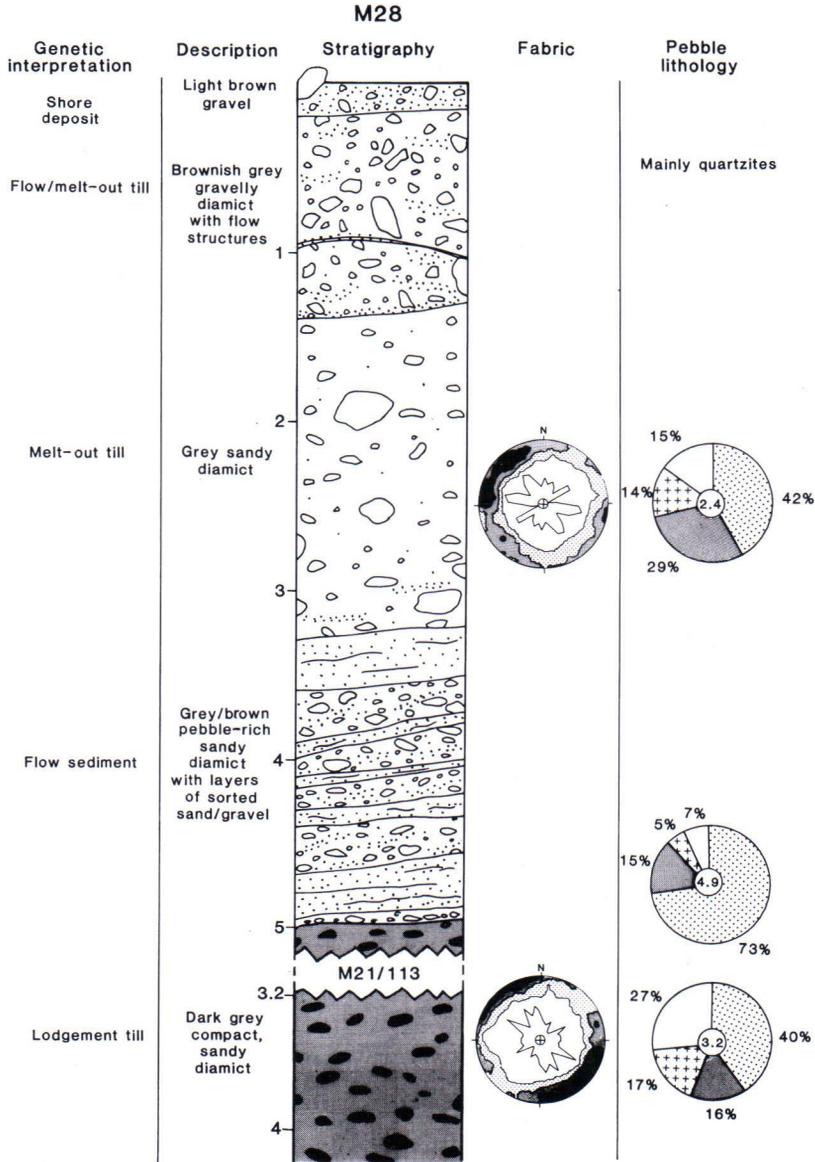


Fig. 15. Lithostratigraphy of section M28 and the bottom part of section M21/113 at Vammavaara. Pebble lithology: symbols as in Fig. 14.

variation. The correlation between different metals is poor.

The areal distributions of Au, Cu and Co contents are shown in Fig. 17. The highest contents are concentrated to the northwestern and central parts associated with the occurrence of basic volcanic rock and its contact with quartzite.

Three fractions of the 45 till samples from nine test pits have been sieved from the brownish grey till unit. Gold, Cu, S and Te contents in the different size fractions are shown in Fig. 18. In test pits M14 and M33 Au and Cu contents are clearly anomalous. Sulphur contents in the 0.06–0.5 mm fraction are almost tenfold compared with other

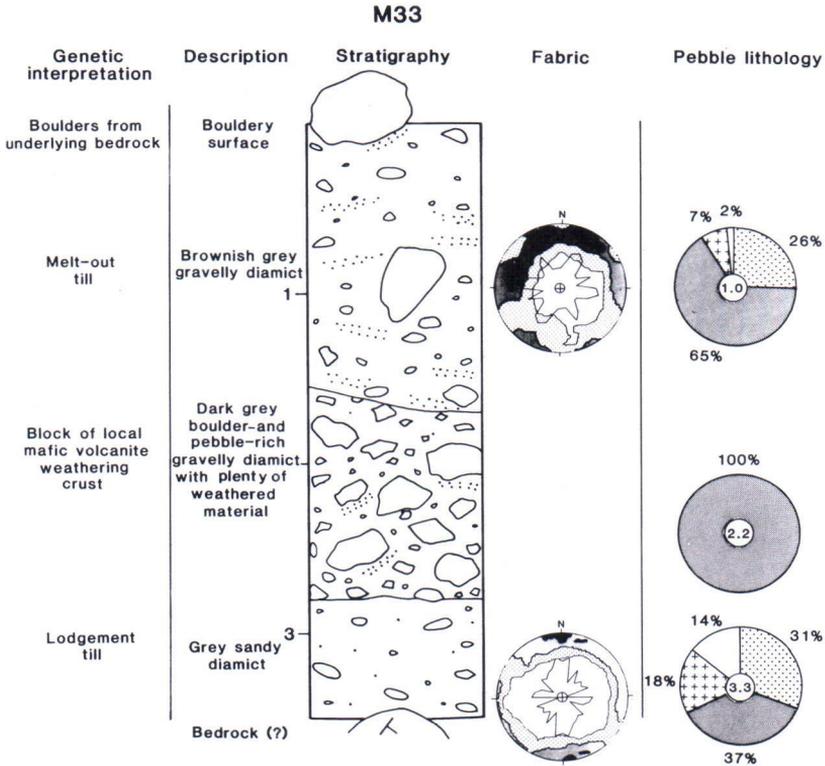


Fig. 16. Lithostratigraphy of section M33 at Vammavaara.

fractions. This feature may be explained with the same reason as at Petäjäväära, because S occurs as sulphide grains in the 0.06–0.5 mm fraction.

HEAVY MINERAL GEOCHEMISTRY

No Au grains have been found in the heavy mineral separates, although some high Au contents in the separates both at Petäjäväära (16.9, 15.0 and 12.5 ppm) and Vammavaara (17.8, 8.3 and 2.6 ppm) have been analyzed. The reason may be the very small grain size of Au particles and also the nugget effect. Polished thin sections of ore boulder samples from Vammavaara show that the size of Au grains is some microns only. Statistical parameters of the analyzed metals of the heavy mineral samples are shown in Table 5. Both Au and Cu show highly skewed distribution. Samples from Petäjäväära have higher contents of Au and Cu than those from Vam-

mavaara. Instead As and Co contents are at normal levels. A remarkable feature is the presence of well-preserved sulphide minerals (Fig. 19), which could suggest that Au might occur as inclusions in chalcopyrite and pyrite grains (cf Nikkarinen 1991). However, the results show that under favourable circumstances heavy mineral geochemistry of till is also a suitable prospecting method in searching for sulphide ores as Peuraniemi has suggested earlier (1990, 1991).

CONCLUSIONS

Rogen moraine is the most prominent glacial landform type in the study area. In places it has transitional forms with drumlins. Large areas are also covered by ground and cover moraines. Proglacial Ancyclus Ice Lake and the subsequent Litorina Sea have also modified the surface morphology.

Table 3. Statistical parameters of elements in the fine fraction of till from test pits at Vammavaara. x = arithmetic mean, s = standard deviation, md = median, c = coefficient of variation, min = minimum and max = maximum. n = number of samples.

	Au ppb	As ppm	Co ppm	Cu ppm	Ni ppm	Te ppb	n
x	3	4	19	107	25	16	178
s	6	2	16	114	9	12	150 (As)
md	1	4	14	60	23	13	
c	2.2	0.6	0.8	1.1	0.4	0.7	
min	< 1	< 3	7	16	12	5	
max	57	13	140	923	74	73	

Table 4. Statistical parameters of elements in the fine fraction of till from percussion drilling at Vammavaara. x = arithmetic mean, s = standard deviation, md = median, c = coefficient of variation, min = minimum and max = maximum. n = number of samples.

	Au ppb	Co ppm	Cu ppm	Ni ppm	Te ppb	n
x	4	15	58	30	19	236
s	23	8	52	13	18	
md	1	12	39	26	15	
c	5.8	0.5	0.9	0.4	0.9	
min	< 1	6	3	8	2	
max	322	71	331	95	170	

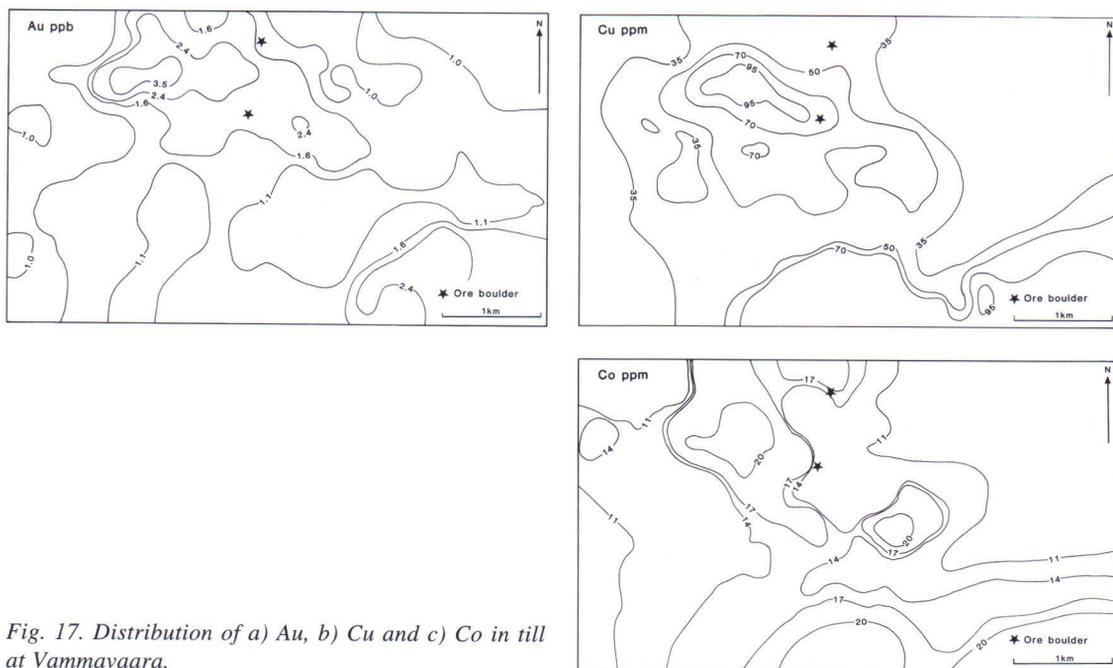


Fig. 17. Distribution of a) Au, b) Cu and c) Co in till at Vammavaara.

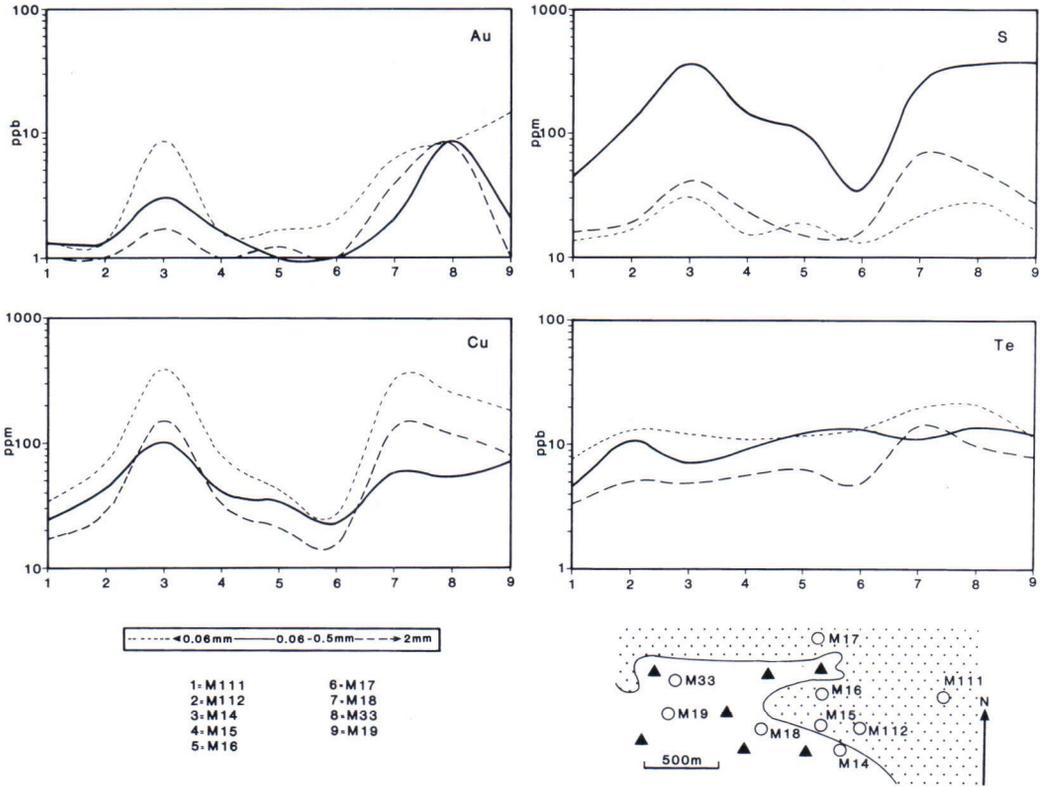


Fig. 18. Gold, Cu, S and Te contents in three till fractions of brownish grey till at Vammavaara. Total number of samples is 23 and arithmetic means have been used. Bedrock geology and location of test pits are shown in the map (symbols as in Fig. 14).

Three till beds with sorted interlayers have been found in the area. The lowest till bed, found at Vammavaara only, has a dark bluish grey colour, is rich in clay and silt and has a homogeneous and compact structure. That till bed with its NW-SE clast orientation has been interpreted as being formed in subglacial conditions during very early stages of Weichselian glaciation after Eemian interglacial, as proposed by Rainio and Lahermo (1976, 1984). The dark grey till is correlated with till bed III described by Hirvas et al. (1977) and Hirvas (1991). The second till bed with sandy matrix, far-transported pebbles, some sandy laminae and grey colour deposited as a melt-out till in subglacial conditions during the ice flow stage from west or northwest. The third and the uppermost till bed, composed of brownish grey sandy or gravelly till containing a lot of very local boulders

and pebbles, deposited as a melt-out or flow till as one can conclude from the structures like sorted sandy and silty lenses, fine-grained sediment layers and deformation structures. The main ice flow direction was toward the east, but local variations do occur due to the diverging ice movement around the highest hills. The upper till unit exists on both Petäjäväära and Vammavaara case study sites. Between different till beds, in particular at Vammavaara, there occur gravelly and/or sandy sediments as stratified interlayers. The till beds discussed here correlate with till beds II and I in Lapland (Hirvas 1991) and they also represent the two characteristic till facies of Rogen moraines as described by Aario (1990) at Portimojärvi, Ranua.

The results of till geochemistry show that there are anomalous contents of Au and Cu in all till

Table 5. Statistical parameters of elements in the heavy mineral separates at Petäjävaaara and Vammavaara. *x* = arithmetic mean, *s* = standard deviation, *md* = median, *c* = coefficient of variation, *min* = minimum and *max* = maximum. *n* = number of samples.

	Petäjävaaara n = 19				Vammavaara n = 33			
	Au ppm	As ppm	Co ppm	Cu ppm	Au ppm	As ppm	Co ppm	Cu ppm
<i>x</i>	4	33	48	209	2	35	55	47
<i>s</i>	6	7	14	602	4	11	42	42
<i>md</i>	1	35	46	69	1	33	38	26
<i>c</i>	1.6	0.2	0.3	2.9	2.1	0.3	0.8	0.9
<i>min</i>	< 0.01	21	31	33	< 0.01	21	21	10
<i>max</i>	17	40	89	2690	18	75	169	179

fractions in both case study sites, Petäjävaaara and Vammavaara. Metal contents in coarse till fractions are highest just over the mineralized zone and concentrations decrease rapidly as the transport distance increases. The most effective path-finder elements for Au, besides Au itself, are Cu, Te and Co having good or moderate correlations with Au. Arsenic with very low contents does not show any relation with Au.

As a result of detailed exploration studies, the Cu-Au mineralized zone in the contact of basic volcanic rock and quartzite was discovered at Petäjävaaara. The transport distance of surficial boulders is usually only from some metres to some tens of metres. Metal contents of till at Vammavaara are lower as compared to those at Petäjävaaara. Surficial boulders are mostly of local origin and transport distances are short. The

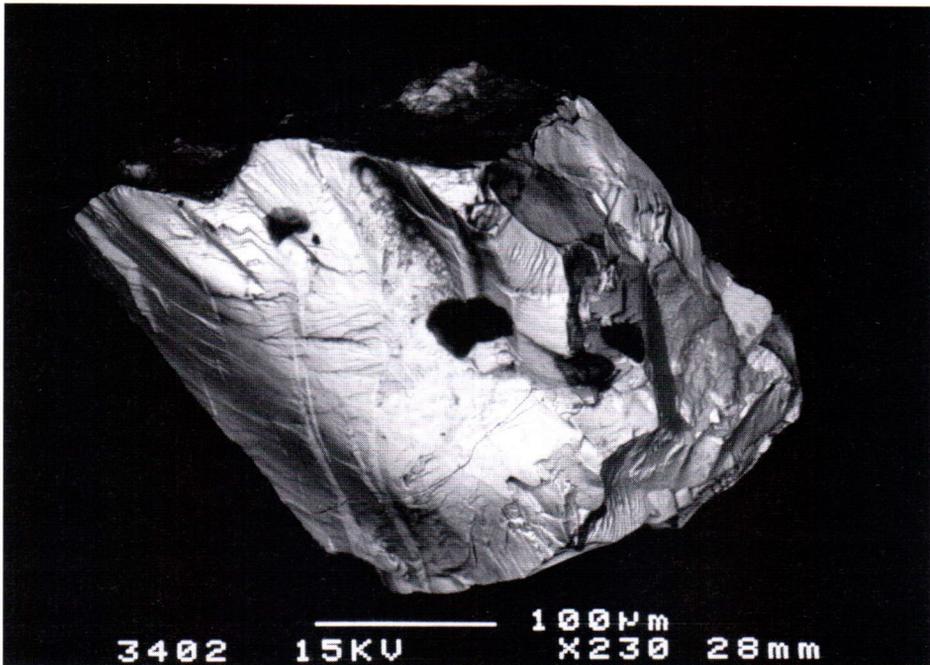


Fig. 19. A well-preserved chalcopyrite grain from till in test pit M1 at Petäjävaaara. Secondary electron image by SEM.

amount of far-transported granites is remarkable in the western part of Vammavaara and it reflects englacial or supraglacial transportation of the material in the surficial till in those areas. This leads to the conclusion that the origin of the two ore boulders could be on the western side of the studied site. However, the Au and Cu contents are anomalous in the middle of the site, so it is still possible that the source rock of the ore boulders is beyond the area studied.

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