MINERALOGY AND GEOCHEMISTRY OF THE FINE AND THE CLAY FRACTIONS OF TILL IN NORTHERN FINLAND

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Abstract

The mineralogy and geochemistry of the fine and clay fractions oftill in different moraine types and in different bedrock areas innorthern Finland have been studied. A total of 250 till samples from 140test pits were studied mineralogically and geochemically. X-raydiffraction, differential thermal and thermogravimetric analyses,transmission electron microscopy, X-ray fluorescence and atomicabsorption spectrometry were used as analytical methods.

In the clay fraction of till quartz, plagioclase, microcline andamphibole are the primary minerals occurring. The clay minerals properinclude vermiculite, chlorite, illite, swelling-lattice vermiculite andmixed-layer clay minerals. Kaolinite occurs most abundantly in the clayfractions of till in the Kittilä, Jerisjärvi, Kaaresuvanto and Puljuareas. In the clay fraction of Kittilä and Jerisjärvi illite isdioctahedral type, but in their of other study areas both di- andtrioctahedral types occur. Kaolinite and dioctahedral illite areevidence of the mixing of the weathered bedrock material into the tillmatrix. In the fine fraction of till most abundant minerals are primaryminerals and clayminerals are in a minor role.

In the clay fraction of till the content of primary minerals areat higher and secondary minerals are at lower level in the Granitic andArchaean gneiss areas than in the Greenstone Belt, Svecokarelian schistsand gneiss and Granulite areas. Amphibole, microcline and plagioclaseoccur in very low amounts or are totally destroyed by chemicalweathering in the clay fraction of the till in the Kittilä area. Themineral composition of fine and clay fractions in the tills of northernInari gives an indication that there occur much more mafic volcanitesthan is known today. The mineralogical compositions of fine fraction ofthe tills correlates quite well with the underlying bedrock in all studyareas, but clay fraction does not.

Geochemical results are in accordance with the mineralogicalcomposition of both fractions. In the fine fraction of the till Si, Caand Na contents are higher than in the clay fraction. Clay fraction isenriched in Al, Fe, Mg, K and trace elements as compared to the finefraction. Present study material points out that the distribution ofchemical elements in the clay fraction of the till does not correlatewith the composition of the underlying bedrock, but fine fraction doesso with a few exceptions. The chemical composition of till inKaaresuvanto and Inari does not fully correspond to the composition ofthe underlying bedrock as known today. In northern Inari and Kittilä theresults give an indication that there are more mafic volcanites and/orsulphide mineralizations occurring in these areas than is known at thepresent time.

The most important factors controlling the mineralogical andgeochemical composition of the fine and clay fractions of the tills innorthern Finland are the composition of the bedrock and the possibleoccurrence of an old weathering crust. The final grain size compositionof the tills and consequently the quantitative proportions of thedifferent minerals are often related to the last glacial quarrying andsorting processes; therefore the mineralogical composition of the tillsis to a certain extent bound also to the respective moraine type.

Keywords: clay minerals, geochemistry, moraines, northern Finland, till, trace metals, weathering

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Contents

1 Introduction

The study area in northern Finland is located in the central part of the former Fennoscandian ice sheet (Figs 1 and 2). The bedrock in northern Finland is composed of Archaean basement gneiss complex (over 2600 Ma), Palaeoproterozoic schist belts and greenstone belts (2450 Ma) and Palaeoproterozoic central Lapland late orogenic granite (1750–1800 Ma) (Fig. 1). Bedrock in central Finnish Lapland is covered by continuous or semicontinuous ancient weathering crust, which probably was formed during Tertiary or Cretaceous periods (Fricks 1906, Virkkala 1955, Vartiainen & Woolley 1976, Afanasev & Evezerov 1981). The area of weathered bedrock mostly coincides with the former ice divide zone of central Lapland (Figs 1 and 2).

Most of the glacial landforms in northern Finland were formed during the last deglaciation and were created predominantly under warm-based ice sheet, which was divided into separate ice lobes. There is evidence of several glacial cycles in northern Finland and it has been possible to compile regional ice flow patterns (e.g., Hirvas *et al*. 1977, Hirvas 1991, Aario & Forsström 1979, Sutinen 1984). There occur different morainic (ground moraine, cover moraine, hummocky moraines, drumlins, flutings, end moraines and several types of transverse ridges) and glaciofluvial landforms (eskers, deltas, sandurs and kames) in the study area. These landforms have been studied by several researchers (Brenner 1944, Virkkala 1952, Kujansuu 1967, Piirola 1972, Seppälä 1972, Hyvärinen 1973, Aartolahti 1974, Hirvas *et al*. 1977, Hirvas 1991, Heikkinen & Tikkanen 1979, Ignatius *et al*. 1980, Johansson & Nenonen 1991, Aario 1977a, 1977b, 1987, 1984, 1990, Aario & Forsström 1979, Aario *et al*. 1985, Aario & Peuraniemi 1992, Punkari 1996). In Sweden same types of studies have been made by Hoppe (1952), Minell (1979), Markgren and Lassila (1980), Lagerbäck (1988) and Lundqvist (1969, 1980, 1989).

In the Ancylus Lake phase of the Baltic (9000 B.P.) large areas were covered by water and the highest shorelines in the area are from this stage. At present time these ancient shorelines are seen as so-called calotte hills, in the high altitude areas. Also some areas were covered by local ice-dammed lakes. The highest shoreline in northern Finland is metacronous in nature and the whole area can be divided into subaquatic and supraaquatic parts. These parts have experienced different ice retreat mechanisms and resulting different glacial and glaciofluvial morphology (Eronen & Haila 1981, Eronen 1974, 1983, 1987, Aario 1990).

The principal aim of this thesis was to study mineralogical and geochemical composition of tills in different types of morainic landforms in the northern Finland. A second aim was to investigate the influence of the weathering crust and unweathered bedrock onto the mineralogy and geochemistry of tills. The material for this survey has been gathered during the so-called SOMA-project (Project for Applied Surficial Geology), (Aario 1984), which was financed by the Finnish Academy.

2 Earlier studies

The first comprehensive study on the mineralogy of Finnish tills using modern X-ray diffraction and differential thermal techniques was that of Soveri and Hyyppä (1966). Their till samples were only from southern Finland and they were exceptionally clay-rich (over 10% clay fraction < 2 μm) compared to the more normal Finnish sandy tills (2-3% < 2 μm). They found that the finest fractions of the tills are composed of quartz, feldspars, amphibole, illite, chlorite, vermiculite, so-called clay-vermiculite and the mixed-layer clay minerals of illite, chlorite and/or vermiculite. According to Soveri and Hyyppä (1966), the tills in the granitic bedrock areas contain less illite than the tills in the areas of other bedrock type. In the studies of Soveri and Hyyppä (1966) and Virkkala (1969), they concluded that the origin of the till fines are in part from preglacial weathered bedrock or from sediments deposited during interglacial ice-free stages.

Virkkala (1969), Perttunen (1977) and Nevalainen (1983, 1989) studied mineralogy and geochemistry of Finnish tills from several fractions, which included clay and silt fractions. They concluded that as the grain size becomes smaller, the homogeneity of the till increases. The till matrix represents bedrock material from much wider area than the coarse fractions do. The influence of the local bedrock upon the till material is most clearly shown in the boulder and pebble fractions. Also elsewhere, as for example, in Sweden (Linden 1975) and North America (Dreimanis & Vagners 1971a, 1971b) this same conclusion was done. The investigations by Haldorsen (1983) in Norway show that besides the composition of the source rocks also the till-forming processes and the depositional type of the till have an effect on the mineralogical and geochemical composition of the tills. According to Ihalainen (1994) the mineralogy of the fine fraction of the tills in northern Finland reflect both the original composition of the bedrock and the effect of postglacial weathering. Lintinen (1995) suggests a model for the regional scale distribution of till properties, with the emphasis on ice dynamics, hydrology, hydrography and the regional distribution and recycling of fine-rich material during the waning stages of the continental ice sheet. The quantitative contribution of the different factors can not be established, as their impact has been varied from one area to the other during the numerous glaciations.

In Canada Dreimanis and Vagners (1965, 1969, 1971a, 1971b, 1972) investigated the lithologic and mineral composition of basal till from several grain sizes. They concluded that every lithologic component of basal till has a bimodal size distribution. This is true for rocks that are monomineralic or contain minerals with similar physical properties. The clast sizes (>2 mm) have one of the modes and it appears near the bedrock source areas (clast mode). In the matrix (<2 mm) the mineral fragments have modes farther away from the source area (matrix mode) that are typical for each mineral. These mineral grades (terminal grades) represent the final product of glacial comminution. In Finland, in the areas of metamorphic rocks, where rock types change in short distance from one to the other, the nature of a moraine matrix is usually polymodal (Perttunen 1977, Nevalainen 1983, 1989).

Nieminen (1985) studied the quality of the fine fractions of a till and its influence on frost susceptibility. He became to the conclusion that the specific surface area is more reliable criterion in judgment for frost susceptibility than grain size.

Later studies in Finland have mainly used the dry-sieved < 60 µm fraction (a so-called fine fraction) and the method of analysis has been solely X-ray diffraction. Mäkinen (1992) investigated the relation between unit weight and geochemical and mineralogical compositions in the fine fraction of till. He concluded that as unit weight increases when the abundance of primary minerals increase and secondary minerals decrease. This is reflected in decrease of the contents of trace elements, Fe and Mn. In their investigations Räisänen and co-author (1992) and Räisänen (1996) demonstrated that the weathering of trioctahedral micas and chloritic clay minerals was the predominant process during the podzolization of till, in both thick and shallow tills. The rate of weathering, as well as the rate and maturity of podzolization, was more dependent on the composition of the till and hydrological conditions in the soil profile than on the age of podzolization. Throughout the profile, the predominant clay minerals were vermiculitic mixed-layer clays. Räisänen (1996) concluded that the postglacial weathering cycles are as follows: Chlorite --> chlorite-vermiculite --> vermiculite --> vermiculite-montmorillonite --> montmorillonite and trioctahedral illite --> illite-vermiculite --> vermiculite --> vermiculite-montmorillonite --> montmorillonite and dioctahedral illite --> illite-montmorillonite --> montmorillonite. Contradictory conclusions about effect of time to the postglacial weathering have been made by Righi and co-author (1997) and Gillot and co-author (1999). Righi and co-author (1997) investigated clay mineral transformations in podzolized tills in central Finland. According to this investigation pedogenic transformations of clay minerals occur essentially in the E horizons of podzols. Smectites and illite-smectite mixed-layers are the dominant clay minerals in the E horizons of soils older than 6500 years. The number of mixed-layers decreases with evolution of the soil, leaving a nearly pure smectite phase in the oldest soil (10 000 years). The smectites are dioctahedral with tetrahedral charge. Groups of low-charge and high-charge interlayers are both present in the samples, but low-charge smectite layers were found only in the two older soils (9500-10 000 years). This suggests alteration with time of the high-charge smectites. In the investigation on pedogenic formation of clay minerals in till and glaciofluvial sand sequences Gillot and co-author (1999) presented that the same pedogenic transformations of clays occurred in both sample types. Dioctahedral smectites (beidellite) were formed in podzol older than 6500 years when developed from tills, whereas only 1200 years were required to produce smectites from glaciofluvial sands. For all the podzols the layer-charge of the smectites decreased with time; low-charge smectites were observed in the oldest podzols (more than 9000 years), suggesting a possible alteration with time.

Lintinen (1995) studied the variable content of clay in the fine till fraction, but he analyzed the fraction < 20 µm, which besides clay contains also fine silt. This was due to the small sample size. He used X-ray diffraction as the main method and infrared spectroscopy in identifying kaolinite. According to Lintinen (1995), the mineralogy of the Finnish tills is similar in different parts of Finland. The mineralogy of the Finnish bedrock is fairly monotonous. Differences in bedrock are mainly reflected in the occurrence of chlorite and talc of the till in the area of greenstones containing these minerals. In the area of Lapland schist belt and in the komatiite zone chlorite, talc and amphibole occur in higher abundances than elsewhere. He also concluded that the abundances of these minerals also depend on the grain-size distribution. The clay mineralogy of the till samples from the oxidized surficial parts of sampling profiles often differs from that of the samples from the lowest parts of profiles, which are partly below the groundwater level. The mineral alterations are thought to have taken place in soil forming processes once the land surface was exposed from under the continental ice sheet or water (Lintinen 1995). He has become to the conclusion that the time, which has passed since the area was liberated from either the continental ice or water does not seem to have a clear correlation with the process of weathering. He became to conclusion that the rate of postglacial weathering depends on the clay fraction content of fines more than on time. On the basis of the Marjapuhto section at Ylivieska Lintinen suggested the following weathering order: Chlorite --> chlorite-vermiculite (14 Å) --> vermiculite-chlorite --> vermiculite and trioctahedral mica --> trioctahedral illite --> mica-vermiculite (12 Å). On the basis of the profile of Päntäne, the weathering cycle in the Kertturinkylä section is probably following: Trioctahedral mica --> trioctahedral illite --> mica-vermiculite --> vermiculite-chlorite with Al-hydroxy interlayers --> chlorite. There is some kaolinite present in the profile of Marjapuhto suggesting far-advanced weathering that was taken place during postglacial time.

Droste (1956) studied the weathering of clay minerals in Wisconsinan tills in the northern USA. He noticed that each zone in the weathering profile of till is characterized by a specific clay-mineral assemblage (chlorite--> chlorite/vermiculite -->vermiculite).

The weathering of clay minerals during the podzolization process have been studied also in Norway, Sweden and Canada (Gjems 1960, 1963, 1967, Wiklander & Loste 1966, Wiklander & Alexandrovic 1969, Kodama & Brydon 1968, Kodama 1979, Kapoor 1972, Björnbom 1979, Melkerud 1983, 1984, 1986, 1991, Snäll *et al.* 1979, Snäll 1986, Olsson & Melkerud 1989). They concluded that the gradual decomposition of biotite and chlorite is a major weathering process in the podzolic layers of tills. Gjems (1967) noticed that some smectite type minerals are developed during the podzolization process. According to him it happened in acid weathering conditions. For example Kapoor (1972) inferred that the weathering process occurs as follows: biotite--> mixed-layer mineral and vermiculite (C and B layers)--> hydrobiotite (E layer)--> vermiculite (E layer)--> smectite (E layer). According to investigations of Wiklander and Alexandrovic (1969) and Melkerud (1983, 1986), smectite is directly developed from weathering products of chlorite and vermiculite. In the studies of Melkerud (1983, 1984, 1986, 1991) and Olsson and Melkerud (1989) the clay mineral species of podzolized till was vermiculite, Al-hydroxy interlayer vermiculite, mica/illite, kaolinite and chlorite. Smectite occurred only in the upper acid layer of the soil (A_2 layer). Snäll (1986) analyzed clay fraction from Swedish till samples and reached the conclusion that Fe-rich biotite has been weathered into vermiculite, and that the high kaolinite content in till indicates areas where preglacial kaolinitic weathering products occur beneath the till cover. According to X-ray diffraction studies of Snäll and co-author (1979), Björnbom (1979), Melkerud (1984), Snäll and co-author (1992) and Snäll (1986) the clay mineral composition of tills in Sweden is basically the same as that in Finland.

The mineralogical composition of the tills has been studied widely in ore exploration in Finland, but the main emphasis has been on sand fraction (0.06–0.5 mm) heavy minerals (Peuraniemi 1982, 1990). Investigations of glacial dispersal of till constituents in morianic landforms of different types serving ore exploration have been carried out by Peuraniemi (1982, 1991), Aario and co-author (1984), Aario (1990, 1992, 1994) and Aario and Peuraniemi (1992). They concluded that flow paths and transport distances vary with each landform type. In cover moraine areas, which are composed of some meters of lodgment till only, glacigenic dispersion commonly forms a narrow train with short transport distances. Ground moraine areas containing a thick overburden, the till material is transported over a further distance and the till matrix is mature and includes a large amount of fine-grained material. Drumlins and flutings are commonly composed of more or less homogeneous sandy till which is mostly distantly derived. Rogen moraines are commonly layered, with the lower part composed of distantly derived material and the surficial part usually of chiefly local material. The material of hummocky moraines built by active ice is counted as moderate range material. Pulju moraines consist of both hummocks and winding, arcuate ridges. Pulju moraines as well as lee-ridges are composed of long distance material. A Sevetti moraine forms a train of morainic landforms, which includes both parallel ridges and also hummocks and diversely oriented ridges. The till making up the landforms is immature and material is commonly of very local origin. Also the Vika moraine landforms are composed of very local material. End moraines are a heterogeneous group of landforms. The larger ones represent deposition over a long period of time with a steady ice margin position, and debris can be derived from long-distance transport. The smaller end moraines usually represent short-lived events and the till is very much the same as that of the intervening areas. Tills are poor in clay fraction and enriched with rockorming minerals in the areas of active ice (e.g., drumlins and flutings) and the areas of effective glacifluvial processes (e.g., eskers). On the contrary to former, tills are enriched with clay minerals (e.g., vermiculite, illite, chlorite ect.) and impoverished by rock forming minerals in the areas of passive ice process. The experienced cycles of glacial erosion, entrainment, transportation and deposition further contribute to the total amount of the clay fraction and consequently the clay minerals (Aario & Peuraniemi 1992).

Kauranne and co-authors (1977) and Salminen (1980) presented in their drift prospecting studies that the fine fraction (< 60 µm) of till has the best anomaly-background contrast. The difference between fine fraction and coarser fractions is mainly due to terminal grade-phenomenon and differences between rock types. They studied easily weathering sulphide minerals (cf., Dreimanis & Vagners 1971a, 1971b, Virkkala 1969, and Perttunen 1977).

In North America tills are usually richer in clay content than Finnish tills. Shilts (1971, 1973) noticed that such metals as Ti, Cu, Pb, Zn, Cr and Ni are enriched in clay fraction of the till. There is a good positive correlation between the amount of the clay fraction content in a till and these metals.

Shilts (1975, 1976, 1980, 1984, 1993, 1995), Klassen and Shilts (1977), DiLabio and Shilts (1977, 1979), DiLabio (1989) and Shilts and Kettles (1990) have studied the effects of weathering on the labile ore minerals in till and have carried out chemical partitioning studies in till. The phyllosilicate minerals and secondary minerals have a tendency to be enriched in the clay fraction. These phases have a high total surface area and exchange capacity, so they act as scavengers, adsorbing representative portions of trace metals that are released during weathering process. The clay fraction is the best fine-grained fraction of weathered till to use when analyzing for many elements because it is more metal-rich than any other fraction.

Shilts suggests, that the use of the clay fraction in till geochemistry is to be recommended for the following reasons: (1) dilution of the metal contents by quartz and feldspars is not so high in the clay as in the fine fraction; (2) there is a textural variation due to the variable clay content in the fine fraction but not in the clay fraction; (3) the higher level of the metal contents; (4) better anomaly/background contrast; (5) dispersal trains could be found where the primary sulphide minerals have been weathered away and the liberated metal ions have been partly scavenged by clay minerals and Fe-Mn oxides; (6) it is possible to find and map longer dispersal trains with a sparse sampling grid.

In Finland the geochemical composition of the clay fraction of till has been analyzed in occasional cases (Nikkarinen *et al*. 1984, Peuraniemi *et al*. 1996, 1997) as compared to the Canadian till geochemical studies. Nikkarinen and co-author (1984) studied mode of occurrence of Cu and Zn in till. They came in same conclusion as Canadian researchers. The contents of Cu and Zn tend to be highest in the < 2 µm fraction, and to decrease with increasing grain size. Nevalainen (1983, 1989) concluded that tills having a high content of clay minerals (including mica) have been enriched with trace elements.

Till has been the most widely used sampling medium in geochemical studies in Finland (Bölviken *et al*. 1986, Koljonen 1992 and the references therein) and even then only the fine fraction has been analyzed. In the study of Lestinen and co-author (1996) analyzed also the fine fraction of the till. The results showed that the geochemistry of the fine fraction of the till reflect well of the composition of the local bedrock.

In their investigations Peltoniemi (1981), Saarnisto and co-author (1980, 1981) and Saarnisto and Taipale (1984, 1985) inferred that the influence of bedrock upon the lithology and geochemistry of till is evident. The influence of Kuhmo greenstones on the fine fraction of the till can be seen as increased trace metal contents over long distances. Taipale and co-author (1986) analyzed the fine fraction chemically and on the basis of major element contents calculated the normative mineralogical composition of the samples. Usually the importance of the clay fraction has been omitted (cf., Saarnisto & Taipale 1985).

3 Study areas

The present study area (Figs 1 and 2) is situated in the northern part of Finland. In the west it is bounded by Sweden, in the north by Norway and in the east by Russia. Its southern boundary is about 65 ° north latitude. The study areas in this investigation are located in the municipalities of Suomussalmi, Kuusamo, Ylikiiminki, Kemijärvi, Rovaniemi, Kittilä, Ylitornio, Muonio, Kaaresuvanto and Inari.

3.1 Bedrock

The oldest part of the bedrock in northern Finland is Archaean basement gneiss complex (over 2600 Ma), which is composed of granitic and tonalitic gneisses and migmatites (Matisto 1958, Honkamo 1988; 1989, Koljonen *et al*. 1992). These rocks are composed mainly quartz, feldspars and micas (biotite). Elements like Ca, Na, Si and Sr, which are found in light-colored, felsic minerals, are present in the till above average concentrations. The gneisses are depleted in all the alkali metals except sodium and in Cr, Fe, Mg, Ni, Ti, Co, Cu, Pb and Zn. The concentrations of elements typical of mafic minerals are below but close to the average, probably because of the greenstones occurring in the same area (Koljonen *et al*. 1992). The study areas of Suomussalmi, Kuusamo, Kuivaniemi, Kaaresuvanto and northern Inari (Ahvenjärvi, Sevettijärvi, Suojanperä and Pyhävaara) are located in the geochemical province of Archaean basement gneiss complex defined by Koljonen and co-author (1992). The bedrock of northern Finland (after Kärki 1995) and the location of the study areas are presented in Fig. 1.

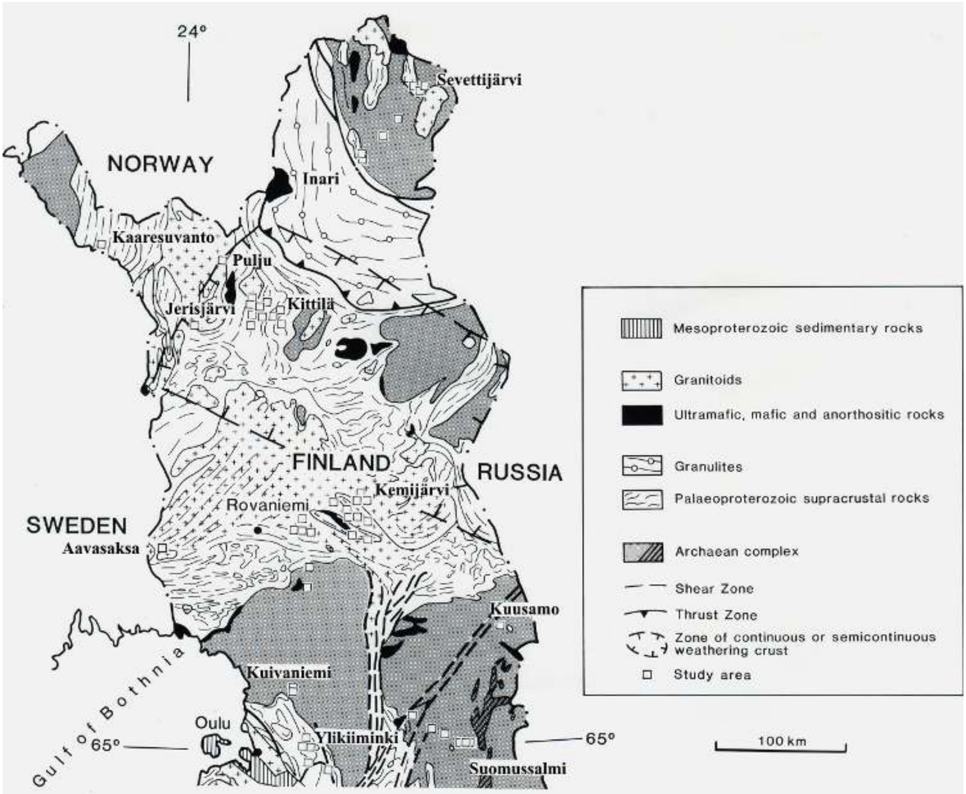

Fig. 1. The bedrock of northern Finland (according to Kärki 1995), the location of the study sites and extent of weathering crust (according to Hirvas 1991).

Palaeoproterozoic supracrustal rocks (1873-2093 Ma) are composed of greywackes, mica shists, black shists, dolomitic limestones, skarn rocks and mafic metavolcanics (Honkamo 1984, 1986, 1988, 1989). The Svecokarelian schists and gneisses are composed mostly of quartz, micas (biotite) and feldspars and as compared with the Archaean gneisses contain more mica (Koljonen *et al*. 1992). The average chemical composition of a till varies only slightly over whole area, is almost the same in all the subprovinces, and is even near the averages for a fine fraction of a till in Finland and upper continental crust. The concentrations of Co, Cr, Cu, Fe, Mg, Ni and Zn are slightly below the average level of Finnish tills (Koljonen *et al*. 1992). The study area of Ylikiiminki is situated in the geochemical province of Svecokarelian schists and gneiss.

The granitoid province of central Lapland (1750-1800 Ma) is composed mostly of granites proper and lesser extent of granitoids. Silica-poor mafic rocks are uncommon. The main minerals of granite are quartz, feldspars, plagioclase, muscovite and/or biotite (Hackman 1910, 1918, Ödman 1937, 1957 ,1958, Koljonen *et al*. 1992). The contents of trace elements are usually low in these rocks. In till the concentrations of major elements are close to the Finnish average, while those of trace elements are low. The chemical composition is similar to that in the areas dominated by Archaean gneisses in eastern Finland and by granitoids in central Finland. The tills are enriched in Na and impoverished in Co, Cu, Pb and Zn (Koljonen *et al.* 1992). The study sites of Kemijärvi and Aavasaksa are located in the geochemical province of Granitoid area of central Lapland defined by Koljonen and co-author (1992).

The greenstones in Lapland (2450 Ma) occur in the association with Lapponian schists and in places are ultramafic, komatiitic in composition. The chemical composition of greenstones, which are mostly composed of amphibole, chlorite and plagioclase, differs sharply from that of the Finnish schists and gneisses. Greenstones are also softer, weather more easily, and have been less resistant against the glacial abrasion than igneous plutonic rocks or gneisses and schists. All these volcanic rocks are composed mainly of amphiboles, biotite and plagioclase. Kittilä and Jerisjärvi are also situated in the area of preglacial weathering crust and former ice divide zone. In these areas great amounts of weathered bedrock material are mixed into tills (Lehtonen *et al.* 1985, Kallio *et al.* 1980, Peuraniemi *et al.* 1996, 1997, Koljonen *et al.* 1992). The greenstone area in Lapland is enriched in elements like Al, Ca, Co, Cr, Fe, Mg, Mn, Ni, and Ti, which are typical of mafic rocks. Tills are depleted in elements like K, P, Pb and Si, which are typical of felsic (granitoid) rocks (Koljonen *et al.* 1992). Study areas of Kittilä, Jerisjärvi and Pulju are situated in the geochemical province of greenstone belts in northern and eastern Finland defined by Koljonen *et al.* (1992).

The granulites in Lapland seem to have formed in the tectonic zone between two converging crustal plates. Palaeoproterozoic Lapland Granulite Belt (1930-1987 Ma) is composed of garnet-sillimanite gneisses (khondalites) and pyroxene granulites (enderbites) (Korja *et al.* 1996). The chemical composition of till in the granulite zone differs strikingly from that of the Archaean basement and greenstone areas nearby, and is not unlike that of the Proterozoic areas of southern Finland. Aluminum, Co, Cr, Cu, Fe, Mg, Mn, Ni and Zn are enriched in the granulite zone. The till is depleted in K, Na, Si, and Pb and in many of the other elements associated with granites. The high content of Al can be attributed to the above average content in the granulite and to the abundances of Al-rich preglacial weathering products in the till. The material metamorphosed to granulite was probably similar to laterite because the till is enriched in elements characteristic of laterite. In relation to the average composition of Finnish tills, the abundances of elements typically incorporated in mafic and ultramafic rocks are high, suggesting that these rocks may be more common in the area indicated by the present knowledge (Koljonen *et al.* 1992). In the present study the area of southern Inari (Väylä and Valkkojärvi) is located in geochemical province of Granulite zone in Lapland defined by Koljonen and co-author (1992).

3.2 Weathering crust

Bedrock is covered by continuous or semi-continuous ancient weathering crust in central Finnish Lapland (Figs 1 and 2) (Virkkala 1955, Niini 1968, Kujansuu 1972, Salminen 1975, Hirvas *et al.* 1977, Niini & Uusinoka 1978, Hirvas 1991, Hyyppä 1977, 1983, Peuraniemi & Islam 1993, Islam 1996). The occurrences of weathering crust are not related to rock type, but it has been met in almost all the major lithological areas in northern Finland (Salminen 1975). Outside of the ice divide zone there are only random occurrences of weathered bedrock, which occur mainly in depressions and fracture zones protected from glacial erosion. The thickness of this crust is usually 1-2 m, but in valleys and fracture zones of the bedrock it may be over 100 m (Sederholm 1913, Virkkala 1955). Weathering has taken place during the preglacial time, probably in Tertiary and even Cretaceous periods (Tanner 1915, Uusinoka 1975, Hirvas 1991, Peuraniemi & Islam 1993, Islam 1996).

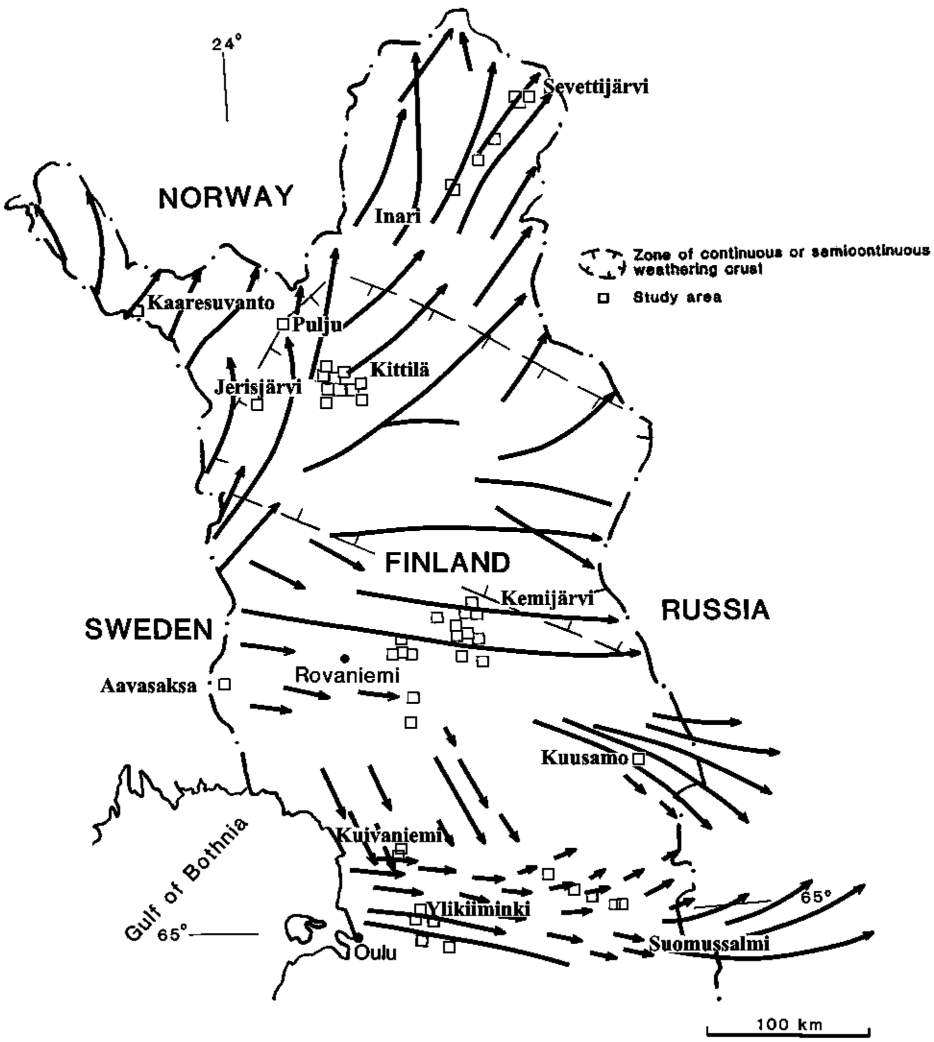

Fig. 2. Location of study sites, central Lapland weathering crust and main directions of ice movements (Late Weichselian), (Aario *et al.* 1974, Aario and Forström 1979, Hirvas 1991).

Chemical alteration has led to the formation of true clay minerals as kaolinite, halloysite, vermiculite, chlorite, illite and montmorillonite, and it also very often contains hydrous iron oxides (goethite and lepidocrocite) (Hyyppä 1977, 1983, Pulkkinen 1985, Peuraniemi & Islam 1993, Islam 1996). Trace elements such as Cu, Ni, Co, Zn and Mo have become enriched in the fine fraction of the weathering crust (Hiltunen 1982, Peuraniemi 1990). Weathering crust is coarse-grained in places, but it may be also very fine-grained, even clayey (Peuraniemi 1989). The weakness of glacial erosion in this ice divide zone has usually been regarded as the main cause for the preservation of the soft weathering crust through the successive glaciations. Predominantly the late Pleistocene ice divide lay approximately in the same area as the weathering crust zone. Successive glaciations have eroded the upper parts of the weathering profile and only the root parts are left in situ. The upper parts have been mixed up with glacially induced fresh rock flour and together they constitute the fine fraction of the till. There are places, however, where one can see even with a naked eye that the till contains material from the weathering crust.

The study sites of Kittilä and Jerisjärvi are located in the former ice divide zone and in the area of the preglacial weathering crust. In these areas great amounts of weathered bedrock material are mixed into tills (Kallio *et al*. 1980, Peuraniemi *et al*. 1996, 1997, Koljonen *et al*. 1992). Kittilä and Jerisjärvi both are also situated in the areas of Palaeoproterozoic mafic volcanics. Occurrences of weathering crust are also known in the study sites of Inari (Sevettijärvi and Pyhävaara).

3.3 Moraines

Northern Finland has experienced several cycles of glacial activity. The first of the Pleistocene glaciations met the loose preglacial weathering crust and consequently was responsible for large proportion of the total erosion and till deposition. Most of the till debris commonly has been transported only a short distance during each glacial cycle. It follows that the younger tills in a sequence may contain larger amounts of reworked debris from the older tills. The matrix mode in particular may include large amounts of reworked material amongst the more or less fresh rock flour.

Different genetic moraine types were studied, having their differences within debris entrainment, transport and depositional histories. The classification of moraines is based on Aario (1977a,b, 1984, 1990). The moraine types studied include ground moraine, cover moraine, marginal moraine, longitudinal moraine ridge, Rogen moraine, drumlin, Pulju moraine, Sevetti moraine, hummocky moraine, Kianta moraine, lee-moraine, ablation hummocky moraine, Vika moraine and end moraine.

A ground moraine is a veneer of a till that is thick enough to create its own topographical expression uncontrolled by that of the immediate underlying bedrock surface (Flint 1955). The till material in ground moraines is transported farther distance and the till matrix is mature and it includes plenty of fine-grained material. The three sites at Kittilä and the study sites at Aavasaksa lie on ground moraine landscape. The main ice flow directions in the Kittilä area have been from SSW or NNW and those in the Aavasaksa area from NW or WNW.

A cover moraine is a veneer of a till, the surface of which consists of low relief predominantly devoid of transverse or linear elements. A cover moraine owes its major topographical expression to the underlying bedrock, and its own topographical expression is that of its minor till relief. A cover moraine is the most common till relief in Finland. It varies in thickness, but is commonly thinner than the other types (Aario 1977a, 1981, 1990). Cover moraines are thin and usually seem to represent short-distance transport and the till matrix is commonly immature. The study site of Kuivaniemi lies on cover moraine landscape and the main ice flow direction in the Kuivaniemi area has been from W to E and from WN. Also the study site of Jerisjärvi is cover moraine area and the last ice flow directions has been from SN and SW-NE.

A Vika moraine is an assemblage of small ridges a few meters high, 10-30 m broad and often some hundreds of meters long running transverse to the direction of ice flow. These ridges are composed of sandy till and interpreted as being melt-out till. It is suggested that these ridges were created at the very margin of the ice sheet owing to the push effect of the ice and a consequent piling up of debris-loaded sheets of ice (Aario 1990). These formations are present in the study area of Kemijärvi.

A Pulju moraine is a landform assemblage composed of winding ridges and hummocks, which are usually non-orientated relative to the direction of the ice flow. A downslope orientation is frequently detectable on hill slopes, being sometimes at an oblique angle to the contours (Kujansuu 1967, cf., Aartolahti 1974). The till ridges are commonly 2-5 m high, 10-15 m broad and 50-100 m long, and often give a vermiculated impression in aerial photographs. Horse-shoe forms are common, and there are also more or less closed circles (ring ridges) in places. Viewed from the ground, the area seems to be only slightly hummocky, especially as the lower ground between the ridges is often subdued by peat cover (Aario 1990b, 1992). The till matrix is commonly unimodal and mature and the clasts are distantly derived. It has been suggested that the till deposition took place first and the processes leading to the characteristic Pulju landscape were post-depositional (Aario 1992). The Kaaresuvanto study area and the study site at Puljutunturi are located on a Pulju moraine field. The main ice flow direction at both study sites has been from SW.

A Sevetti moraine is an assemblage of very rugged-surfaced landforms, consisting in some places of ridges running parallel to the ice flow, but in others of hummocky, dead-ice hollows and diversely oriented ridges, all characterized by a boulder-strew surface. The till ridges have an uneven crestline and are commonly about 10 m high, 40 m broad and 100-200 m long (Aario 1984, 1990, 1992). The matrix is bimodal and the till debris represents minimal glacial transport, often only a few meters. The composition and texture of the till is related to the pronounced quarrying processes during the late phases of deglaciation. The Sevettijärvi site in Inari is located on the Sevetti moraine train. The main ice flow direction has been from SW.

In the Suomussalmi area exist a long train of morainic hummocky assemblage that is called Kianta moraine (Aario & Forsström 1978b, 1979, Aario 1977a, 1984, 1990). The hummocky assemblage was created in an interlobate position between the westerly flow and the new ice lobes, the Kuusamo lobe in the north and the Oulu lobe in the south. This is Suomussalmi train of morainic hummocks, which is about 80 km long, and stretches from Puhosjärvi eastwards to the area of Kiantajärvi. The Kianta moraine is mainly composed of hummocks with a minority of ridges. Till includes plenty of fine-grained material and has a mature matrix. The Suomussalmi study area is located on the Kianta moraine train end the main ice flow direction has been from WNW.

Rogen moraines are characterized particularly by transverse till ridges, which can frequently be interpreted as transverse rows of hummocks linked together by ridges of slightly lower relief. Crescentic till landforms with their horns pointing in the down-glacier direction are frequent. More or less rounded hummocks are present, especially in areas where a Rogen assemblage grades into other landform assemblages. Rogen landforms and drumlins are often intimately interrelated, so that one end of the transverse Rogen ridge for example, may also continue as a drumlin in the direction of ice flow. An assemblage of these landforms may also grade into the other, either in the direction of the ice or transverse to it. Like drumlins, Rogen landforms can be considered bedforms determined by flow behavior of the ice itself (Lundqvist 1969, Aario 1977a,b, 1990, Aario & Peuraniemi 1992, Shilts 1977, Shaw 1979, Bouchard 1989). Rogen moraines are mostly restricted to areas surrounding the central parts of the glaciated areas within about 200 km of the ice divide. Where the distributions of Rogen moraines and drumlins coincide in the Finland, the latter usually occur on higher ground, whilst the former occupy the valleys and flatter country. Commonly the landforms are composed of two till facies. The lower till facies usually has mature till matrix and it represents long-distance transport. The upper till facies has a bimodal matrix, it is often very heterogeneous and layered, and clasts are of more local derivation, related to the late quarrying processes during deglaciation. The study sites at Kemijärvi are located on a Rogen moraine field (Poikkioja, Heralampi, Peuranselkä Kuusivaara and Peltojärvi). The main ice flow direction has been from WNW.

The length of the drumlins in Koillismaa area varies from 100 m to 2-3 km. However, those over 2 km in length are rather rare. Their height varies from a few meters to about 20 m, but commonly they are lower than 15 m. The shape of the drumlins is rather variable; often they are symmetrical, sometimes the proximal end is broader and steeper than the distal end, however, the reverse is also common. The highest point is generally somewhat closer to the proximal than the distal end. Drumlins, which are very close to each other, often coalesce (Aario *et al*. 1974, 1977a,b, 1990, Aario & Peuraniemi 1992). Lee-moraines resemble drumlins and they have been deformed in the inner part of marginal ice-zone (see drumlins and Rogen moraine). These small ridges are present in the Kemijärvi area.

A hummocky moraine has been usually classified as more or less non-directional type of feature. According to Aario (1977a,b) the group of forms covered by the term hummocky moraine is truly polygenetic. If one takes account genetically different depositional, deformational and erosional features it is possible and also advantageous to make a subdivision into hummocky disintegration moraine, hummocky squeeze-up moraine and hummocky active-ice moraine. The hummocky disintegration moraine is a widely occurring moraine often referred to as ablation moraine or hummocky dead-ice moraine etc.. Hummocky moraines are located to the study sites at Kemijärvi (Sarvimännikkö, Sarriojärvi, Luusua, Kuluskaira and Sarvilampi). The main ice flow direction has been from WNW.

There are end moraines of various types from huge marginal complexes to minor ones on one meter scale. They are naturally also genetically different, their creation often being bound to certain special ice-margin stages. The glacial dispersion they represent is also variable and in some cases very complex. The large marginal complexes can include material from hundreds of kilometers away, whilst the minor ones may represent small-scale ice-oscillations and locally reworked till (Aario 1990, Aario & Peuraniemi 1992).

Korppikangas and Torviselkä have been interpreted as an end moraine hills, a fairly common type in Finland, though not so often seriously noticed. It is just a till mound, 10 m high and 100 m in diameter, which together with many similar hills forms an arc reaching from Kirvesselkä, near Nuorittajoki to Löytökylä in Ylikiiminki. There occur drumlins and active-ice moraine hummocks proximal to the hill (Aario 1990, Aario & Peuraniemi 1992).

3.4 Location and topography

The study areas, their separate study sites, survey pits and moraine types there are listed in Table 1.

Table 1. The areas, sites, survey pits and moraine types studied.

Area	Study site	Survey pit	Moraine type
Suomussalmi	Lahna	200-217	Kianta moraine
	Papinaho	220-227	Kianta moraine
	Isopalo	230-237	Kianta moraine
	Leppälä	240-244	Kianta moraine
	Puhos	245	Kianta moraine
Kuusamo	Säynäjäluoma	251,254,259,263	Drumlin
Ylikiiminki	Vepsänselkä	12-19	Longitudinal moraine ridge
	Torviselkä	21-27	End moraine
	Korppikangas	31-38	End moraine
	Kiviharju	50-51	Marginal moraine
	Puutturi	101-105	Longitudinal moraine ridge
	Viitamaa	111-113	Longitudinal moraine ridge
Kuivaniemi	Käärmeaapa	181, 184	Cover moraine
	Ruonansuo	182, 183	Cover moraine
Kemijärvi	Poikkioja	601-604	Rogen moraine
	Heralampi	605-608	Rogen moraine
	Peuranselkä	703	Rogen moraine
	Kuusivaara	709	Rogen moraine
	Peltojärvi	710,711,716,741	Rogen moraine
	Kiisavaara	613-614	Longitudinal moraine ridge
	Kuluskaira	681	Hummocky moraine
	Kuusivaara	731	Longitudinal moraine ridge
	Hanhikoski	750	Longitudinal moraine ridge
	Luusua	774	Longitudinal moraine ridge
	Sarvimännikkö	615	Hummocky moraine
	Sarriojärvi	704	Hummocky moraine
	Luusua	769	Hummocky moraine
	Palo-Rakkavaara	620,623	Lee-moraine

Table 1. Continued.

Area	Study site	Survey pit	Moraine type
Kittilä	Sukseton	306-310	Ground moraine
	Näätäkuusikko	311-315	Ground moraine
	Sierumaselkä	316-320	Ground moraine
	Vänköselkä	321	Ground moraine
	Seurujärvi	322-327	Ground moraine
	Mustapakula	328	Ground moraine
	Kolvalehto	331-334	Ground moraine
Aavasaksa	Aavasaksa	381-384,388,391,395	Ground moraine
Jerisjärvi	Jerisjärvi	410-412	Cover moraine
Kaaresuvanto	Kaaresuvanto	352-359,362-366	Pulju moraine
Pulju	Pulju	351	Pulju moraine
Inari	Ahvenjärvi	504-510	Sevetti moraine
	Sevettijärvi	511-516	Sevetti moraine
	Suojanperä	517-520	Sevetti moraine
	Pyhävaara	521-525	Sevetti moraine
	Väylä	526-530	Sevetti moraine
	Valkkojärvi	531-535	Sevetti moraine

Suomussalmi

The survey area is situated in eastern Finland in the municipality of Suomussalmi. The study sites Lahna and Papinaho are 20 km north of a village of Suomussalmi, study sites Isopalo and Leppälä are 40 km NW from a village of Suomussalmi and study site Puhos is 50 km NW of village of Suomussalmi (Fig. 3). The local relief is great, the absolute height above sea level varying between 175 and 325 m a.s.l.. The features dominating the topography are hills and numerous lakes, ponds and mires.

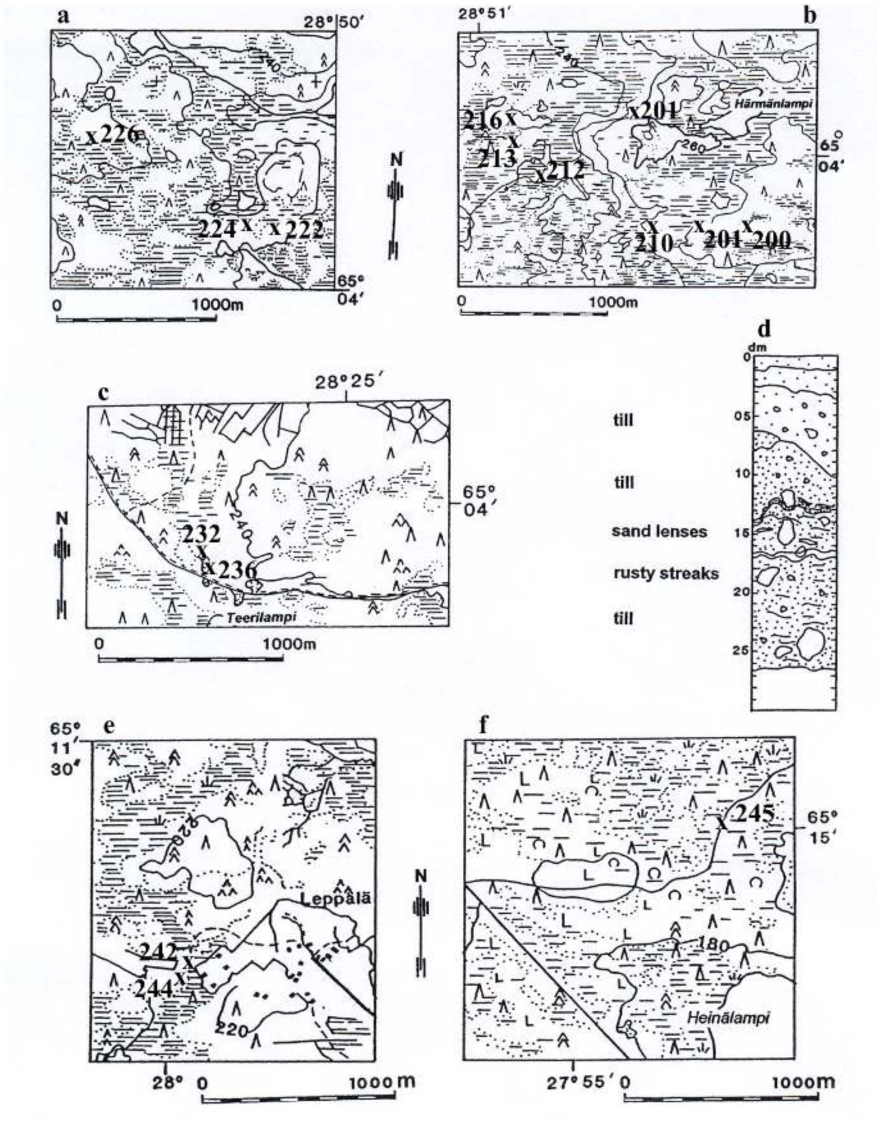

Fig. 3. Kianta moraines of Suomussalmi a) Papinaho, b) Lahna, c) Isopalo, d) stratigraphic column represents the typical till stratigraphy of Kianta moraine, pit number 232 e) Leppälä and f) Puhos. X= survey pit.

Kuusamo

The survey area is situated in the municipality of Kuusamo, 20 km northwest of Kuusamo village. The local relief is quite great, absolute height being 283-340 m a.s.l.. The drumlins and the bogs lying between them constitute a striated pattern peculiar to the area (Fig. 4).

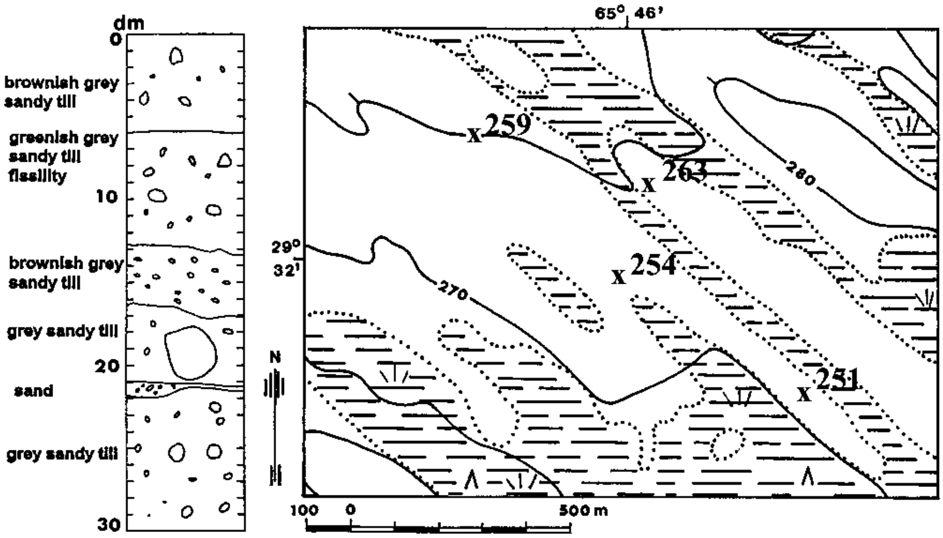

Fig. 4. Säynäjäluoma drumlin at Kuusamo and its typical stratigraphic column, pit number 251. X= survey pit.

Ylikiiminki

The survey area is situated in northern Ostrobothnia in the municipality of Ylikiiminki. The study sites Vepsänselkä and Viitamaa are 12 km SE of the village of Ylikiiminki; study site Korppikangas is 10 km NE from the village; study site Puutturi is 32 km SE from the village; study site Kiviharju is 30 km E from the village and study site Torviselkä is 10 km SE from the village (Fig. 5). The local relief is low and in the western part of the study area the absolute height varies between 20 and 40 m a.s.l.. Farther to the east, in the Ylivuotto area the absolute height varies between 80 and 120 m a.s.l..

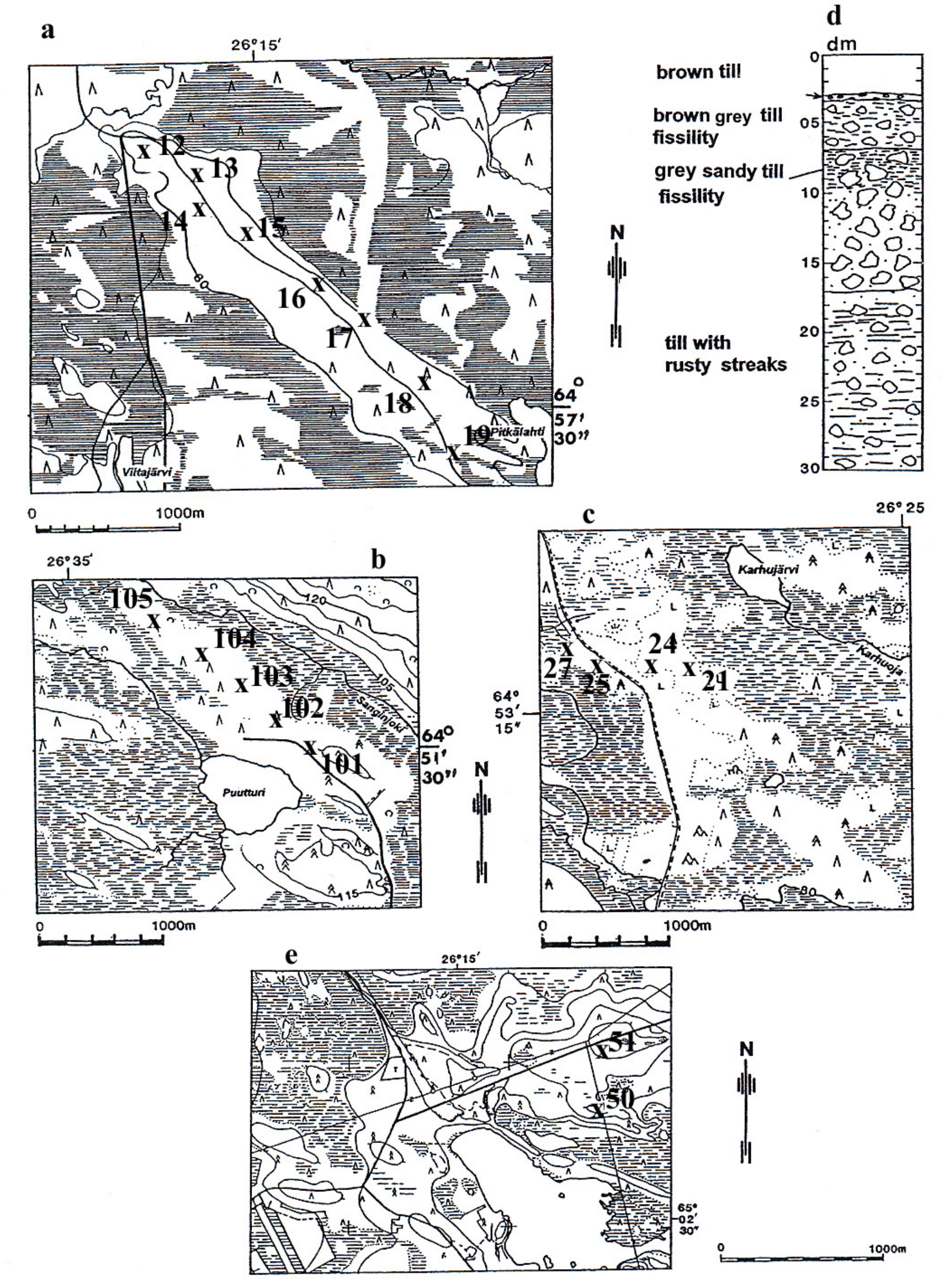

Fig. 5. a-e. Moraine formations of Ylikiiminki, a) longitudinal moraine ridge of Vepsänselkä, b) longitudinal moraine ridge of Puutturi c) end moraine of Torviselkä, d) stratigraphic column represents the typical till stratigraphy of end moraine, pit number 25 e) marginal moraine of Kiviharju. X= survey pit.

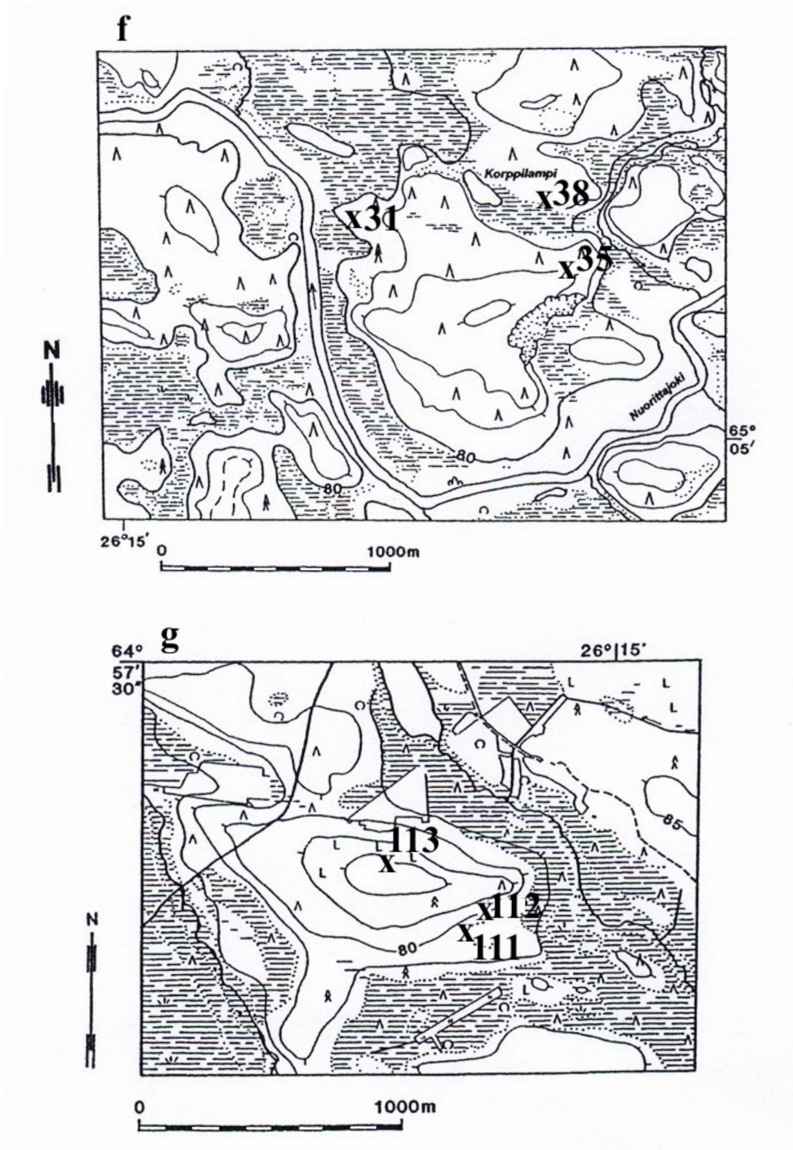

Fig. 5. f-g. Moraine formations of Ylikiiminki, f) end moraine of Korppikangas and g) longitudinal moraine ridge of Viitamaa. X= survey pit.

Kuivaniemi

The survey area is situated in northern Ostrobothnia in the municipality of Ylikiiminki, 32 km SE of Oulu (Fig. 6). The terrain is quite low-lying and flat, the absolute height being 20-40 m a.s.l..

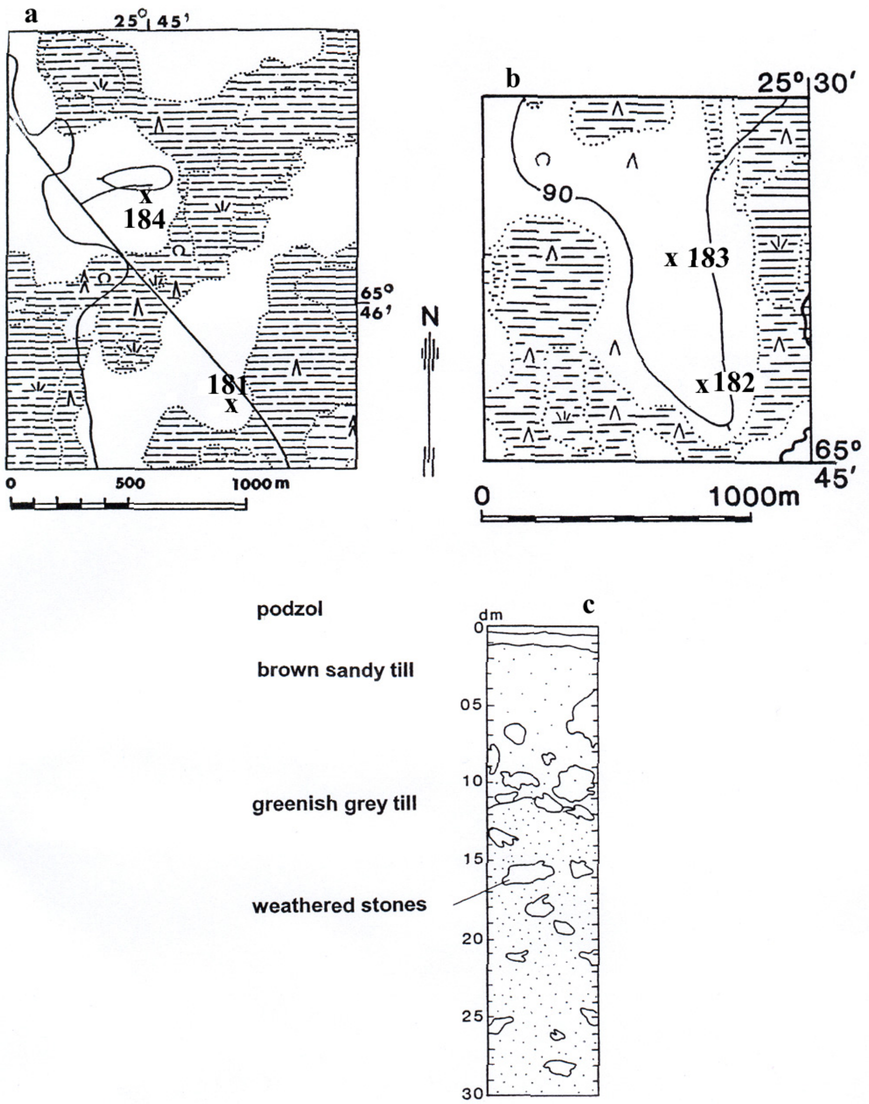

Fig. 6. Cover moraines of Kuivaniemi, a) Käärmeaapa and b) Ruonansuo c) stratigraphic column represents the typical till stratigraphy of cover moraine, pit number 184. X= survey pit.

Kemijärvi

The survey area is situated in central Lapland in the municipalities of Kemijärvi and Rovaniemi. The study sites Poikkioja and Peltojärvi are 5,5 km NW and Heralampi is 2,5 km NW of the city of Kemijärvi; study sites Sarvilampi, Sarvimännikkö, Kiisavaara, Palo-Rakkavaara and Kuusivaara are 25 km SW from the city of Kemijärvi; study site Luusua is 25 km S from the city of Kemijärvi; study site Martinvaara is 25 km W from the city of Kemijärvi; study site Martinvaara is 25 km W from the city of Kemijärvi; study site Peuranselkä is 8,5 km W from the city of Kemijärvi; study site Sarriojärvi is 36 km NW from the city of Kemijärvi and study site Hanhikoski is 20 km SW from the city of Kemijärvi. The study sites Vikajärvi and Kuluskaira are 20 km NE from Rovaniemi (Fig. 7). The local relief is great, the absolute height above sea level varying between 140 and 300 m a.s.l..

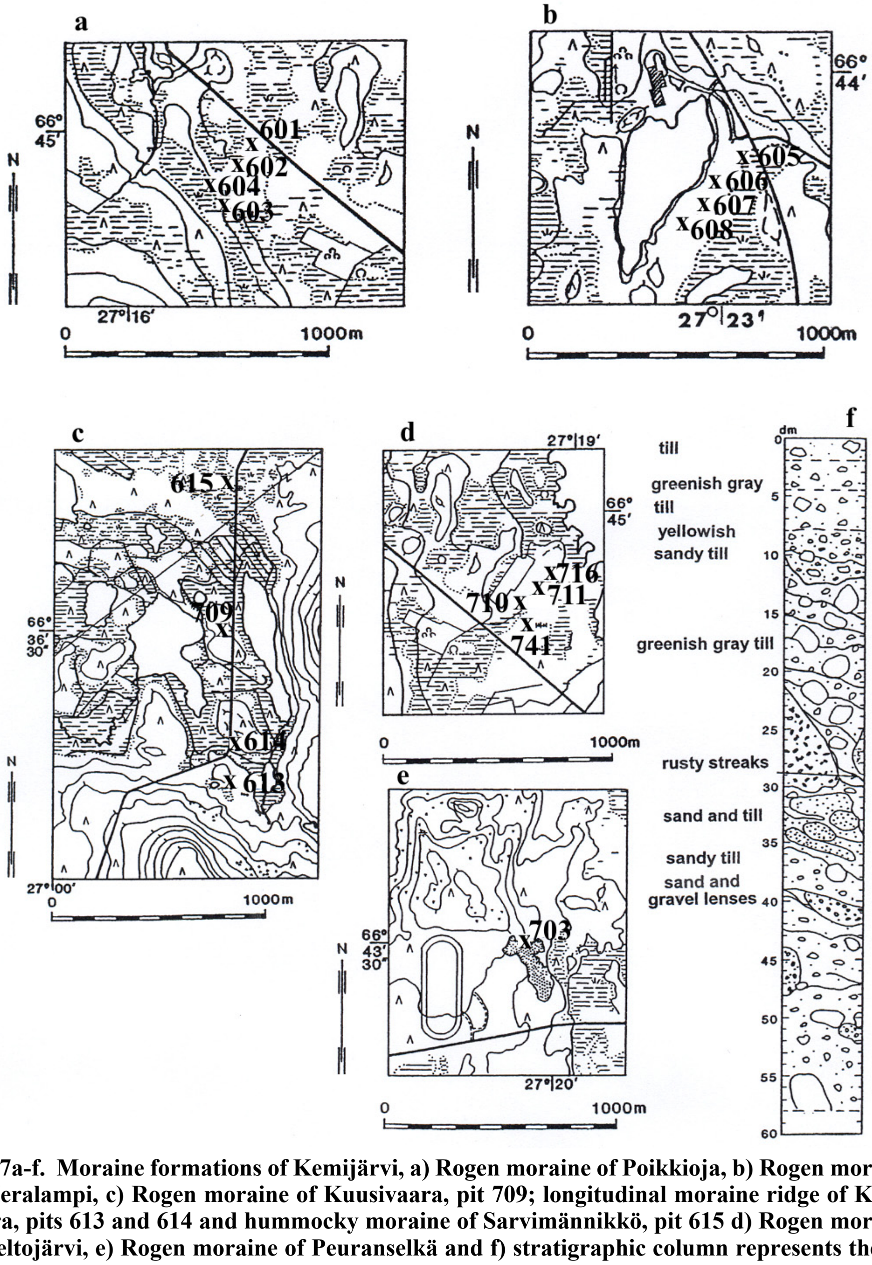

Fig. 7a-f. Moraine formations of Kemijärvi, a) Rogen moraine of Poikkioja, b) Rogen moraine of Heralampi, c) Rogen moraine of Kuusivaara, pit 709; longitudinal moraine ridge of Kiisavaara, pits 613 and 614 and hummocky moraine of Sarvimännikkö, pit 615 d) Rogen moraine of Peltojärvi, e) Rogen moraine of Peuranselkä and f) stratigraphic column represents the typical stratigraphy of Rogen moraine, pit number 710. X= survey pit.

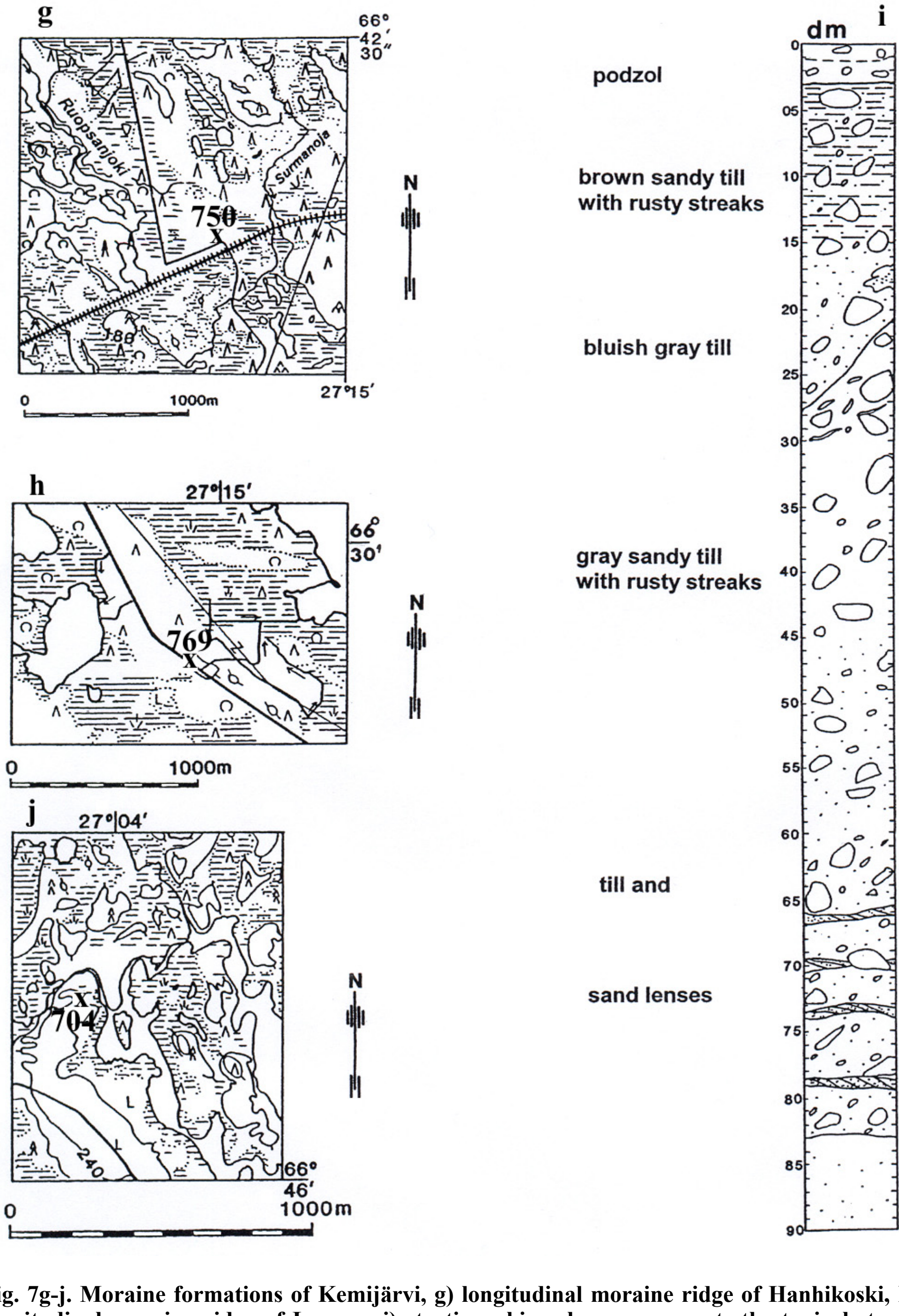

Fig. 7g-j. Moraine formations of Kemijärvi, g) longitudinal moraine ridge of Hanhikoski, h) longitudinal moraine ridge of Luusua, i) stratigraphic column represents the typical stratigraphy of longitudinal moraine ridge, pit number 769 and j) hummocky moraine of Sarriojärvi. X= survey pit.

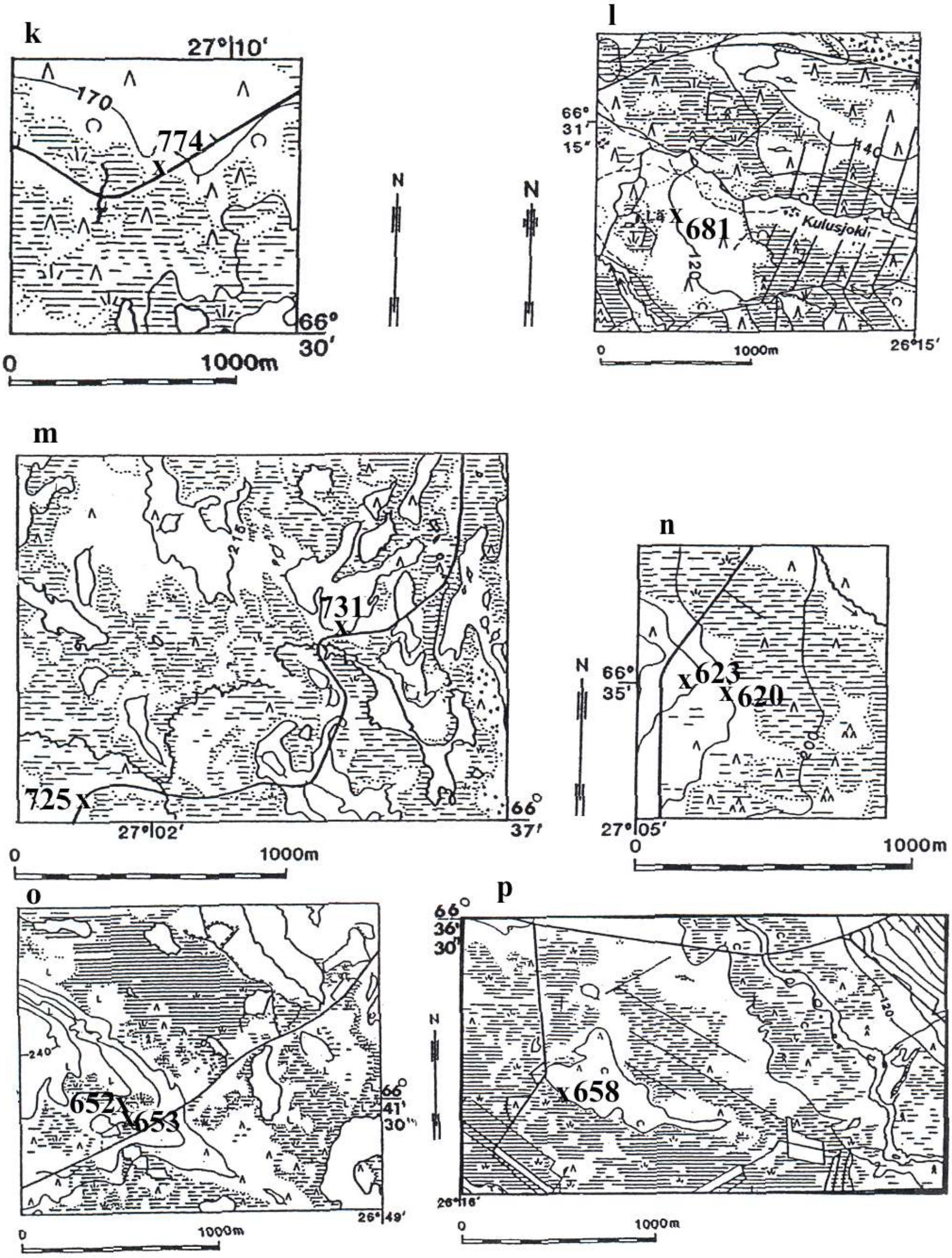

Fig. 7k-p. Moraine formations of Kemijärvi, k) hummocky moraine of Luusua, l) hummocky moraine of Kuluskaira, m) longitudinal moraine ridge of Kuusivaara, pit 731 and ablation hummocky moraine of Sarvilampi, pit 725, n) lee-moraine of Palo-Rakkavaara o) lee-moraine of Martinvaara and p) Vika moraine of Vikajärvi. X= survey pit.

Kittilä

The survey area is situated in Central Lapland in the municipality of Kittilä. The study site Sukseton is 20 km SW of village of Pokka; study site Näätäkuusikko is 15 km SW from village of Pokka; study site Mustapakula is 15 km SW of village of Pokka; study site Seurujärvi is 20 km S of village of Pokka; study site Kolvalehto is 10 km N of village of Kiistala; study site Sierumaselkä is 15 km NE of village of Kiistala; study site Vänköselkä is 15 km NE of village of Kiistala (Fig. 8). The survey area is situated on the NE side of the Ounasjoki river valley. The local relief is great, the absolute height above sea level varying between 200 and 400 m a.s.l.. Features dominating the topography are hills and numerous mires.

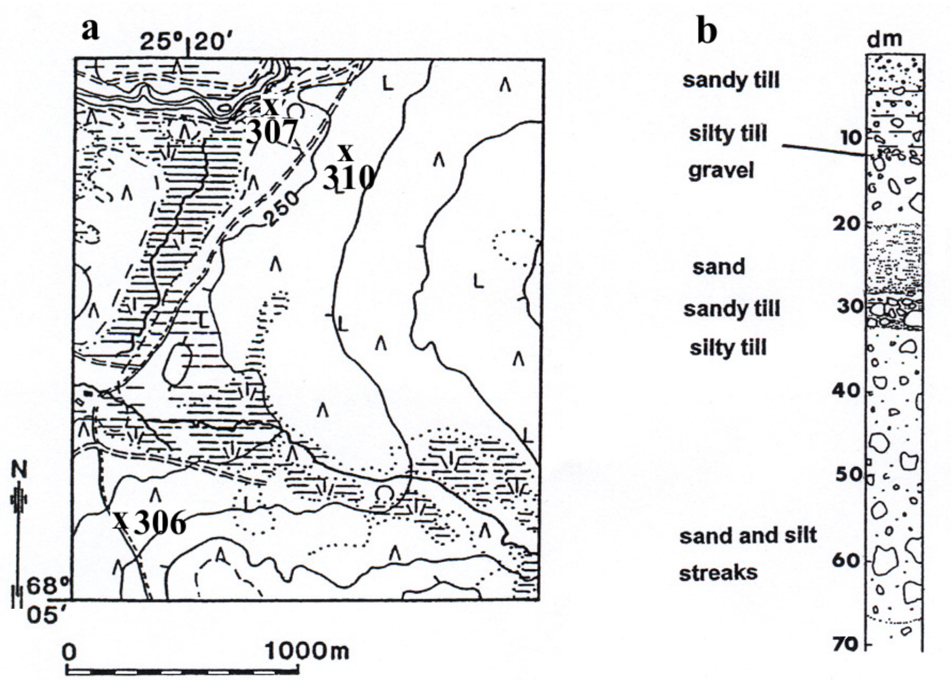

Fig. 8a-b. Ground moraines of Kittilä, a) Sukseton and b) stratigraphic column represents the typical till stratigraphy of ground moraine, pit number 306. X= survey pit.

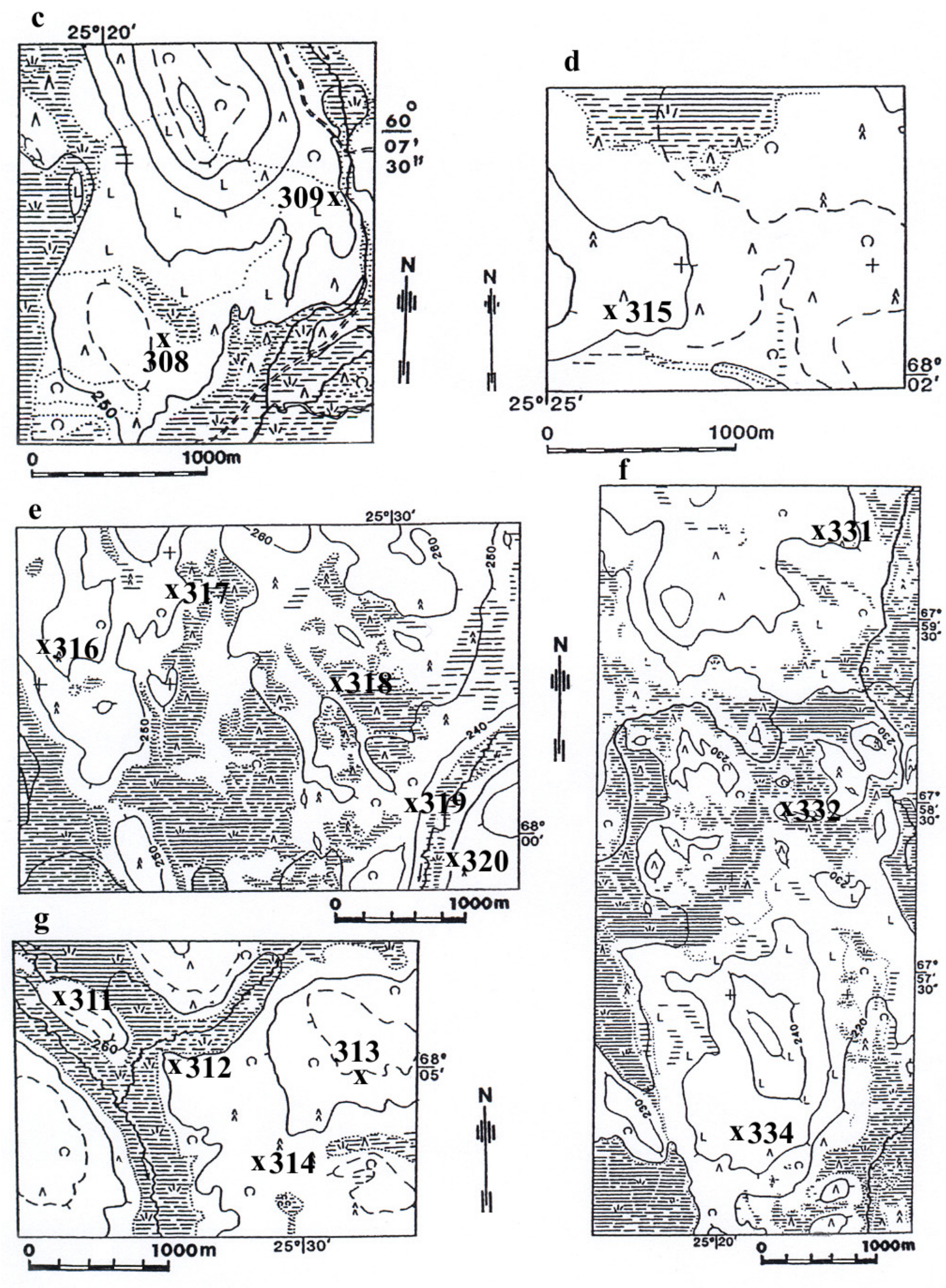

Fig. 8c-g. Ground moraines of Kittilä c) Sukseton d) Näätäkuusikko e) Sierumaselkä, f) Kolvalehto and g) Näätäkuusikko. X= survey pit.

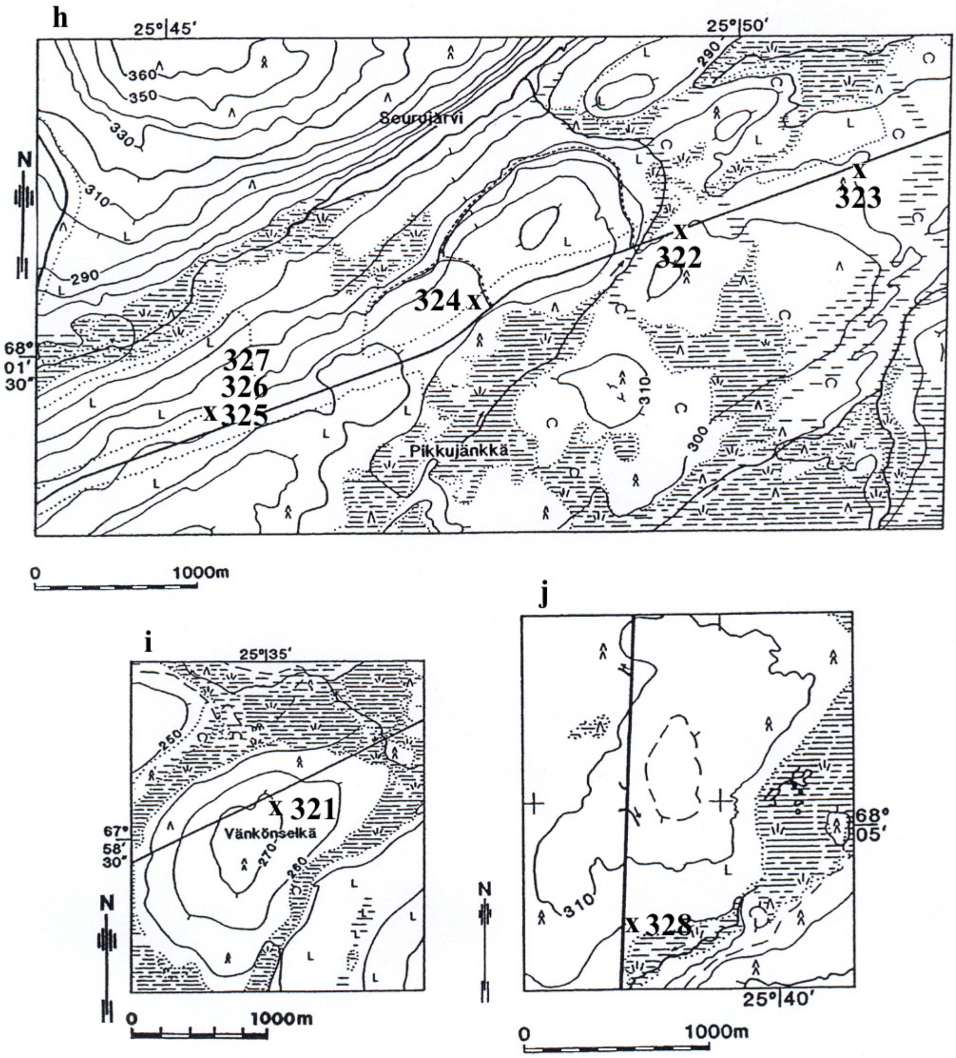

Fig. 8h-j. Ground moraines of Kittilä, h) Seurujärvi, i) Vänköselkä and j) Mustapakula. X= survey pit.

Aavasaksa

The survey area is situated in Western Lapland in the municipality of Ylitornio, about 2 km from Aavasaksa hill (Fig. 9). The area is subaquatic and the local relief is great. The absolute height above sea level varying between 50 and 240 m a.s.l..

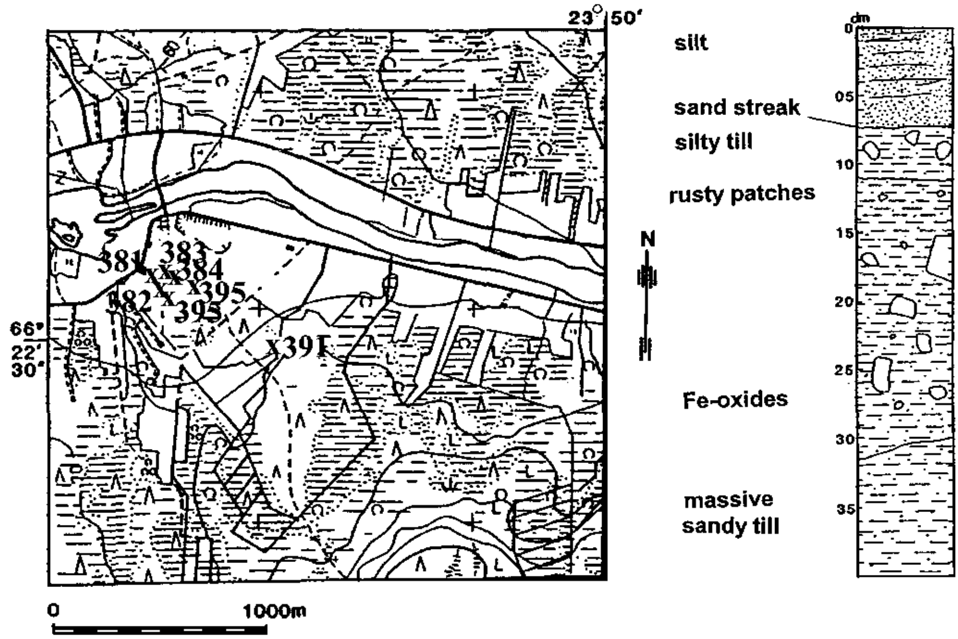

Fig. 9. Ground moraine of Aavasaksa and stratigraphic column of pit number 391. X= survey pit.

Jerisjärvi

The survey area is situated in Western Lapland in the municipality of Muonio. Study site is situated along the road, which is south side from Lake Jerisjärvi (Fig. 10). Glacial ice-dammed lakes covered the surrounding areas and the local relief is rather low. The absolute height above sea level is varying between 260 and 290 m a.s.l..

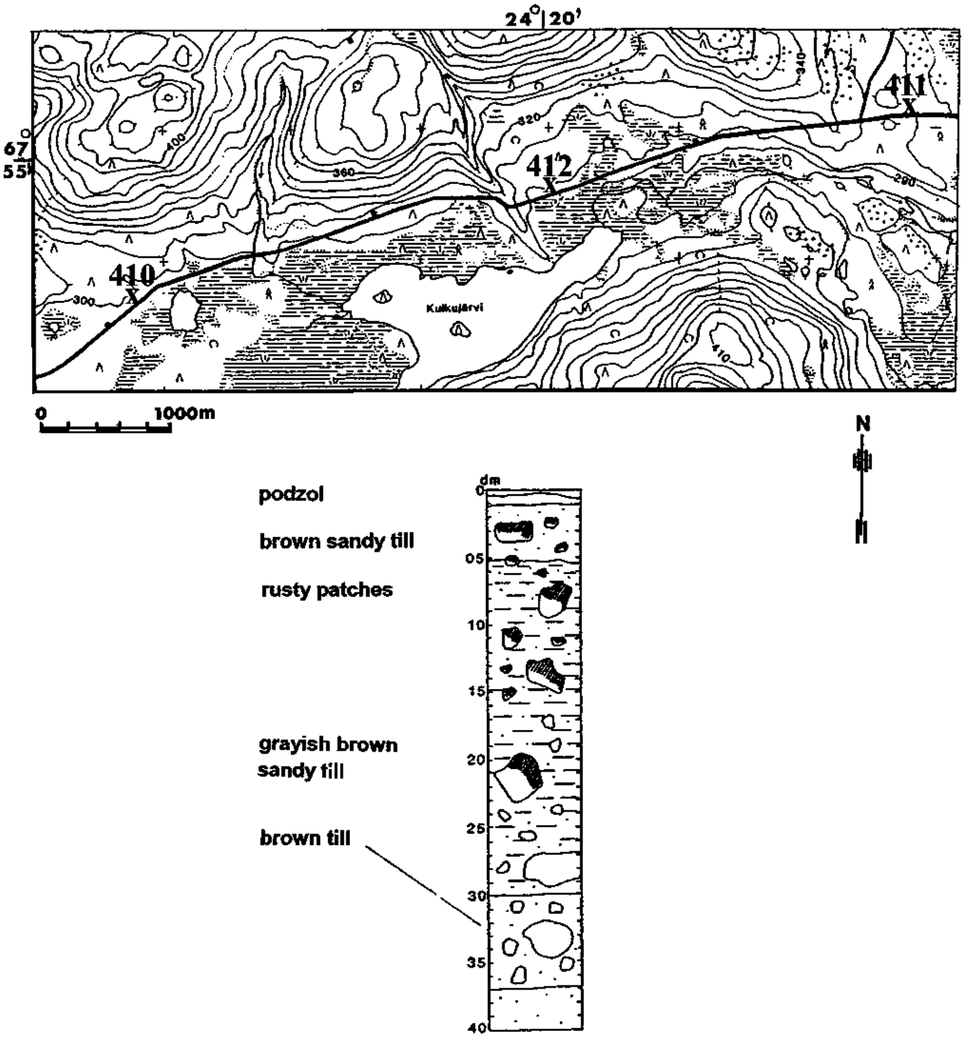

Fig. 10. Cover moraine of Jerisjärvi, Muonio and stratigraphic column of pit number 410. X= survey pit.

Kaaresuvanto

The survey area is situated in Northwestern Lapland in the municipality of Kaaresuvanto, about 4 km east from the village of Kaaresuvanto (Fig. 11). The local relief is low, and the absolute height above sea level is varying between 340 and 420 m a.s.l..

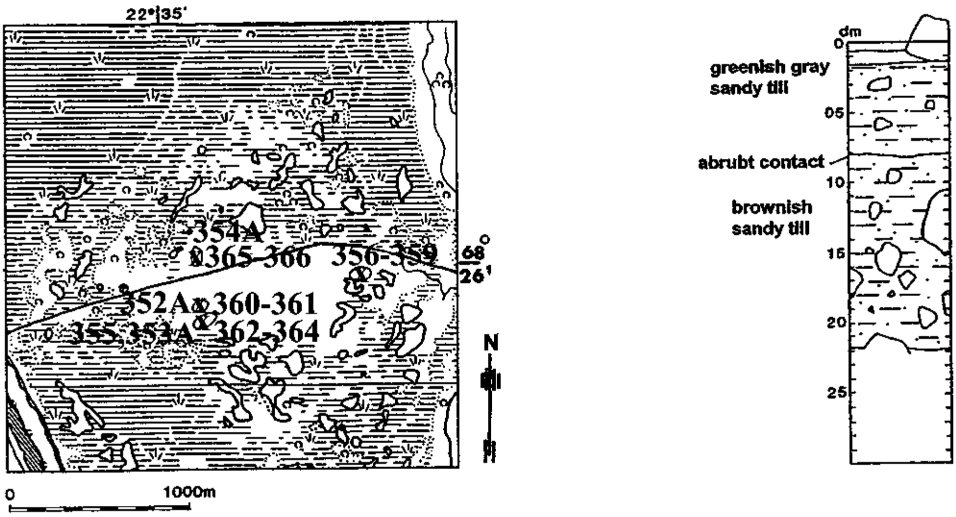

Fig. 11. Pulju moraine of Kaaresuvanto and stratigraphy of pit number 360.

Pulju

The survey area is situated in Northwestern Lapland in the municipality of Kittilä, in the hill of Puljutunturi (Fig. 12). The local relief is low and the absolute height above sea level varying between 340 and 420 m a.s.l..

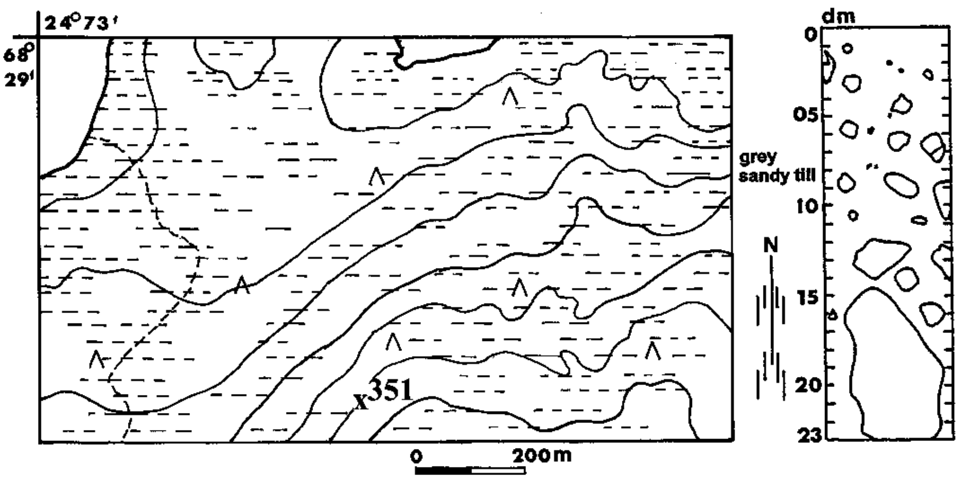

Fig. 12. Pulju moraine of Puljutunturi and stratigraphic column of pit number 351 of Puljutunturi area. X= survey pit.

Inari

The survey area is situated in Northern Lapland in the municipality of Inari. The study sites are located in the western side of the Lake Inari (Fig. 13). The study site Ahvenjärvi is 4,5 km NE of the village of Sevettijärvi; the study site Sevettijärvi is 2,5 km NNE of the village of Sevettijärvi; the study site Suojanperä is 30 km SW of the village of Sevettijärvi; the study site Pyhävaara is 43 km SW of the village of Sevettijärvi; the study site Väylä is 11 km E of the village of Kaamanen and the study site Valkkojärvi is 6,5 km SE of the village of Kaamanen. The local relief is great, the study area the absolute height above sea level varying between 0 and 200 m a.s.l.. Features dominating the topography are hills and numerous small lakes and ponds.

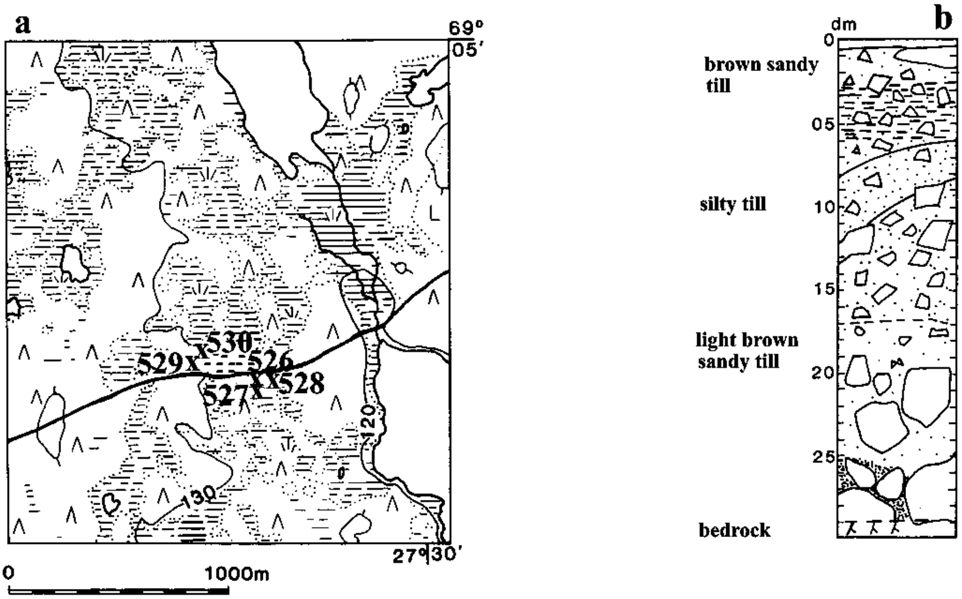

Fig. 13a-b. Sevetti moraines of Inari, a) Väylä and b) stratigraphic column of pit number 528. X= survey pit.

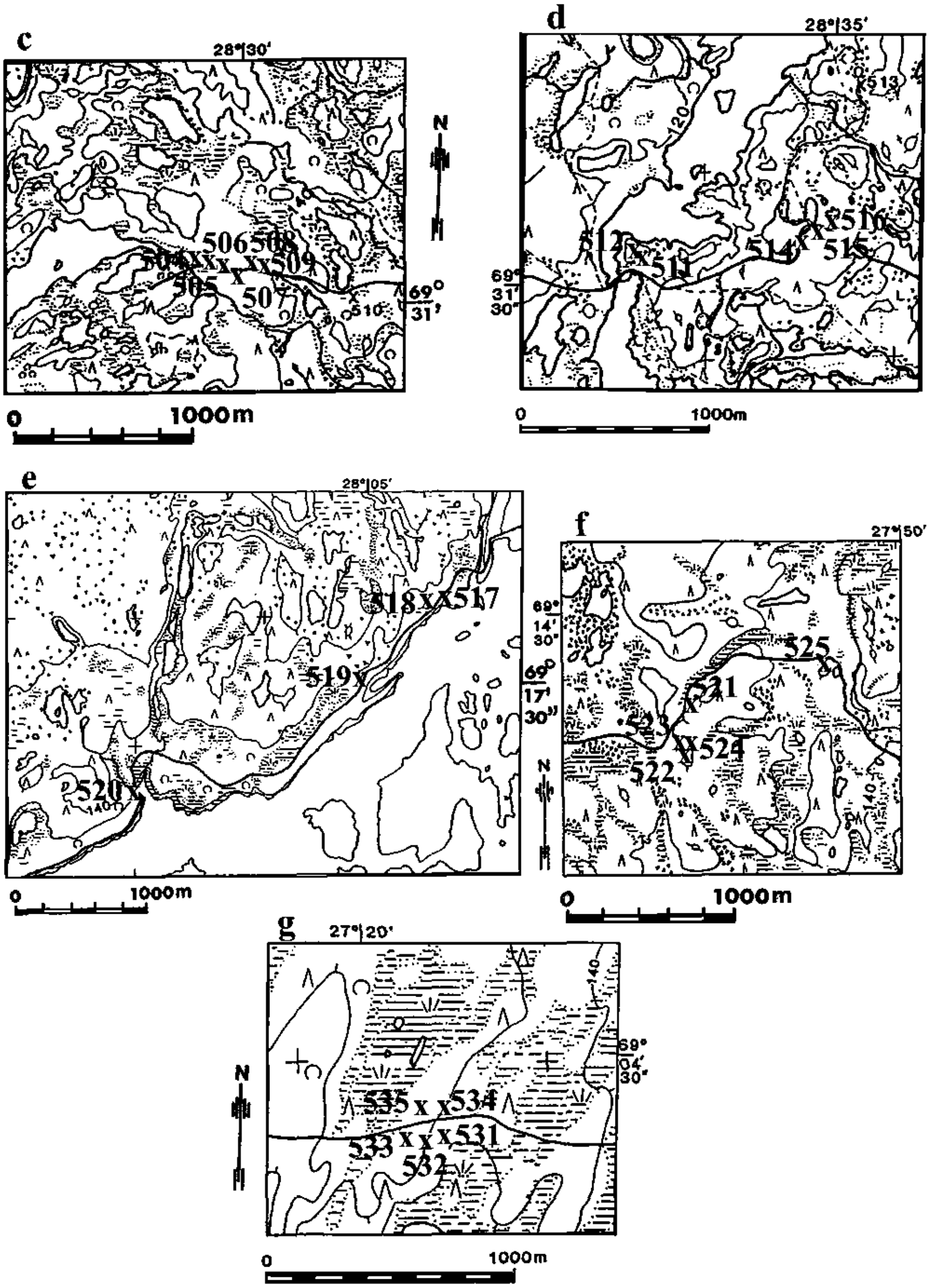

Fig. 13c-g. Sevetti moraines of Inari, c) Ahvenjärvi, d) Sevettijärvi, e) Suojanperä f) Pyhävaara and g) Valkkojärvi. X= survey pit.

4 Methods of investigation

An aerial photo interpretation was used in order to interpret and map morainic landforms of different types in the study area. Oblique aerial photos from a low flying aeroplane were taken in order to get a better view of the different moraine types. The stratigraphy, lithology, texture and structure of the landforms were carefully studied from pits and sections dug with a tractor-excavator. Samples for granulometric, geochemical and mineralogical analyses were taken from different beds and layers. A total of 250 till samples from 140 test pits were studied mineralogically. A total of 813 till samples were analyzed by XRF and AAS from fine fraction of the till and 231 clay fraction samples were analyzed with AAS and 49 samples by XRF.

4.1 Grain size

The so-called fine fraction (< 60 µm) (including silt and clay fractions), which is normally used for geochemical and mineralogical analyses of the till in Finland, was separated by dry sieving from the samples. The clay fraction proper (< 2µm) was separated by centrifugation at 2000 rpm for 54 s after a sample (1 kg) was dispersed in water and wet-sieved through a 60 µm sieve (cf., Lindsay and Shilts 1995).

4.2 Geochemical analyses

Both the fine fraction and the clay fraction were analyzed chemically for major, minor and trace elements by X-ray fluorescence (Siemens SRS 303 AS) and by atomic absorption spectrometry (Varian SpectrAA-300). The fractions being analyzed were dissolved in a mixture of hydrofluoric, perchloric, nitric and hydrochloric acids ($HF + HClO_4 + HNO_3 + HCl$).

4.3 Mineralogical analyses

Mineralogical analyses were performed using X-ray diffraction (Siemens Diffractometer D5000), transmission electron microscopy (TEM; JEOL JEM-100 CX II) and thermal analyses using differential thermal (DTA) and thermogravimetric (TGA) techniques (Netzsch Simultaneous Thermal Analyzer STA 409 EP). Thermogravimetry (TGA) is used to count the of total weight loss of selected samples. In this way it is possible to estimate the amount of secondary minerals in each study areas. Differential thermal analyses (DTA) show characteristic endothermic reactions due to dehydration and to loss of crystal structure and exothermic reactions due to the formation of new mineral phases at elevated temperatures. Thermal analyses were performed with a heating rate of 15 EC / minute from 20 to 1100 EC in an air atmosphere. Calcined aluminium oxide (Al_2O_3) was used as the inert material. For X-ray diffraction analyses a part of the clay fraction was mounted onto a glass slide (oriented sample) to get stronger basal reflections of the clay minerals in X-ray diffraction. Heating techniques (200 EC, 450 EC, 550 EC and 620 EC), ethylene glycol treatment, glycerol treatment (with Mg-saturated samples) and potassium saturation with KCl were also used in X-ray diffraction in order to obtain some help in clay mineral identification. Ni filtered CuKα radiation with voltage of 40 kV and current of 40mA was used in X-ray diffraction.

4.4 Identification criteria of the minerals

4.4.1 X-ray diffraction and thermal analyses

4.4.1.1 Primary minerals

Quartz (Q) is a common constituent in clay and fine fractions of the till and it provides a strong diffraction pattern with sharp lines. It was identified from its 3.34 Å, 4.26 Å and 2.46 Å reflections. In DTA analyses quartz has an endothermic reaction at 574 EC when α-quartz changes into β-quartz. Feldspars can be divided into two main groups, alkali feldspars in composition $KAlSi_3O_8$ (microcline) and plagioclases, from $NaAlSi_3O_8$ (albite) to $CaAl_2Si_2O_8$ (anorthite). Alkali feldspars (microcline) was identified from 4.21 Å and 3.25-3.23 Å reflections. Identification of plagioclases was confirmed from 6.42-6.33. Å, 4.04-4.00 Å and 3.21-3.17 Å reflections. Amphibole (A) was recognized by reflections at 8.4 Å, 3.13-3.05 Å and 2.75-2.69 Å.

4.4.1.2 Secondary minerals

Kaolinite

X-ray analysis: Kaolinite is identified by basal reflections at about 7.16 Å (001) and 3.57 Å (002). These main peaks overlay with those of chloritic clay minerals but chlorite also has a third order reflection at 4.7 Å (see below). Another difference is that the c-axis dimension of these two minerals may show as a doublet peak at 3.50-3.57 Å. When kaolinite is heated to 600 EC, it tends to loose its crystalline character and 7.16 Å peak disappears (see also below). To confirm the existence of kaolinite in samples, it is necessary to use some other analytical methods (Grim 1968).

Thermal analysis: Differential thermal curves of kaolinite show an intense, sharp endothermic reaction corresponding to the loss of OH water. The reaction begins at about 400 EC, and for well-crystallized kaolinite the peak is at about 600 EC. At this temperature the metakaoline is formed. The exothermic reaction happens between 900-1000 EC and at about 1000 EC the mullite is formed. The intensity of the reaction and hence the size of the peak, as well as the peak temperature, is reduced slightly as the particle size decreases and as the crystallinity decreases. The variation seems to be greater for the crystallinity factor than for the particle-size factor. The peak temperature is about 20 to 30 EC lower for poorly crystalline kaolinite as compared with the well-crystallized variety (Grim 1968).

Illites

X-ray analysis: Illite is recognized by a strong first order basal reflection at 10 Å (001), which remains unchanged by thermal, KCl- and ethylene glycol treatments (Grim 1968). Illite minerals have also moderate 4.90-4.98 Å (002) reflection. If the intensity ratio I(001)/I(002) is less than 4, the illite is assumed to be of dioctahedral type (Graff-Petersen 1961). Trioctahedral illite and biotite studied by Bradley and Grim (1961), have intensity ratios I(001)/I(002) in the range of 5-10. In the present study mixtures of di- and trioctahedral illites are assumed to have intensity ratios between 5 and 10.

Thermal analysis: Differential thermal curves for illite shows an initial endothermic reaction at about 100 EC corresponding to the loss of interlayer water. A second endothermic reaction begins at about 450 to 500 EC with a peak at about 550–650 EC corresponding to the loss of OH lattice water. Third, a slight endothermic reaction between about 850 and 950 EC, and an exothermic reaction happens between about 900 and 1000 EC and the spinel is formed (Grim 1968).

Chlorite

X-ray analysis: The identification of the various forms of chlorite is very difficult. Chlorites rich in iron provide relatively weak ~14 Å (001) and 4.70-4.79 Å (003) reflections and strong 7.05-7.10 Å (002) and 3.56 Å (004) reflections. Iron-rich chlorites, therefore, are readily confused with kaolinite. The chloritic clay minerals have a third order reflection at 4.7 Å, which kaolinite does not have (see above). Likewise, 14-Å spacing of chlorite may be confused with that of smectite or vermiculite. For chlorites 14-Å spacing is neither changed on moderate heating to about 200 EC, as it is in vermiculite, nor is it changed by treatment with ethylene glycol, glycerol or KCl, as it is in the smectite (see below). Mg-rich chlorites provide a strong reflection at 13.60-14.70 (001) and 7.02-7.14 Å (002) reflections and weak 3.52-3.56 Å (004) reflection. Heating of Mg-rich chlorite to about 600 EC creates an increase in the intensity of (001) reflection and decrease in the intensities of the (002), (003) and (004) reflections (Grim & Johns 1955, Soveri 1956, Walker 1949b, 1958, Grim 1968).

Thermal analysis: Differential thermal curves of chlorite show a sharp endothermic reaction between 500 and 700 EC and sometimes a second endothermic reaction at about 800 EC. These reactions are correlated with the dehydration of the mica layer and loss of its structure. The immediate, sharp exothermic reaction is followed at about 800 to 900 EC, which is correlated with the development of the olivine (Grim 1968).

Vermiculite

X-ray analysis: The strong reflection at 14 Å is characteristic for vermiculite, but care must be used to differentiate vermiculite from chlorite and smectite. They all may show a 14-Å reflection. Vermiculite can be distinguished from chlorite and smectite by the fact the 14-Å spacing of the vermiculite is shifted toward 10 Å, when the sample is heated. The same effect is with KCl-treatment. These treatments do not affect chlorite and smectite minerals. Also with ethylene glycol treatment smectites 14-Å peak shifts to 16.90-17.1 Å, when peak for vermiculite minerals stays below 16.70 Å (Walker 1949a,b, 1957, 1958, 1961,Grim 1968, Thorez 1975, Brindley & Brown 1980).

Thermal analysis: Differential thermal curves of vermiculite show a large initial endothermic reaction with a peak at about 150 to 200 EC, immediately followed by a smaller peak at about 250 to 275 EC. These endothermic reactions correspond to the removal of interlayer water. The next endothermic reaction takes place at about 700 to 800 EC and is due to the destruction of silicate structure, accompanied by the loss of the hydroxyl water. At about 800 EC there occurs an exothermic reaction, which is due to the formation of enstatite (Grim 1968).

Smectite and swelling-lattice vermiculite

X-ray analysis: Smectites constitute a large group of 2:1 minerals, marked by low layer charge ($x < 0.6$). This characteristic determines a weakness of the linkage between the different layers of given particle, and allows considerable swelling phenomena. The interlayers are occupied by a wide range of cations (mainly Na, Ca, Mg and K), organic ions, and by several layers of water. Smectite clay minerals may form in different chemical environments and this is the reason why they may have various chemical compositions, in both dioctahedral and trioctahedral subgroups (Chamley 1989, Brindley & Brown 1980). Basal spacings of smectite may vary from 10 to 20 Å depending on the cation involved. With smectites glycerol was alleged to provide a spacing of 18 Å. Ethylene glycol shifted 14 Å spacing to 16.9 - 17.1 Å when for vermiculite mineral spacing stayed below 16.70 Å (Grim 1968, Thorez 1975, Brindley & Brown 1980). According to Thorez (1975), after KCl-treatment 14 Å peak of smectite shifts between 12.40-12.80 Å. Best way to differ these minerals from each other is using either ethylene glycol or KCl-treatment.

Thermal analysis: Differential thermal curves of smectite show a considerable interlayer water loss as showed by endothermic reaction with a peak at 100 to 200 EC and immediately followed by a smaller peak at 250 to 275 EC. Next endothermic reactions take place at about 500 to 600 EC and at about 750 to 850 EC. These reactions are due to the loss of the OH lattice water. An exothermic reaction between at about 900 to 1000 EC corresponds to the formation of enstatite, mullite, anorthite or β-quartz (Grim 1968).

Mixed-layer clay minerals

X-ray analyses: Mixed-layered or interstratified clay minerals refer to remarkable phyllosilicate structures, characterized by a vertical stacking sequence of two or more types of single layers. The layers involved can be of 2:1, 2:1:1 and even 1:1 types. Most mixed-layers can be considered as clay species intermediate between two single clay minerals. They mainly form through weathering or middle-late diagenesis, but also characterize some hydrothermal and sedimentary environments. The mixed-layer minerals show in X-ray analyses characteristics that are intermediate between those of the individual minerals involved. Typical peaks for mixed-layer clay minerals between 11-14 Å. Three main types of interstratification are recognized (Chamley 1989):

1. A periodic alternation of layers of two types. A and B refers to regular or ordered mixed-layers:
   ABABAB...
   These minerals show well-defined reflections on X-ray diagrams and tend to be given specific names (for example corrensite).
2. A random alternation of each type of layer corresponds to irregular and randomly mixed-layered clays:
   AABABBBBAAABAABA
   This group often corresponds to poorly defined X-ray diffraction patterns, with dome-, plateau- or wedge like shapes, and locations at intermediate positions between those of the single minerals involved.
3. Partially ordered structures appear to exist, especially in some soils (MacEvan 1949). Intermediate between both former types, they are little known and not specifically labeled.
   Thermal analysis: See above.

Oxides of iron

X-ray analyses. Oxides of iron are usually poorly crystalline or totally amorphous and they provide no reflections in X-ray study. Both goethite and lepidocrocite are comparatively easily decomposed to provide anhydrous ferric oxide.

Thermal analysis: Goethite begins to decompose in air at approximately 250 EC, and a heat treatment for 1 hour at 300 EC in a slow current of air will effect complete decomposition to α-ferric oxide (Mackenzie 1957, Mackenzie & Berggen 1970, Rooksby 1961).

According to Barshad (1965) clay minerals loose their crystal-lattice water when heated between either 150 EC or 350 EC and 1000EC (see Table 2). Clay minerals can be divided into two distinct groups on the basis of the total amount of crystal-lattice water:

1. 2:1 minerals (montmorillonite, vermiculite, illite, muscovite, biotite and talc) and

2. 1:1 minerals (kaolinite) and 2:2 minerals (clinochlore)

Among the 2:1 minerals the water content lies in the range from 4.2 to 5.1 %. Among 1:1 and 2:2 minerals it lies in the range from 13.4 to 16.2 %. Through this method it is possible to determine approximately the relative content of 2:1 minerals and 1:1 and 2:2 minerals in a clay sample. If an X-ray analysis and chemical analysis are available also, it is possible to determine the amount of each mineral species present.

Table 2. Adsorbed and crystal-lattice water of clay minerals, and the temperature at completion of desorption and at start and completion of dehydroxyation (Barshad 1965, Table 50-2).

Clay mineral	Absorbed water, %		Chrystal lattice water, %	Temperature at completion of desorption, °C		Temperature at start of dehydroxylation, °C	Temperature at completion of dehydroxylation, °C
	Layer water	Cavity water		Layer water	Cavity water		
Montmo-rillonite	14.00-20.16	0.00-3.37	5.05-5.08	250-150	370	150-370	1000
Vermiculite	10.14-20.00	3.08-4.66	4.76-4.80	250-150	700	150-250	1000
Illite	3.45-5.16	0.66-1.06	4.97-5.07	150	370	370	1000
Muscovite	1.00	0.45	4.74	250	370	370	1000
Biotite	0.4-1.5		4.17	350	350	350	1000
Talc	0.7-1.0		4.99	350	350	350	1000
Kaolinite	0.2-1.2		16.20	350	350	350	1000
Halloysite	13.2		16.20	250			
Clinochlore	0.2-0.5		14.81	250	370	370	1000

4.4.2 Transmission electron microscopy

Identification of clay minerals is quite difficult using TEM+EDS, because chemical composition of illite, muscovite, chlorite, swelling-lattice vermiculite and vermiculite are very similar to each other. In the present study material these minerals have very poor crystal shape due to chemical and physical weathering processes. The method allows for direct measurement of several dimensions of the particle and also the shape of the particles. TEM was used in measuring the size of individual particles and identification of minerals.

5 Results

5.1 Influence of grain size distribution on till mineralogy and geochemistry

5.1.1 Mineralogy

In the present study the clay fraction (< 2 µm) of the tills is composed of vermiculite, chlorite, illite, swelling-lattice vermiculite, kaolinite and mixed-layer clay minerals (Table 5). The primary rock-forming minerals found in the clay fraction of the till in all survey areas are quartz, plagioclase, microcline and amphibole. In X-ray diffraction analyses quartz (Q) was identified from its 3.34 Å and 4.26 Å peaks. In DTA analyses quartz shows an endothermic reaction at 574 EC when α-quartz change into β-quartz. Quartz was also identified with transmission electron micrograph (TEM/EDS). Quartz was the most abundant primary mineral (Table 5). Plagioclase (P) was confirmed in X-ray diffraction from 3.191 Å, 4.03 Å (albite); 3.195 Å, 3.184 Å (anorthite); 3.20 Å, 4.02 Å (oligoclase) peaks. In all survey areas typical reflections were between 6.42-6.33 Å, 3.19 Å and 4.30 Å, which corresponds to albite. Plagioclase was also identified with a transmission electron micrograph (TEM/EDS) (see Fig. 25 and Fig. 35). Microcline (M) was identified in X-ray diffraction from reflections at 4.21 Å and 3.23-3.24 Å. Feldspars occur in very small amounts or are totally absent in the samples of the Kittilä area (ground moraine). Amphibole (A) was recognized in X-ray analyses by reflection at 8.4 Å. Amphiboles also occur in low contents in the samples of the Kittilä area. Amphibole was also identified with a transmission electron micrograph (TEM/EDS) (see Fig. 25). Absence of feldspars and amphibole is best explained so that feldspars and amphiboles have been strongly weathered in preglacial times and that the clay fraction of the till in the area contains much material, which is derived from the weathering crust.

Rock-forming minerals play a minor role in the clay fraction of the till. Exceptions are the tills of Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) and Kuusamo (drumlin), where plagioclase, quartz and amphibole are the dominant minerals (see Figs 17a and 29a). In these areas the quantity of clay fraction is low and the weathering rate is also low. The tills of Kemijärvi and Kuusamo are more immature. In the study of Soveri and Hyyppä (1966) till samples were only from Southern Finland and they were exceptionally clay-rich (over 10% of the fraction < 2 µm) compared to the more normal Finnish sandy tills (2-3 % of the fraction < 2 µm). Soveri and Hyyppä found that the finest fractions of the tills are composed of quartz, feldspars, amphibole, illite, chlorite, vermiculite, so-called clay-vermiculite and the mixed-layer clay minerals of illite, chlorite and/or vermiculite. The clay fraction of the till is usually enriched with mica/illite and other clay minerals (cf., earlier studies).

In X-ray diffraction there are no specific reflections of mixed-layer clay minerals. They are usually constructed of illite, chlorite, vermiculite and swelling-lattice vermiculite. Also the structure can be ordered or disordered. Ordered mixed-layer minerals have exact reflection angles but disordered mixed-layer minerals have reflection between 10-14 Å. In this study all mixed-layer minerals are disordered-type. In X-ray diffraction main reflections are between 12.96-10.33 Å. A part of the 12 Å peak moves toward 14 Å when treated by ethylene glycol. This confirms that swelling-lattice vermiculite is one component present. Also part of the 12 Å reflection is still observed and this is due to chlorite. Glycerol-treatment does not affect these reflections, so smectite is not present. After KCl-treatment 12 Å is moved toward 10 Å and at the same time a weak 12 Å reflection is still present. Heat treatments also confirm presence of illite, chlorite, vermiculite and swelling-lattice vermiculite (see below).

Table 3. Type of illite in the clay fraction of the till in the study areas.

Area	Number of samples	Dioctahedral (%)	Trioctahedral (%)
Suomussalmi	36	35	65
Kuusamo	7	43	57
Ylikiiminki	36	44	56
Kuivaniemi	5	20	80
Kemijärvi	64	35	65
Kittilä	39	79	21
Aavasaksa	8	13	87
Jerisjärvi	7	71	29
Kaaresuvanto	6	0	100
Pulju	2	0	100
Inari	40	15	85
n = 250			

In the study areas of Suomussalmi (Kianta moraine), Ylikiiminki (longitudinal moraine ridge, end moraine and marginal moraine), Kuivaniemi (cover moraine), Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) and Aavasaksa (ground moraine) 12 Å mixed-layer minerals are composed of illite, chlorite, vermiculite and swelling-lattice vermiculite. In the study area of Kuusamo (drumlin) main reflections are between 12.96 Å and 10.50 Å. After heat-, ethylene glycol-, glycerol and KCl-treatments it can be point out that 12 Å mixed-layer minerals are composed of illite, vermiculite and chlorite. In the Kittilä (ground moraine), Jerisjärvi (cover moraine), Pulju (Pulju moraine) and Kaaresuvanto (Pulju moraine) area main reflections are between 12.82 Å and 10.16 Å. The behavior of these reflections after heat-, ethylene glycol-, glycerol and KCl-treatments confirm that the corresponding mixed-layer minerals are illite, vermiculite and swelling-lattice vermiculite (see below). In the clay fraction of Northern and Southern Inari (Sevetti moraine) main reflections are between 12.96 Å and 10.50 Å. After heat-, ethylene glycol-, glycerol and KCl-treatments it can be pointed out that 12 Å mixed-layer minerals are composed of illite, vermiculite and chlorite. There may possibly be also swelling lattice vermiculite involved in these samples.

In the fine fraction (< 60 µm) of the till the rock-forming minerals are in the main role. Minerals occur in following order: quartz, plagioclase, amphibole, microcline, chlorite and illite. There exist also vermiculite and mixed-layer minerals, but they are minor components. A dominance of rock-forming minerals in the fine fraction is due to grain size distribution and that these minerals are bound to certain terminal grain size modes. Dreimanis and Vagners (1965, 1969, 1971a, 1971b, 1972) concluded that every lithologic component of basal till has a bimodal size distribution. This is true of rocks that are monomineralic or contain minerals with similar physical properties. On the other hand, in the areas of metamorphic rocks, where rock types change in short distance from the one to the other, the nature of a moraine matrix is usually polymodal (Perttunen 1977, Nevalainen 1983, 1989). There are some exceptions in present study material. In the sample from Sukseton (306) (ground moraine) the most dominant minerals in the fine fraction are illite, quartz and plagioclase (see Fig. 33d). There are also some amounts of chlorite and/ or kaolinite. Also, in the fine fraction from Kaaresuvanto, Pulju (Pulju moraines) and Inari (Sevetti moraine) high amounts of secondary minerals occur (see Figs 21d, 38b and 24c). The influence of weathered bedrock is clearly seen in these samples.

Table 4. The weight loss (%) in the clay fraction of the till in the study areas.

Area	Number of samples	20 - 220 °C e.g., crystal lattice and adsorbed water (%)	220- 430 °C e.g., organic matter burns and start of dehydroxylation (%)	430-1100 °C e.g.,dehydroxylation (%)	total weight loss e.g., completion of dehydroxylation (%)
Suomussalmi	36	3.0-5.8	1.0-2.0	2.8-3.5	7.9-11.3
Kuusamo	7	2.5-2.6	1.3-1.4	2.6-2.8	6.4- 6.8
Ylikiiminki	36	3.1-4.6	1.4-2.0	2.8-3.2	8.8- 9.8
Kuivaniemi	5	4.0-4.6	2.4-3.0	2.4-2.6	9.6-10.2
Kemijärvi	64	1.5-4.0	1.0-2.0	1.1-2.4	4.9- 8.5
Kittilä	39	5.0-6.0	2.5-3.5	4.0-5.8	12.4-15.4
Aavasaksa	8	2.8-3.8	1.4-2.0	1.6-1.8	6.6- 8.0
Jerisjärvi	7	4.5-4.9	3.3-3.8	3.4-3.6	11.6-13.0
Kaaresuvanto	6	2.6-5.8	1.3-1.6	1.6-2.8	6.6-10.6
Pulju	2	2.6-5.1	2.4-3.5	2.8-4.7	7.8-13.3
Inari	40	3.2-4.6	1.5-5.0	2.8-4.2	8.7-13.8
n = 250					

Table 5. Semi-quantitative estimation of mineral contents in till of the study areas.

Area	Suomussalmi	Kuivaniemi	Northern Inari
Moraine type	Interlobate hummocy moraine	Cover moraine	Sevetti moraine
Bedrock	Archaean gneiss	Archaean gneiss	Archaean gneiss
	vermiculite	vermiculite	illite
	chlorite	chlorite	chlorite
	swelling-lattice vermiculite	swelling-lattice vermiculite	vermiculite
	illite	illite	quartz
	quartz	mixed-layer minerals	amphibole
	plagioclase	quartz	plagioclase
	amphibole	plagioclase	microcline
	mixed-layer minerals	amphibole	mixed-layer minerals
	microcline	microcline	swelling-lattice vermiculite
		**kaolinite	**kaolinite
	n= 36	n= 5	n= 26
Area	Kittilä	Jerisjärvi	Southern Inari
Moraine type	Ground moraine	Cover moraine	Sevetti moraine
Bedrock	Mafic volcanite	Mafic volcanite	Granulite
	illite	vermiculite	chlorite
	vermiculite	kaolinite	illite
	kaolinite	illite	vermiculite
	quartz	swelling-lattice vermiculite	quartz
	swelling-lattice vermiculite	quartz	plagioclase
	*plagioclase	amphibole	mixed-layer minerals
	*mixed-layer minerals	plagioclase	amphibole
	*microcline	microcline	microcline
	*amphibole	mixed-layer minerals	*swelling-lattice vermiculite
			**kaolinite
	n= 39	n= 7	n= 14
Area	Kaaresuvanto	Pulju	Ylikiiminki
Moraine type	Pulju moraine	Pulju moraine	Endmoraine
Bedrock	Archaean gneiss	Mafic volcanite	Svecokarelian schists and gneiss
	swelling-lattice vermiculite	swelling-lattice vermiculite	illite
	vermiculite	vermiculite	vermiculite
	illite	kaolinite	chlorite
	quartz	illite	quartz
	plagioclase	mixed-layer minerals	plagioclase
	amphibole	quartz	swelling-lattice vermiculite
	kaolinite	plagioclase	amphibole
	mixed-layer minerals	microcline	microcline
	microcline	amphibole	mixed-layer minerals
			**kaolinite
	n= 6	n=2	n= 36
Area	Kemijärvi	Kuusamo	Aavasaksa
Moraine type	Rogen-, Lee-, Vika- and hummocky moraines	Durmlin	Ground moraine
Bedrock	Granitoids	Archaean gneiss	Granitoids
	plagioclase	quartz	swelling-lattice vermiculite
	quartz	plagioclase	vermiculite
	amphibole	chlorite	mixed-layer minerals
	illite	amphibole	illite
	chlorite	illite	plagioclase
	vermiculite	mixed-layer minerals	quartz
	microcline	vermiculite	chlorite
	mixed-layer minerals	microcline	microcline
	*swelling-lattice vermiculite	swelling-lattice vermiculite	amphibole
	**kaolinite		
	n= 64	n= 7	n= 8

* very weak intensity
** identyfied with TEM

5.1.2 Geochemistry

There are distinct differences in geochemical composition between fine and clay fractions of the till in this survey. Comparisons of these fractions are presented in Table 6. The contents of Si, Ca and Na in the fine fraction are higher than in the clay fraction. Instead Al, Fe, Mg, K and trace metals are at higher level in the clay fraction than in the fine fraction. These results reflect the differences in the mineralogical composition, because fine fractions has been enriched with primary minerals and depleted with clay minerals. Results point out that geochemical composition of the till is quite dependent on grain-size distribution. High Fe and Mn contents in the clay fraction are mainly caused by the amount of secondary oxides of Fe and Mn (see Shilts 1995, Peuraniemi 1996, 1997). The geochemical results of present study are comparable with the earlier observations of Shilts (1971, 1973a, 1973b, 1975, 1976, 1977, 1980, 1984, 1991, 1993, 1995), Klassen & Shilts (1977), DiLabio and Shilts (1977, 1979), DiLabio (1989) Shilts and Smith (1989), Kettles and Shilts (1989), Shilts and Kettles (1990), Nikkarinen and co-author 1984, Nevalainen (1983, 1989) and Mäkinen (1992).

Table 6. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions of the till in the study area.

	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	65,75	73,90	41,30	5,09	47,67	56,53	35,27	5,46
TiO2	1,00	3,05	0,07	0,33	1,25	2,25	0,81	0,35
Al2O3	14,82	29,50	8,80	2,02	19,79	24,28	16,23	1,70
Fe2O3	6,57	38,10	2,84	3,15	13,54	25,78	7,21	4,80
MnO	0,11	2,00	0,01	0,13	0,12	0,23	0,08	0,04
MgO	2,34	10,40	0,00	1,01	5,19	7,96	3,19	1,09
CaO	3,48	11,30	0,03	0,99	1,76	2,89	0,62	0,57
Na2O	3,22	6,20	0,00	0,71	1,63	3,16	0,39	0,74
K2O	2,23	6,63	0,00	0,54	3,15	4,36	0,94	1,10
P2O5	0,29	5,98	0,00	0,63	0,25	0,76	0,11	0,14
n	813				49			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	75	1096	17	64,8	203	1838	77	155,6
Pb	26	188	0	13,4	28	996	0	74,1
Ni	56	993	13	46,3	104	264	50	38,3
Co	32	307	5	22,1	37	84	18	12,0
Cu	52	787	2	50,3	238	1589	50	246,3
n	813				231			

5.2 Influence of the bedrock type on till mineralogy and geochemistry

The present study material has been divided into geochemical provinces and subprovinces of Finland defined by Koljonen and co-author (1992). Table 5 shows the mineralogical composition of the till in every survey area.

5.2.1 Archaean gneiss areas

The study areas of Suomussalmi (Kianta moraine), Kuusamo (drumlin), Kuivaniemi (cover moraine), Kaaresuvanto (Pulju moraine) and Northern Inari (Sevetti moraine) (Ahvenjärvi, Sevettijärvi, Suojanperä and Pyhävaara) are located in the geochemical province of Archaean basement gneiss complex as defined by Koljonen and co-author (1992).

Mineralogy

In the clay fraction of tills of Suomussalmi (Kianta moraine) the most abundant minerals are vermiculite, chlorite, swelling-lattice vermiculite and illite (Table 5 and Figs 14a,b). Vermiculite is identified on the basis of its strong 14.60-14.00 Å peak, which shifts to 10 Å after heating to 450-550 EC or with saturation with KCl. Swelling-lattice vermiculite is very common and in X-ray analyses it has typically a strong 16 Å peak after ethylene glycol treatment. Vermiculite is termed as swelling when the basal spacing at 14 Å shifts to below 16.70 Å after ethylene glycol treatment while smectites shifts to 16.70-17.1 Å (Grim 1968, Thorez 1975, Brindley & Brown 1980). KCl-treatment shifts smectites 14 Å spacing between 12.40-12.80 Å when vermiculite shifts to 10 Å (Thorez 1975). After KCl- and heat treatment 14 Å peak shifts to 10 Å, this is a typical reaction for vermiculite. Transmission electron micrographs point out that this mineral is fine grained (1 μm) (Fig. 16). The results of the present study point out that swelling-lattice vermiculite is a common clay mineral in the clay fraction of Finnish tills (cf., Soveri 1956, Jörgensen 1965, Gjems 1965, 1967, Byström-Brusewitz 1975). According to Snäll and co-author (1979, 1992), Björnholm (1979), Melkerud (1984, 1986), Snäll (1986), Lång & Stevens (1996) swelling-lattice clay minerals are also common in the tills of Southern Sweden. Soveri & Hyyppä (1966), Räisänen and co-author (1992) and Lintinen (1995) concluded that these types of clay minerals are not common in Finnish tills. Chlorite was identified by the reflections between 13.60-14.70 Å (001), 7.02-7.14 Å (002), 4.70-4.79 Å (003) and 3.52-3.56 Å (004). Heating Mg-rich chlorite to about 600 EC creates an increase in the intensity of 14 Å reflection and decrease in the intensities of the 7.05-7.10 Å, 4.70-4.79 Å and 3.56 Å reflections (Grim & Johns 1955; Soveri 1956; Grim 1968). Both Mg-rich- and Fe- rich chlorite are present but latter type is dominant (Figs 14a,b and 16). In X-ray analyses illite was identified by its peaks at 10.1-9.99 Å (001) and 5.00-4.90 Å (002). According to Srodon and Eberl (1984), so-called degraded illite has an asymmetrical reflection and it leans towards to the lower angle. This is typical of all analyzed till samples. Illite minerals have also a moderate 4.90-4.98 Å (002) reflection. If the intensity ratio I(001)/I(002) is less than four, the illite is assumed to be dioctahedral type (Graff-Petersen 1961).

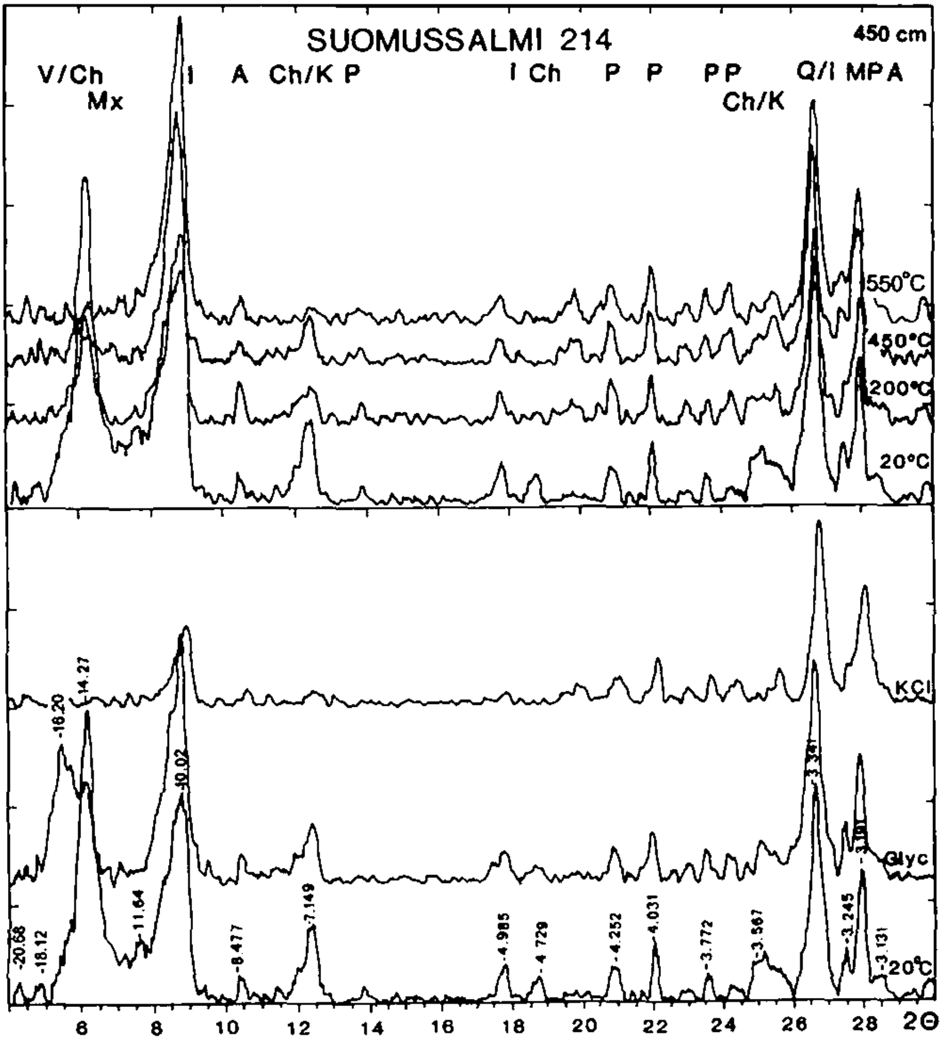

Fig. 14a. X-ray diffraction diagrams of the clay fraction of the till from the Suomussalmi area, Lahna (Kianta moraine), pit number 214, depth 450 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

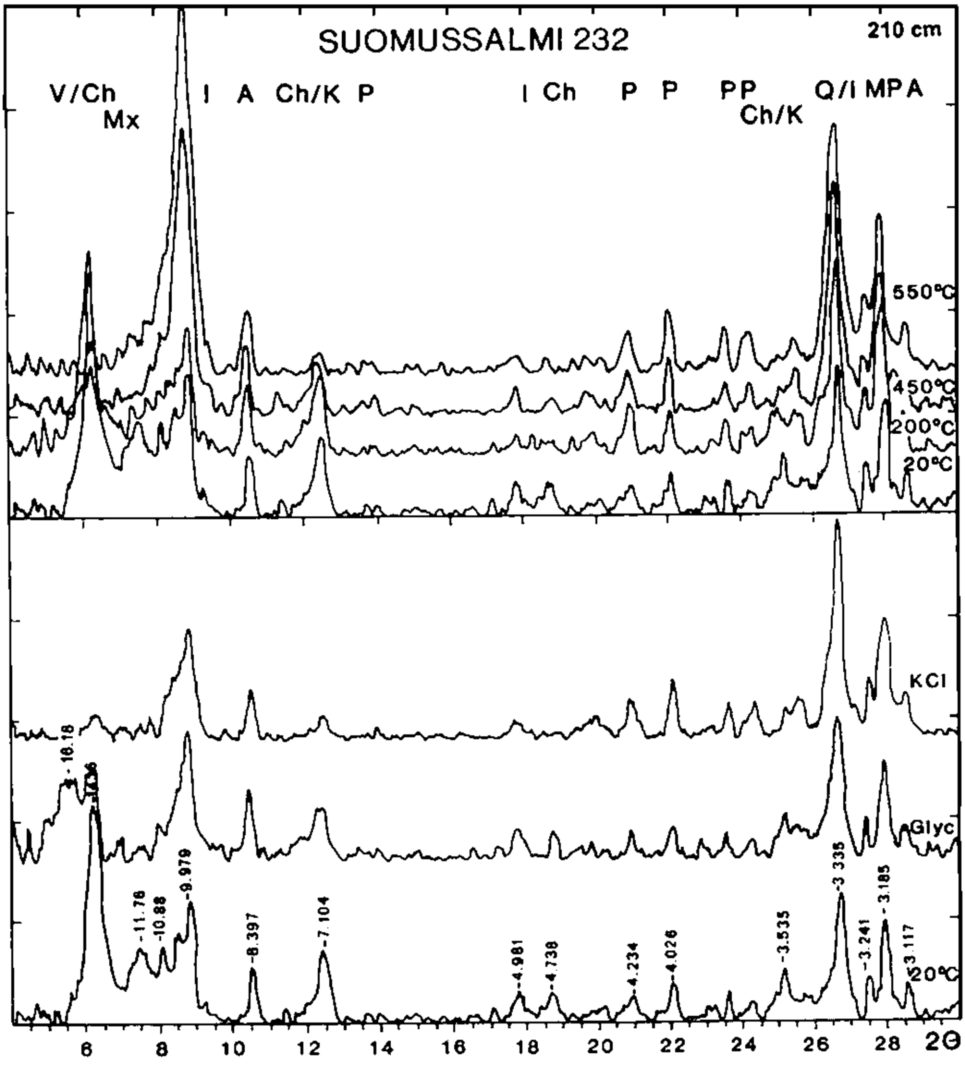

Fig. 14b. X-ray diffraction diagrams of the clay fraction of the till from the Suomussalmi area, Isopalo (Kianta moraine), pit number 232, depth 210 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

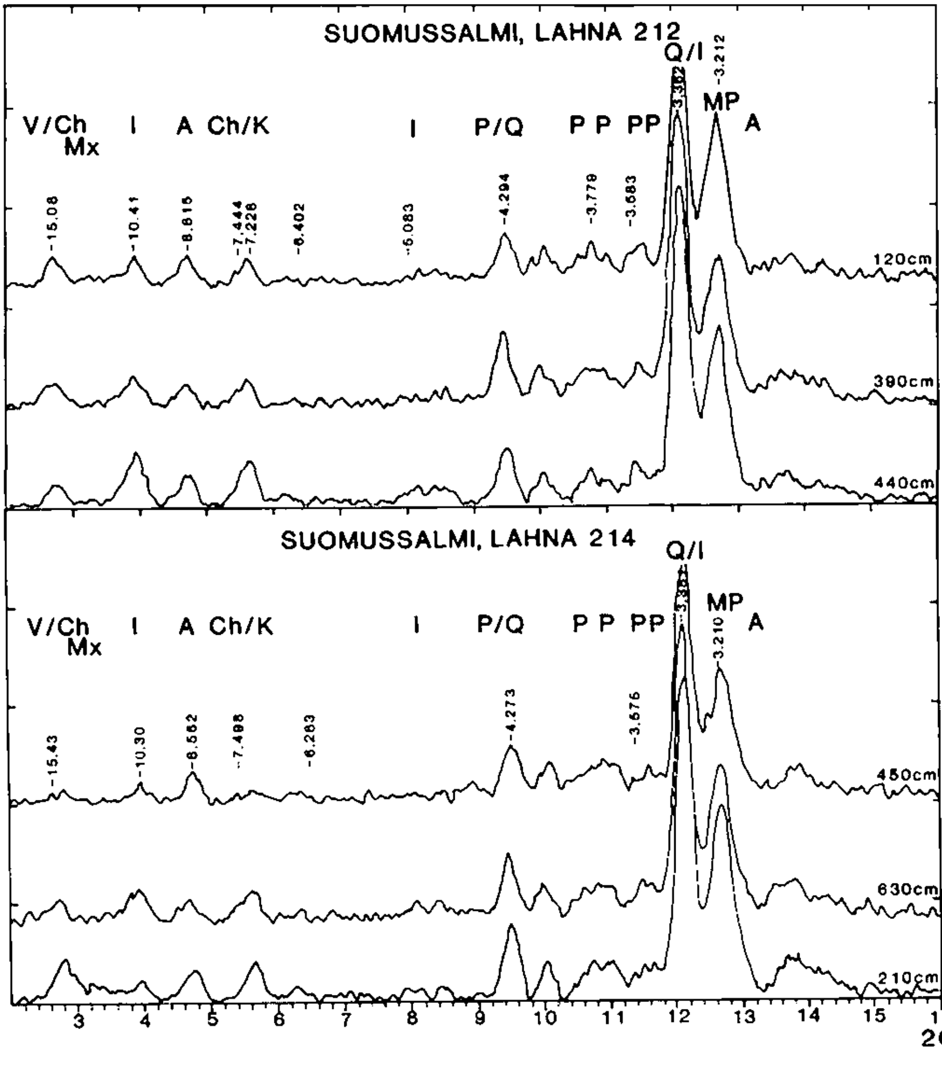

Fig. 14c. X-ray diffraction diagrams of the fine fraction of the till from the Suomussalmi area, Lahna (Kianta moraine), pit number 212 (depths 120 cm, 390 cm and 440 cm) and pit number 214 (depths 210 cm, 450 cm and 630 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

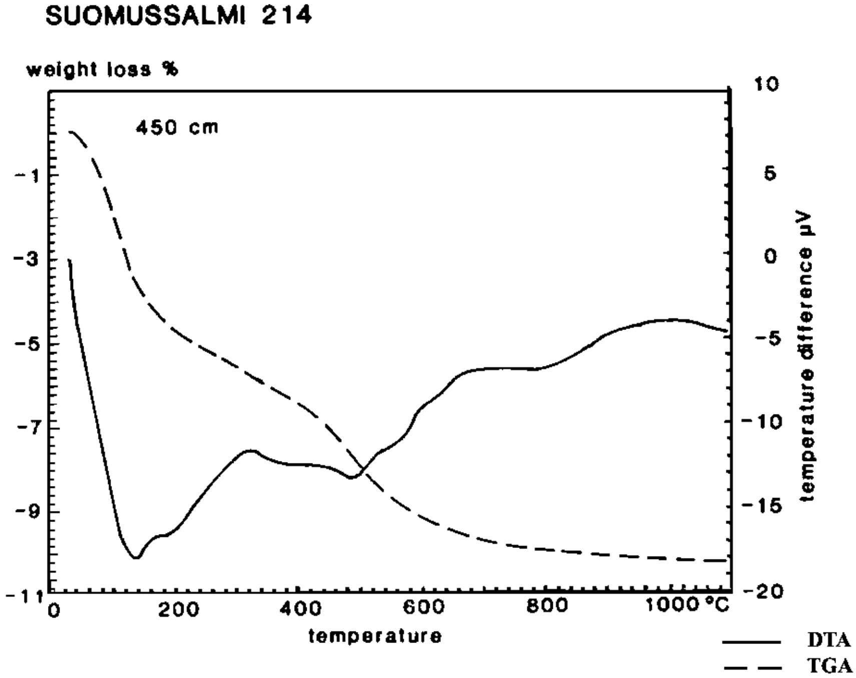

Fig. 15. Differential Thermal (DTA) and Thermogravimetric (TGA) graphs of the clay fraction of the till from the Suomussalmi area, Lahna (Kianta moraine), pit number 214, depth 450 cm.

Trioctahedral illite and biotite studied by Bradley and Grim (1961), have intensity ratios I(001)/I(002) in the range of 5-10. The type of illite has been calculated from XRD data and it is presented in Table 3. According to these calculations, illite is of mainly trioctahedral type in the tills of Suomussalmi (Kianta moraine). Dioctahedral illite is more abundant in the tillsamples of Isopalo (pits 230-237). Small amount of mixed-layer clay minerals is typical in tills of Suomussalmi. Rock forming minerals are in following order: quartz, plagioclase, amphibole and microcline. The result of the thermal analyses one show that all samples of Suomussalmi are strongly dehydrated between 130 EC and 190 EC. This is typical to vermiculite and mixed-layer minerals. Because the amount of mixed-layer minerals on the basis of XRD is not great, these reactions are due to vermiculite and swelling-lattice vermiculite (Figs 14a,b). The hydration peak at 500 EC is due to illite and chlorite, because on the basis of XRD, there is no kaolinite in the samples of Suomussalmi. The faint endo- and exothermic reactions between 700 EC and 1000 EC are also due to illite, chlorite and vermiculite. The total weight loss varies from 7.9 % to 11.3 % (see Fig. 15 and Table 4). The fine fraction of tills of Suomussalmi contains mostly quartz, plagioclase, amphibole and microcline (Fig. 14c). As minor components also illite and chlorite/vermiculite occur. The influence of the local bedrock is clearly seen in the mineral composition of both fractions of these tills. The rock-forming minerals that are typical for Archaean gneisses (e.g., quartz, plagioclase and microcline) are the most common primary minerals in these tills.

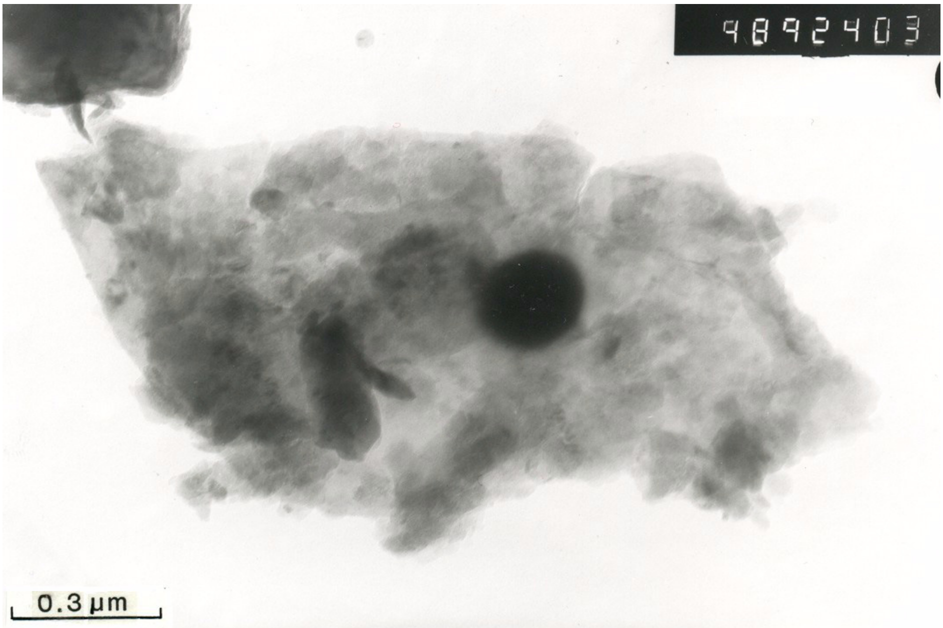

Fig. 16. TEM-photograph of clay fraction: Suomussalmi, Isopalo (Kianta moraine), pit number 232, depth 210 cm. Chlorite/vermiculite crystal (Fe, Si, Al and Mg). Identification is based on chemical elements (EDS) that are presented between parentheses.

In the clay fraction of the tills in Kuusamo (drumlin) primary minerals are dominant (quartz, plagioclase, amphibole and microcline). The most abundant clay minerals are chlorite and illite (Table 5 and Fig 17a). Illite is equally di- and trioctahedral type (Table 3). There is also a moderate amount of mixed-layer minerals. Kaolinite and swelling-lattice vermiculite are not dedected in the clay fraction of these tills (Fig. 17a). The dehydration of the samples of Kuusamo takes place between 20 EC to 200 EC. Instead the dehydroxylation is very faint indicating low content of the clay minerals. The total loss of weight varies from 6.4 % to 6.8 % (see Fig 18 and Table 4), which are the smallest of all samples in this study along with Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) and Aavasaksa (ground moraine). Also XRD-graphs confirm that vermiculite, illite and chlorite are present in these samples (Fig. 17a). In the fine fraction the most abundant minerals are quartz, plagioclase, microcline and amphibole (Fig. 17b). Small amounts of chlorite, illite, mixed-layer clay minerals and vermiculite occur. The influence of the local bedrock is clearly seen in the mineral composition of both fractions of these tills.

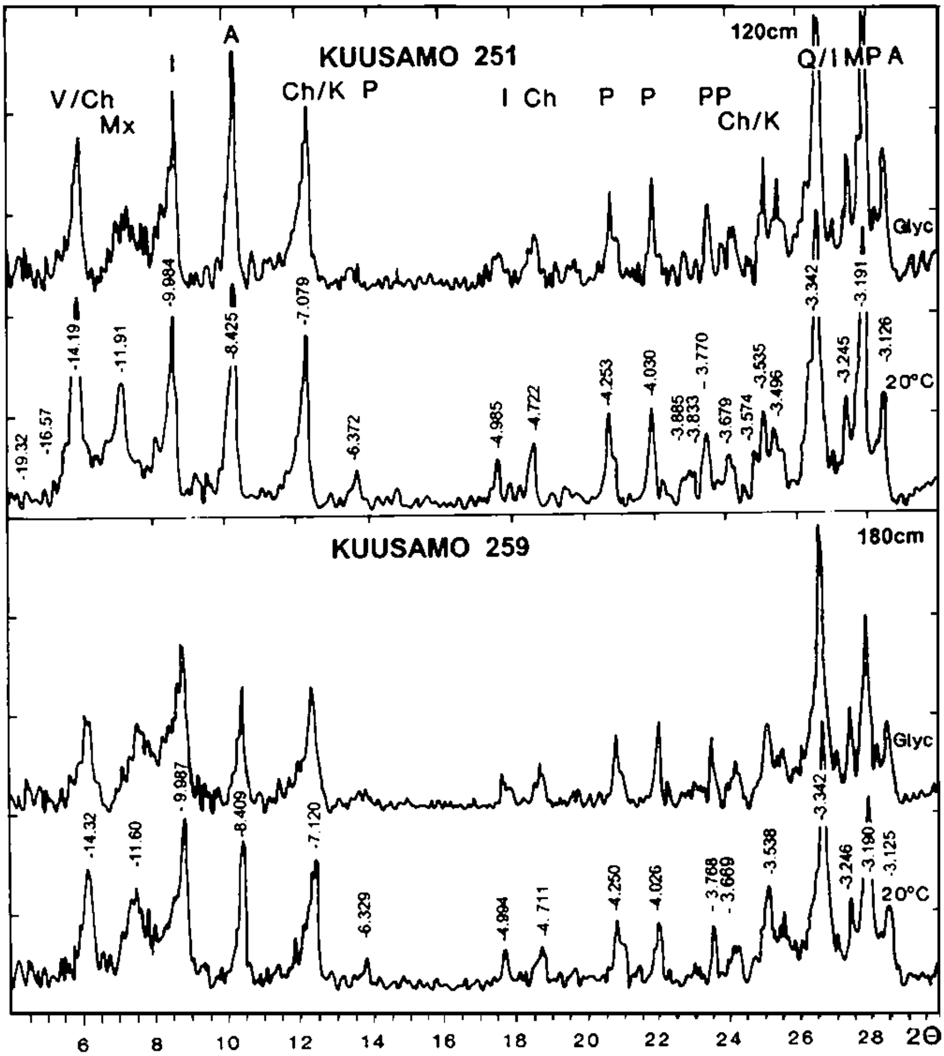

Fig. 17a. X-ray diffraction diagrams of the clay fraction of the till from the Kuusamo, Säynäjäluoma (drumlin), pit number 251, depth 120 cm and pit number 259, depth 180 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz and Glyc= ethylene glycol treatment.

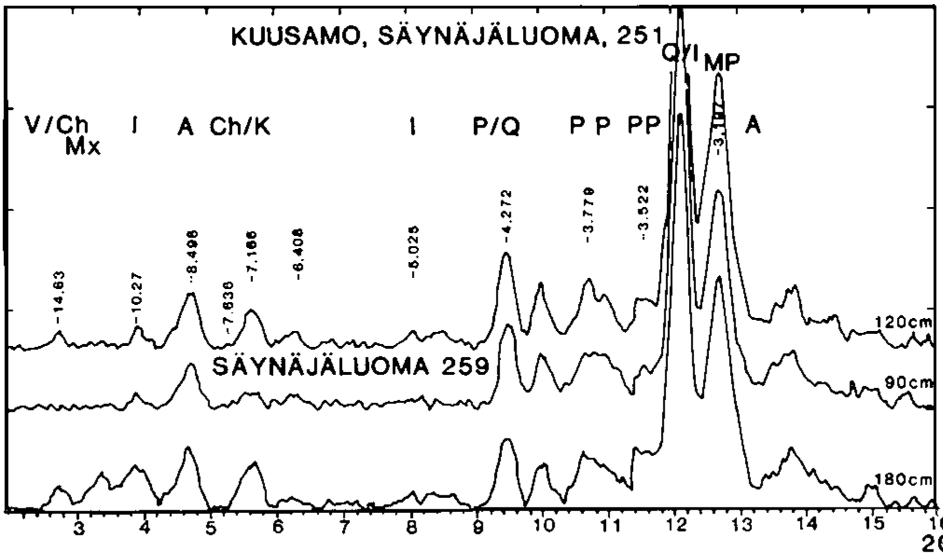

Fig. 17b. X-ray diffraction diagrams of the fine fraction of the till from the Kuusamo, Säynäjäluoma (drumlin), pit number 251, (depths 90 cm, 120 cm and 180 cm). V= vermiculite/ swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

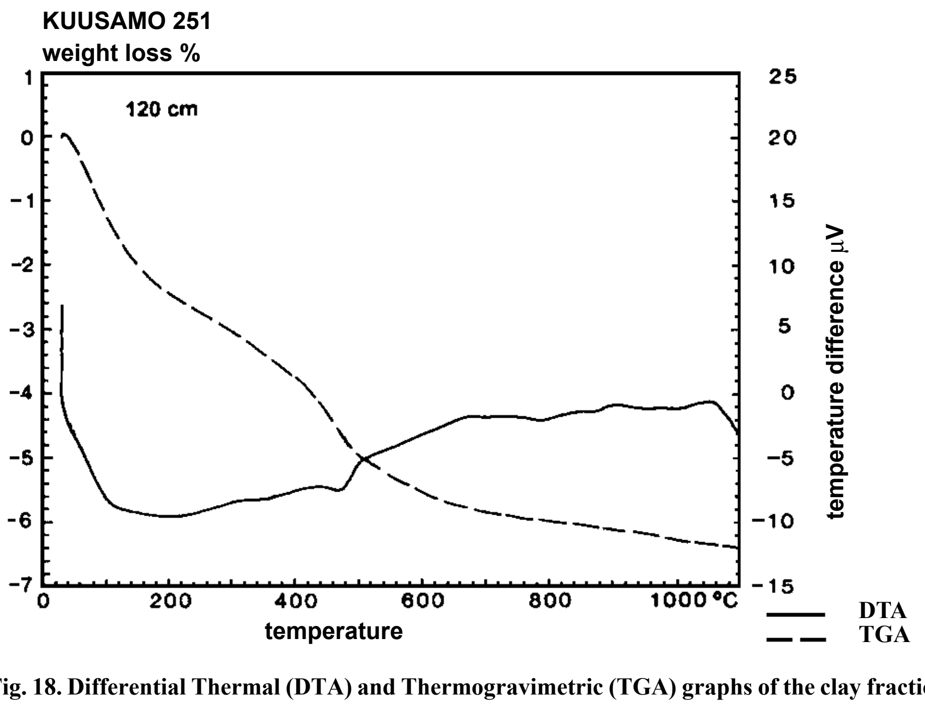

Fig. 18. Differential Thermal (DTA) and Thermogravimetric (TGA) graphs of the clay fraction of the till from the Kuusamo, Säynäjäluoma (drumlin), pit number 251, depth 120 cm.

In the clay fraction of tills of Kuivaniemi (cover moraine) the most abundant minerals are vermiculite, chlorite, swelling-lattice vermiculite and illite. Swelling-lattice vermiculite is very common and in X-ray analyses it has typically a strong 16 Å peak after ethylene glycol treatment (Table 5 and Fig. 19a). After KCl- and heat treatment 14 Å peak shifts to 10 Å, this is a typical reaction for vermiculite.

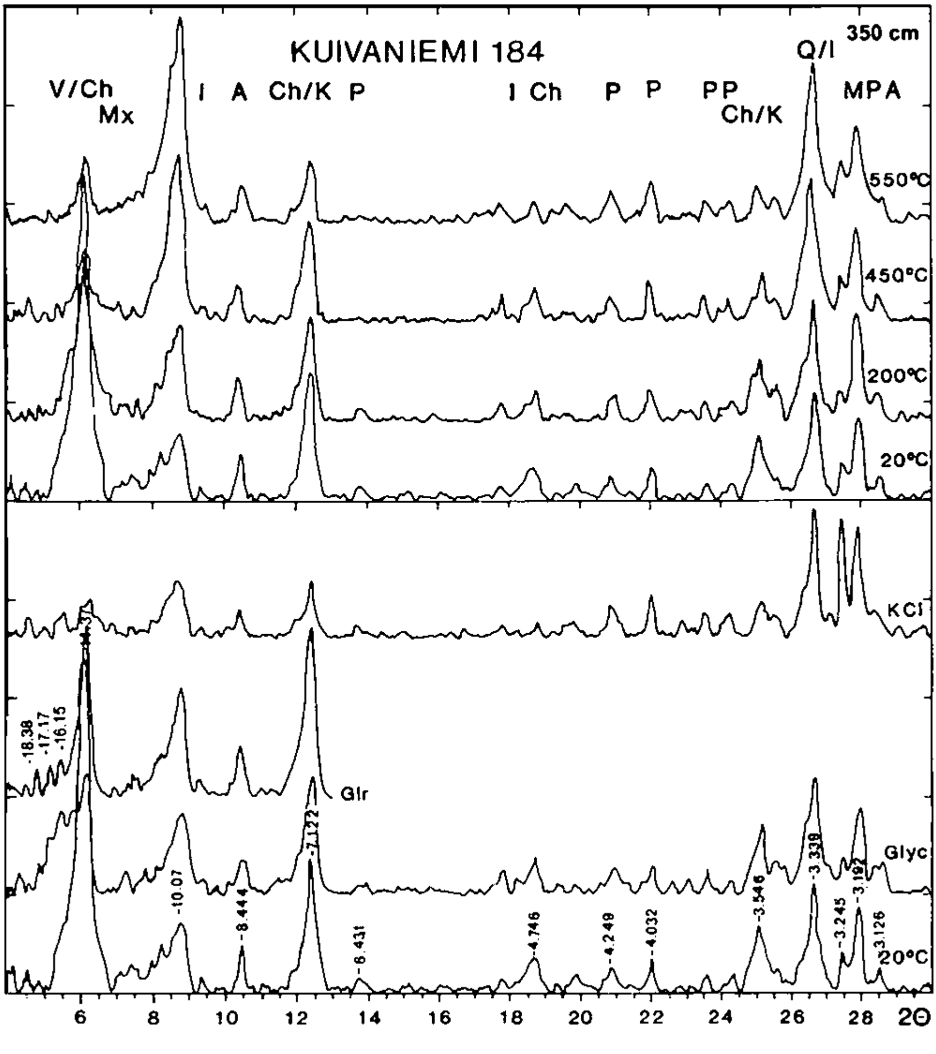

Fig. 19a. X-ray diffraction diagrams of the clay fraction of the till from the Kuivaniemi area, Käärmeaapa (cover moraine), pit number 184, depth 350 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation, Glyc= ethylene glycol treatment and Glr= glycerol treatment.

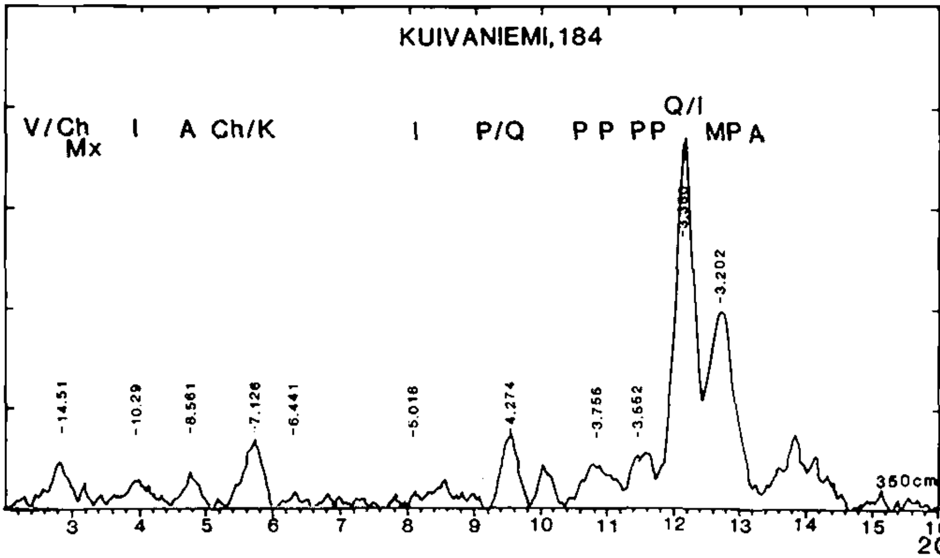

Fig. 19b. X-ray diffraction diagrams of the fine fraction of the till from the Kuivaniemi, Käärmeaapa (cover moraine), pit number 184, depth 350 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

Basal spacings of smectite may vary from 10 to 20 Å depending on the cation involved. With smectites glycerol was alleged to give spacing of 18 Å but this treatment does not effect to vermiculite. Glycerol treatment did not take effect to 14 Å peak and there is no smectite present (Fig. 19a). Both Mg-rich- and Fe- rich chlorite are present but the latter type is dominant. Illite is mainly trioctahedral type (Table 3). There is also a small quantity of mixed-layer clay in the tills of Kuivaniemi (cover moraine). Rock forming minerals are in following order: quartz, plagioclase, amphibole and microcline. In the clay fraction of tills of Kuivaniemi (cover moraine) is a small amount of kaolinite, which was identified by TEM/EDS. The main part of dehydration of the samples of Kuivaniemi takes place between 80 and 250 EC. The double dehydration peak clearly refers to the presence of vermiculite. On the contrary the dehydroxylation peak between 400EC and 700 EC is very faint or missing. The total loss of weight varies from 9.6 % to 10.2 % (see Fig. 20 and Table 4). Also XRD-graphs confirms that vermiculite, illite, chlorite and swelling-lattice vermiculite are present in these samples (Fig. 19a). In the fine fraction of tills of Kuivaniemi (cover moraine) the most abundant minerals are quartz and plagioclase (Fig. 19b). As minor components also amphibole, illite, mixed-layer clay minerals and vermiculite are occurring. Chlorite is present in a moderate amount. The influence of the local bedrock is clearly seen in the mineral composition of both fractions of these tills. The rock-forming minerals that are typical for Archaean gneisses (e.g., quartz, plagioclase and microcline) are the most common primary minerals in these tills.

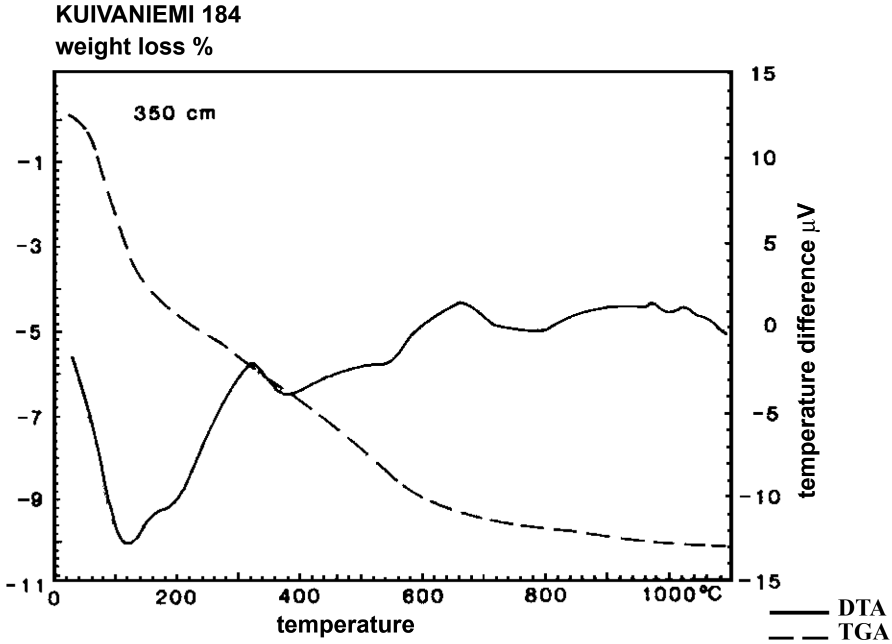

Fig. 20. Differential Thermal (DTA) and Thermogravimetric (TGA) graphs of the clay fraction of the till from the Kuivaniemi area, Käärmeaapa (cover moraine), pit number 184, depth 350 cm.

According to Matisto (1959, 1969) the study site of Kaaresuvanto (Pulju moraine) is mainly in the schist belt area, but there are also some orogenic plutonic rocks. In this area the main rock type is mica gneiss that contain quartz, plagioclase, biotite and/or muscovite. Koljonen and co-author (1992) have been categorized this area as Archaean gneiss area where rock-forming minerals are quartz, feldspars and mica (biotite). The most abundant minerals in the clay fraction of the till are swelling-lattice vermiculite, vermiculite, illite and kaolinite (Table 5 and Figs 21a,b,c). Swelling-lattice vermiculite got its typical reaction after ethylene glycol treatment when 14 Å peak shits to 16 Å. Vermiculite was confirmed with KCl- and heat treatments when 14 Å peak shifted towards 10 Å. An absence of chlorite is remarkable in the samples of Kaaresuvanto (Pulju moraine), but kaolinite is present. Kaolinite was identified by its basal reflections at about 7.16 Å (001) and 3.57 Å (002). It was detected by heat treatment (Figs 21a,b,c) when 7 Å peak disappeared after heating samples to 550 EC. Kaolinite was also identified by TEM/EDS (Fig. 23). Chlorite is probably weathered into vermiculite and swelling-lattice vermiculite. A minor amount of mixed-layer clay minerals is also present. Illite is predominantly trioctahedal type (Table 3). Quartz, plagioclase and amphibole are present in a moderate quantities and microcline occurs as a minor component. Smectite is not present in the samples of Kaaresuvanto (Pulju moraine), due to the fact that glycerol treatment did not affect the 14 Å peak (Figs 21a,b,c).

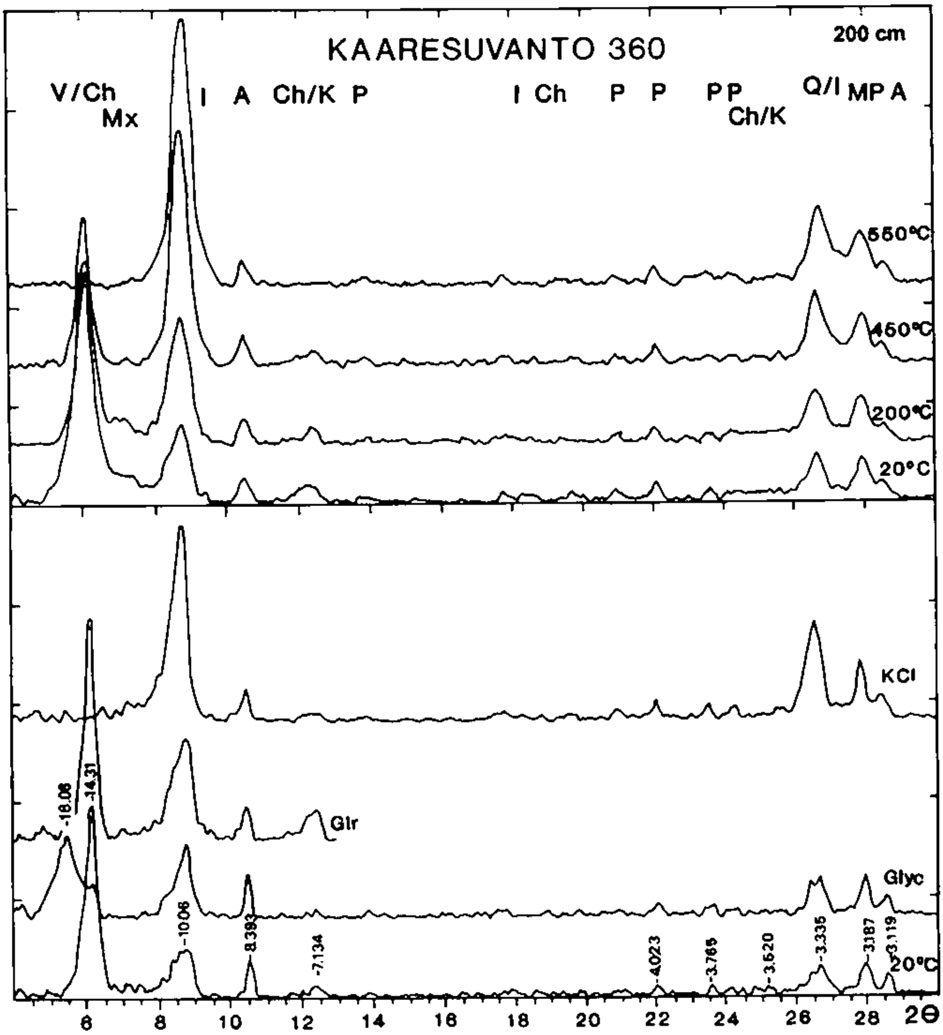

Fig. 21a. X-ray diffraction diagrams of the clay fraction of the till from the Kaaresuvanto area (Pulju moraine), pit number 360, depth 200 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation, Glyc= ethylene glycol treatment and Glr= glycerol treatment.

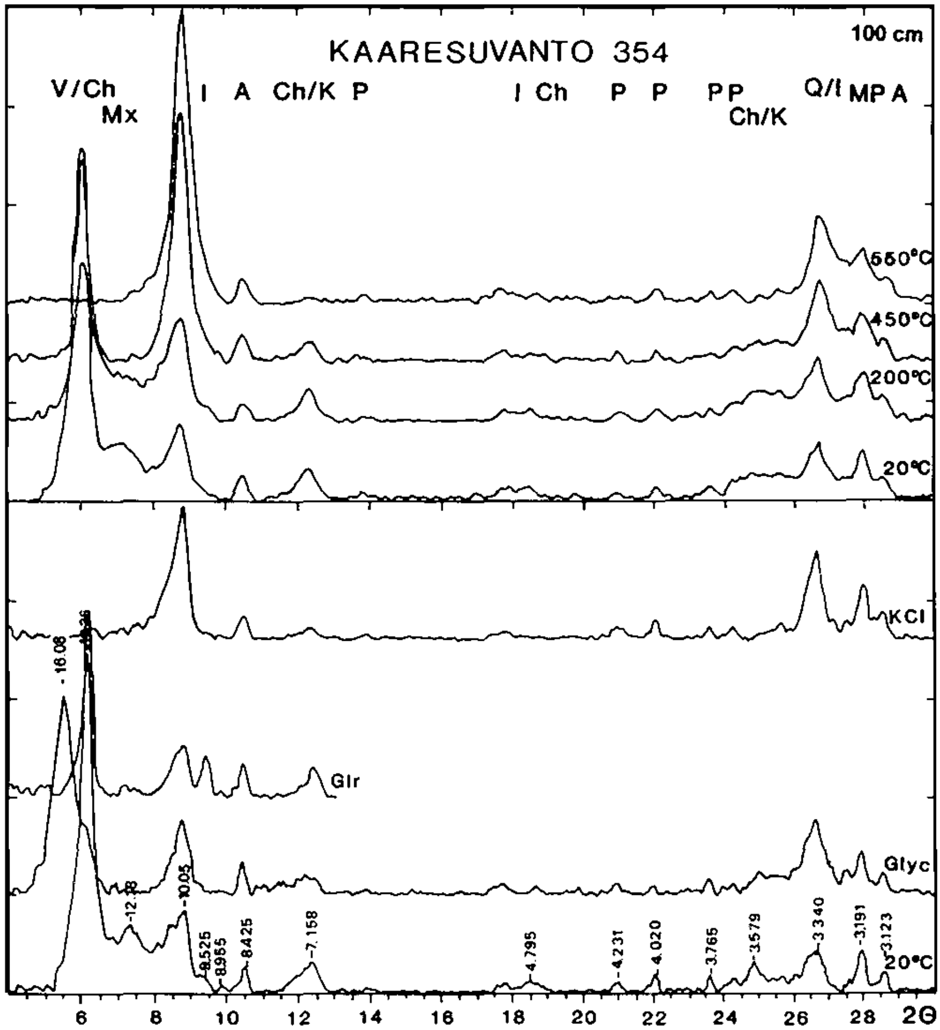

Fig. 21b. X-ray diffraction diagrams of the clay fraction of the till from the Kaaresuvanto area (Pulju moraine), pit number 354, depth 100 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation, Glyc= ethylene glycol treatment and Glr= glycerol treatment.

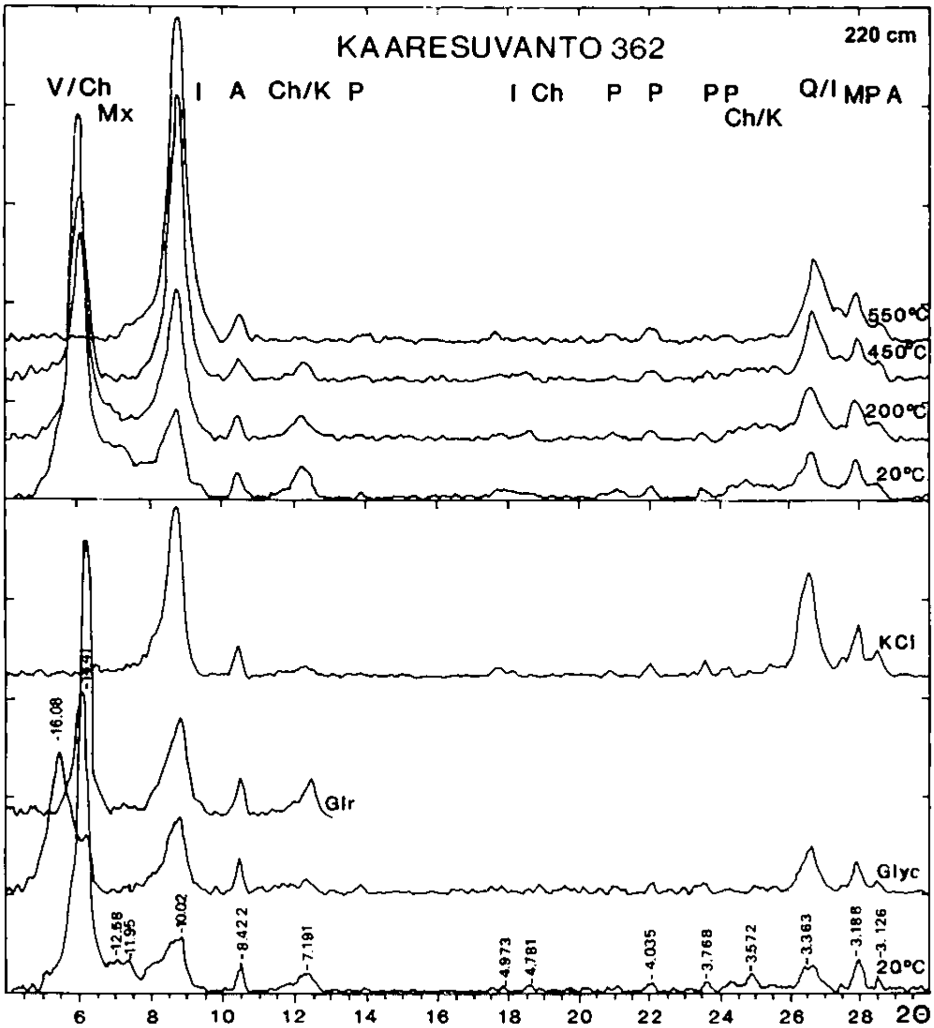

Fig. 21c. X-ray diffraction diagrams of the clay fraction of the till from the Kaaresuvanto area (Pulju moraine), pit number 362, depth 220 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation, Glyc= ethylene glycol treatment and Glr= glycerol treatment.

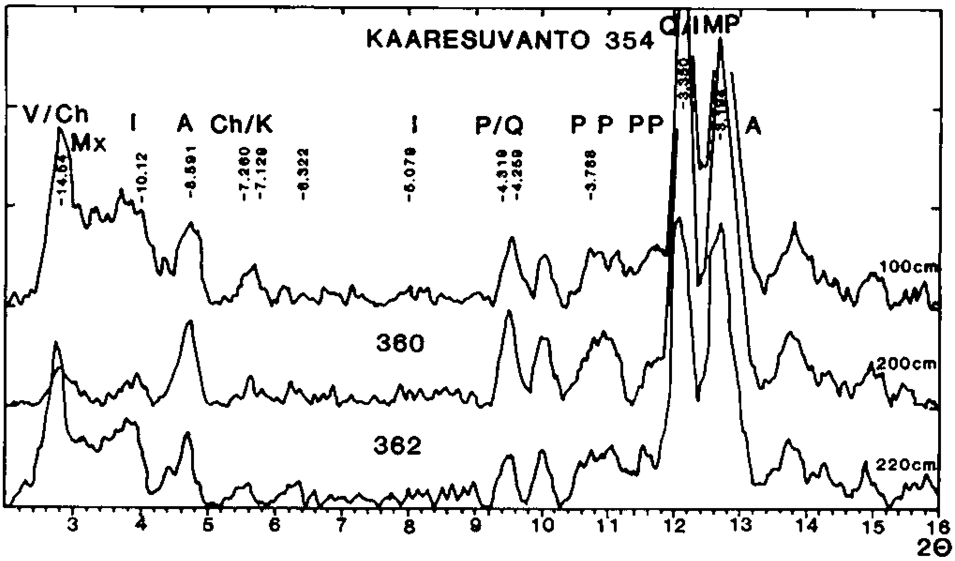

Fig. 21d. X-ray diffraction diagrams of the fine fraction of the till from the Kaaresuvanto area (Pulju moraine), pit number 354 (depths 100 cm, 200 cm and 220 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

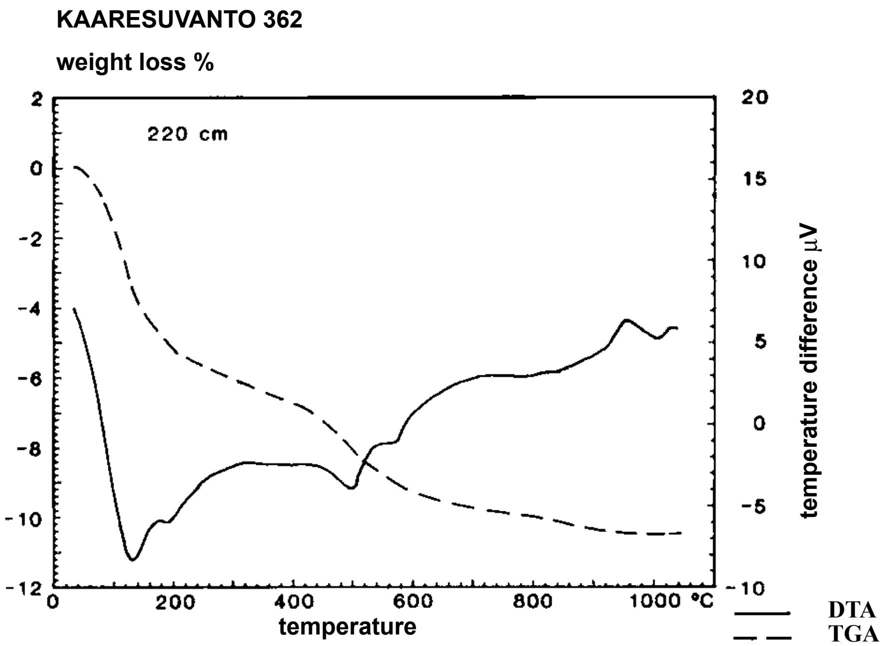

Fig. 22. Differential Thermal (DTA) and Thermogravimetric (TGA) graphs of the clay fraction of the till from the Kaaresuvanto area (Pulju moraine), pit number 362, depth 220 cm.

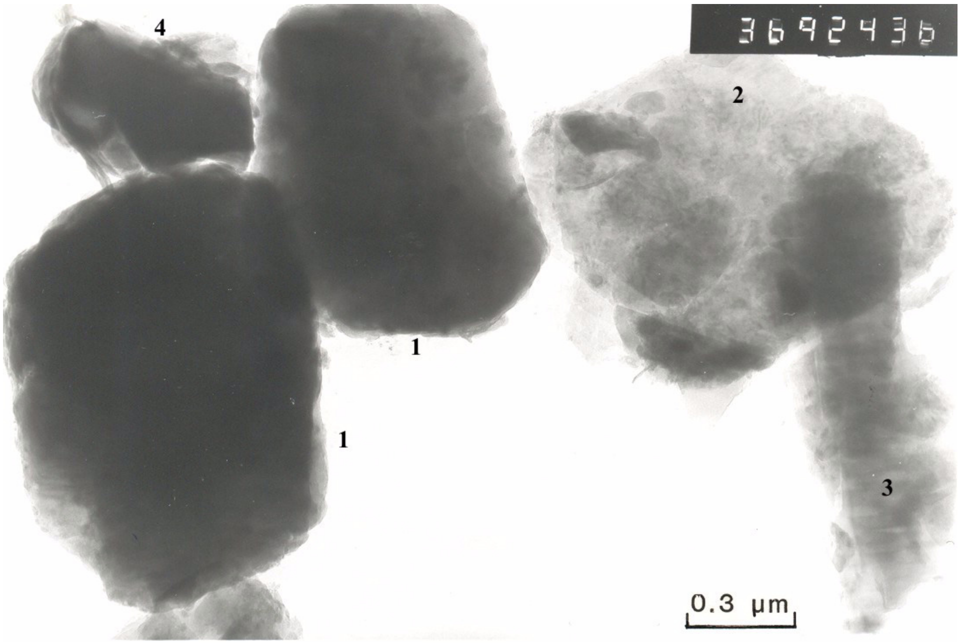

Fig. 23. TEM-photograph of clay fraction: Kaaresuvanto (Pulju moraine), pit number 354, depth 100 cm. On the left side are two dark colored kaolinite (1) crystals (Si, Al). Light colored crystal (2) is illite (Si, Fe, Al, K and Mg). Elongated, light colored crystal (3) on the right below, might be vermiculite (Si, Fe, Ca, Mg and Al). Between kaolinite crystals (4) is small illite crystal (Si K and Al). Identification is based on chemical elements (EDS) that are presented between parentheses.

DTA- graphs of Kaaresuvanto samples show a strong double endothermic peak between 80 EC and 200 EC (Fig. 22). This is due to the existence of vermiculite, which is confirmed also by XRD - graphs (Figs 21a,b,c). The main dehydroxylation peak at 500 EC fits well with illite and kaolinite; the existence of which was confirmed also by XRD - graphs. The exothermic peak at 940 EC is due to recrystallization of new phases. The total weight loss on the basis of TGA varies between 6.6 % and 10.6 % (see Fig. 22 and Table 4) and it is possible to draw a conclusion that weathering processes has not been very strong. In the fine fraction the most dominant minerals are quartz, plagioclase and microcline. Clay minerals are in abundance i.e. chlorite/vermiculite, illite, mixed-layer minerals and possibly kaolinite (Fig. 21d). The influence of weathered bedrock and/or maturity of the tills are possibly causing this. Mineralogy of clay and fine fraction of the tills in Kaaresuvanto (Pulju moraine) does not fully correspond with the Archaean gneiss mineralogical composition. Quite the contrary it corresponds much more with the mineralogy of Greenstone belt area.

The northern part of Inari (Sevetti moraine) (a.k.a Ahvenjärvi, Sevettijärvi, Suojanperä and Pyhävaara) is located in the Archaean basement gneiss complex, but there occurs also mafic volcanite at Sevettijärvi. It is the so-called Opukasjärvi Formation that has been considered to be a continuation of the Petsamo Formation. In the clay fraction of till the most abundant minerals are illite, chlorite and vermiculite (Table 5 and Fig. 24a). After

KCl-treatment and heat treatment main part of the 14 Å peak shift to 10 Å, this is typical for vermiculite. Illite is mainly trioctahedral type (Table 3).

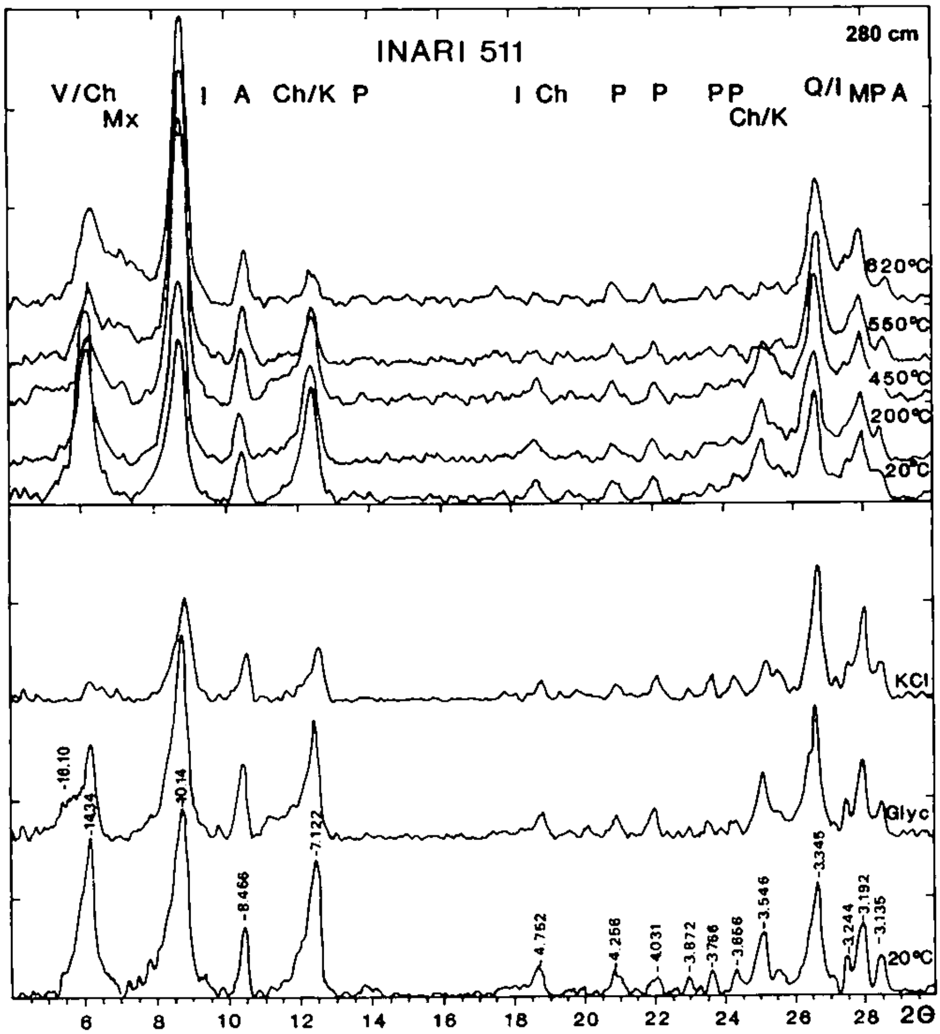

Fig. 24a. X-ray diffraction diagrams of the clay fraction of the till from the Inari area, Sevettijärvi (Sevetti moraine), pit number 511, depth 280 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

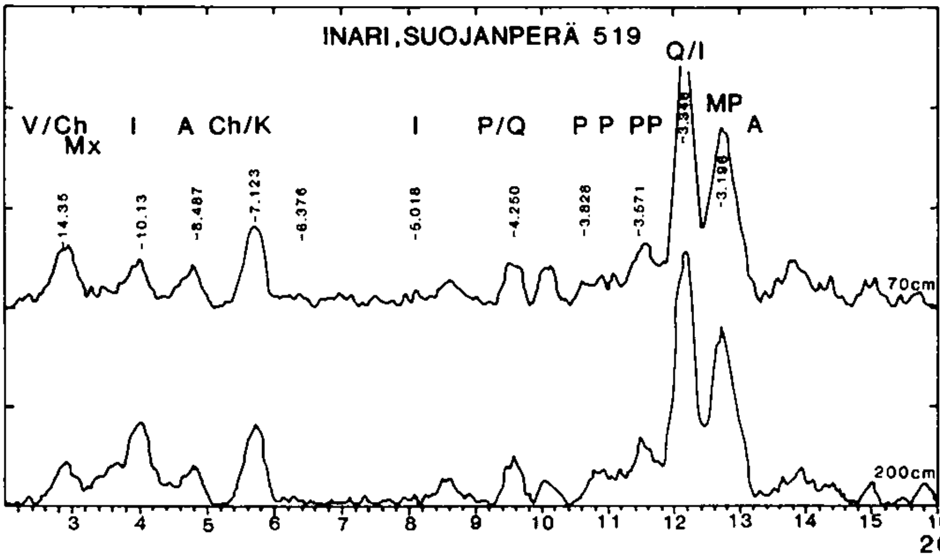

Fig. 24b. X-ray diffraction diagrams of the fine fraction of the till from the Inari area, Suojanperä (Sevetti moraine), pit number 519 (depths 70 cm and 200 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

Both Mg-rich and Fe-rich chlorite are present, but former type is dominant. There are moderate quantities of quartz, amphibole, plagioclase and microcline (Figs 24a and 25). As minor components there are mixed-layer clay minerals and swelling-lattice vermiculite. Latter clay mineral was confirmed with ethylene glycol treatment (Fig. 24a). There is a minor amount of kaolinite present, which was confirmed by TEM/EDS (Fig. 25). Thermal analysis shows (Table 4) that the total weight loss is around 8.7 % (TGA) and most of the crystal lattice and adsorbed water vanish at the lower temperatures e.g., 20-220 EC (DTA). In the fine fraction of till the most dominant minerals are quartz, plagioclase, microcline and chlorite/vermiculite (Figs 24b,c). There are also moderate amounts of amphibole and illite. The mineralogical composition, especially the high content of chlorite, suggests that there would exist more mafic volcanics (sulphide mineralisations) in the bedrock than is presently known (cf., Koljonen *et al.* 1992).

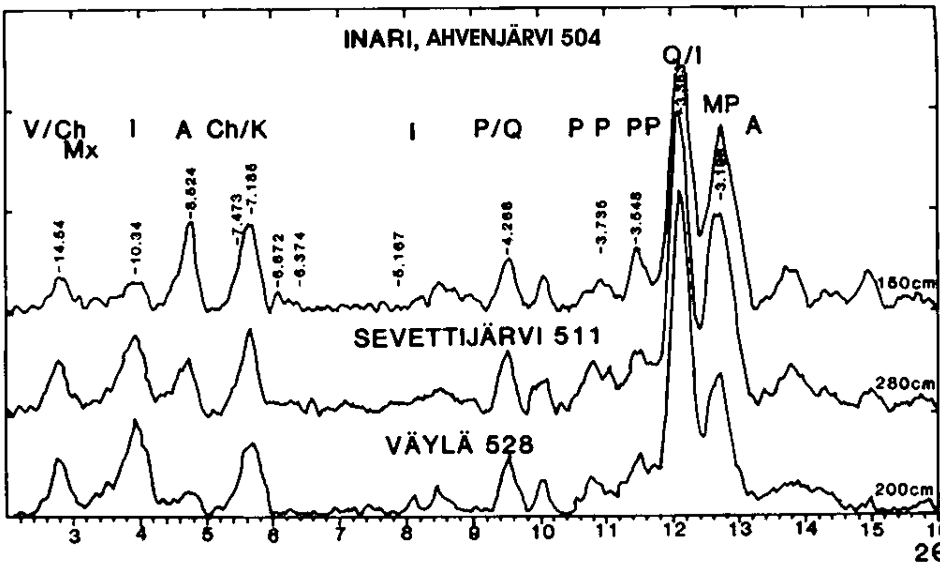

Fig. 24c. X-ray diffraction diagrams of the fine fraction of the till from the Inari area, Ahvenjärvi (Sevetti moraine), pit number 504 (depth 150 cm), Sevettijärvi (Sevetti moraine), pit number 511 (depth 280 cm) and Väylä (Sevetti moraine), pit number 528 (depth 200 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

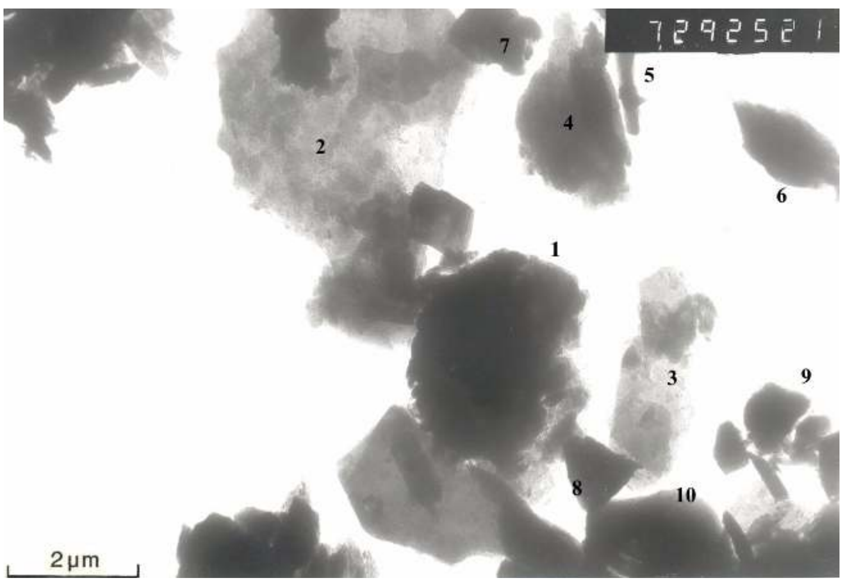

Fig. 25. TEM-photograph of clay fraction: Inari, Ahvenjärvi (Sevetti moraine), pit number 504, depth 150 cm. Illite (1, 2 and 5) crystals (Si, Al, Fe, K, Mg and Ti); vermiculite/chlorite (3) crystal (Si, Al, Fe and Mg); Fe-pigmentated kaolinite (4) crystal (Si, Al and Fe); amphibolite (6,8) crystals (Si, Ca, Mg, Fe andAl); plagioclase (7) crystal (Si, Al, Ca and Na); muscovite (9,10) crystals (Si, Al and K). Identification is based on chemical elements (EDS) that are presented between parentheses.

Geochemistry

Table 7 (Koljonen *et al*. 1992) and Tables 8–9 (present study material) present the median of the chemical elements in the fine fraction of the till in the geochemical provinces and subprovinces of Finland by Koljonen and co-author (1992) and the results of present study. Tables 10-20 present the arithmetic mean, variation and standard deviation of the chemical elements in the clay and fine fraction of the till in each study site.

The fine fraction of tills in Suomussalmi (Kianta moraine) Si has been strongly enriched but in the case of Ca, Na and K there is no remarkable enrichment (Tables 8 and 10). Content of Ti, Al, Fe, Mn and Mg are at a lower level when compared to the contents of other study areas. It is possible to notice that concentrations of Ti, Mg and Mn have the second lowest values of all the study sites and only tills of Kuusamo (drumlin) these concentrations are lower (Tables 8 and 11). There is no significant enrichment with trace element content. In comparison with Archaean gneiss province, the concentrations of elements in the fine fraction are at the same level (Tabels 7 and 8). Only Si is slightly higher (about 5 %) and Na little lower concentrations in the tills of present study material.

Table 7. The median of the chemical elements in the fine fraction of the till in the geochemical provinces and subprovinces of Finland (Koljonen et al. 1992).

Province	A1	A2	A3	A	B1	B2	B	C2	C	D1B	E1
w-%											
SiO2	65,68	55,62	59,69	64,61	57,55	54,78	57,33	65,68	66,96	51,99	60,76
TiO2	0,67	0,83	0,83	0,67	0,83	1,00	0,83	0,67	0,67	0,83	0,83
Al2O3	13,79	14,93	13,98	13,79	14,74	14,93	14,74	13,42	13,60	16,25	14,36
Fe2O3	4,15	7,01	5,29	4,43	6,43	7,72	6,58	4,29	3,72	8,01	5,15
MnO	0,07	0,09	0,08	0,07	0,08	0,10	0,08	0,07	0,07	0,09	0,07
MgO	1,82	2,32	2,32	1,82	2,82	2,82	2,82	1,66	1,35	2,65	1,82
CaO	2,80	3,08	3,50	2,94	3,08	3,36	3,08	2,80	2,52	2,80	2,80
Na2O	3,37	2,70	3,50	3,37	3,24	3,10	3,24	3,37	3,10	2,16	3,50
K2O	2,29	1,57	2,17	2,45	1,81	1,69	1,81	2,65	2,77	1,81	2,53
P2O5	0,14	0,14	0,14	0,14	0,11	0,14	0,11	0,14	0,16	0,16	0,14
n	154	20	18	192	77	13	90	45	204	22	43
Province	A1	A2	A3	A	B1	B2	B	C2	C	D1B	E1
ppm											
Zn	46	74	44	47	55	78	60	47	48	89	40
Pb											
Ni	28	32	29	28	63	60	62	21	15	60	29
Co	15	12	8	14	15	21	16	15	13	17	9
Cu	18	25	15	18	26	39	29	17	18	34	16
n	154	20	18	192	77	13	90	45	204	22	43

A= Archaean gneiss areas, A1= subprovince, A2= subprovince, A3= subprovince; B= Greenstone belts in northern and eastern Finland, B1= subprovince, B2= subprovince; C= Areas of Svecokarelian schists and gneisses; C2= subprovince, D1B= Granulite zone in Lapland, E1= Granitoid area of central Lapland.

Table 8. The median of the chemical elements in the fine fraction of the till in study area. The division of the geochemical provinces and subprovinces of Finland are according to Koljonen and co-author 1992.

province	A1	A1	A1	E1	E1	A3	B1	A2	D1B	B1	B2	C2	
Study area	Ss	Ku	Kn	Kj	As	Ks	Pu	InN	InS	JJ	Kit	Yk	InTot
w-%								504-525	526-538				
SiO2	70,40	70,60	68,40	68,80	66,20	62,60	63,90	61,20	63,50	64,00	62,70	69,60	61,56
TiO2	0,77	0,69	0,88	0,84	0,92	1,10	0,82	0,98	0,88	1,22	1,27	0,81	0,90
Al2O3	13,70	13,20	13,60	13,50	14,15	14,18	14,80	15,70	17,15	13,80	15,19	13,60	15,80
Fe2O3	4,56	4,18	5,58	4,86	5,79	6,91	5,54	8,69	7,74	7,32	7,95	4,20	8,26
MnO	0,07	0,06	0,08	0,07	0,08	0,09	0,08	0,13	0,10	0,11	0,11	0,07	0,12
MgO	1,80	1,60	2,45	1,80	1,90	3,50	3,30	3,30	2,63	3,10	2,90	1,90	3,10
CaO	2,95	3,44	2,96	3,28	3,66	4,79	3,81	4,59	2,99	4,78	3,70	2,94	4,44
Na2O	2,90	3,40	3,60	3,70	3,90	3,80	4,15	3,00	2,39	3,00	3,00	3,62	2,80
K2O	2,39	2,27	2,70	2,69	2,95	1,98	2,50	1,88	2,25	1,92	1,79	2,56	1,95
P2O5	0,13	0,12	0,09	0,15	0,21	0,24	0,00	0,17	0,14	0,19	0,15	0,16	0,16
n	135	45	37	104	24	13	2	70	27	18	219	119	97
province	A1	A1	A1	E1	E1	A3	B1	A2	D1B	B1	B2	C2	
Study area	Ss	Ku	Kn	Kj	As	Ks	Pu	InN	InS	JJ	Kit	Yk	InTot
ppm								504-525	526-538				
Zn	44	36	81	44	46	54	55	101	98	62	90	56	101
Pb	24	23	27	23	22	22	24	29	23	19	25	24	27
Ni	40	40	46	39	32	46	91	62	49	49	72	33	59
Co	25	24	23	18	22	36	34	41	35	34	43	16	41
Cu	25	24	82	23	20	41	31	88	62	43	56	30	79
n	135	45	37	104	24	13	2	70	27	18	219	119	97

Ss= Suomussalmi, Kn= Kuivaniemi, Kj= Kemijärvi, As= Aavasaksa, Ks= Kaaresuvanto, InN= Northerna part of Inari samples 504–505, InS= Southern part of Inari samples 526–538, JJ= Jerisjärvi, Pu= Pulju; Kit= Kittilä, Yk= Ylikiiminki, InTot= Inari total, Ku= Kuusamo; A= Archaean gneiss areas, B= Greenstone belts, C= Areas of Svecokarelian schists; A1= subprovince in northern and eastern and gneisses; A2= subprovince Finland, C2= subprovince; A3= subprovince, B1= subprovince, D1B= Granulite zone in Lapland; B2= subprovince, E1= Granitoid area of central Lapland

Table 9. The median of the chemical elements in the clay fraction of the till in study area. The division of the geochemical provinces and subprovinces of Finland are according to Koljonen and co-author 1992.

province	A1	A1	A1	E1	E1	A3	B1	A2	D1B	B1	B2	C2	
Study area	Ss	Ku	Kn	Kj	As	Ks	Pu	InN	InS	JJ	Kit	Yk	InTot
w-%								504-525	526-538				
SiO2	50,55	55,06	46,99	56,34	50,08	48,20	44,64	47,51		46,86	38,90	49,29	47,51
TiO2	1,02	0,83	1,13	0,95	1,30	1,19	1,31	1,22		1,27	1,73	1,07	1,22
Al2O3	19,91	18,89	18,59	18,57	17,73	17,62	19,26	20,34		22,73	21,24	19,32	20,34
Fe2O3	10,61	8,31	13,51	7,61	12,34	12,79	14,75	13,28		13,47	21,99	11,36	13,28
MnO	0,09	0,10	0,13	0,08	0,14	0,10	0,10	0,13		0,11	0,17	0,10	0,13
MgO	5,10	4,80	6,44	3,52	5,70	7,50	6,23	5,23		4,07	4,21	4,87	5,23
CaO	1,63	2,81	1,65	2,59	2,47	2,36	1,41	2,60		2,08	1,10	1,68	2,60
Na2O	1,77	2,75	1,47	3,16	2,56	1,84	1,19	1,83		1,50	0,54	1,71	1,83
K2O	3,95	3,64	3,83	4,30	3,90	3,21	3,05	2,92		2,19	1,12	3,88	2,92
P2O5	0,16	0,13	0,24	0,15	0,23	0,20	0,24	0,14		0,33	0,46	0,15	0,14
n	17	2	2	3	3	5	1	1		2	11	3	1
province	A1	A1	A1	E1	E1	A3	B1	A2	D1B	B1	B2	C2	
Study area	Ss	Ku	Kn	Kj	As	Ks	Pu	InN	InS	JJ	Kit	Yk	InTot
ppm								504-525	526-538				
Zn	114	102	166	171	146	121	165	300	207	131	187	224	257
Pb	12	23	17	16	19	11	24	34	33	19	11	21	38
Ni	83	92	119	80	67	112	195	124	114	99	127	104	118
Co	27	25	36	34	32	37	37	46	38	40	47	33	39
Cu	109	153	183	130	103	170	144	763	259	219	169	180	378
n	35	5	5	53	14	6	2	26	13	6	34	31	39

Ss= Suomussalmi, Kn= Kuivaniemi, Kj= Kemijärvi, As= Aavasaksa, Ks= Kaaresuvanto, InN= Northerna part of Inari samples 504–505, InS= Southern part of Inari samples 526–538, JJ= Jerisjärvi, Pu= Pulju; Kit= Kittilä, Yk= Ylikiiminki, InTot= Inari total, Ku= Kuusamo; A= Archaean gneiss areas, B= Greenstone belts, C= Areas of Svecokarelian schists; A1= subprovince in northern and eastern and gneisses; A2= subprovince Finland, C2= subprovince; A3= subprovince, B1= subprovince, D1B= Granulite zone in Lapland; B2= subprovince, E1= Granitoid area of central Laplan

The geochemical results of fine fraction of till provide a good correlation when comparing to the geochemical composition of Archaean gneiss (Tabels 7 and 8). The clay fraction of the interlobate hummocky moraines e.g., Kianta-moraines of Suomussalmi have been enriched with Al, Fe, Mg, K, Cu, Ni, Zn and Co. Silicon, Ca, Na and Pb have been depleted in the clay fraction of the tills of Suomussalmi (Table 9 and 10). There are some exceptionally high concentrations of Al (27,2 %) in the fine fraction samples of Papinaho, pit 222 (90 cm) and in the clay fraction of Papinaho, pit 222 (120 cm) Zn (301 ppm). Also in the fine fraction sample of Leppälä, pit 242 (90 cm) is high Zn (744 ppm) concentration and in the clay fraction sample of Leppälä, pit 242 (330 cm) is high Cu (635 ppm) concentration. The former sample is from Fe-Mn-consentration zone and the latter is from a groundwater level zone. The concentration of elements in the clay fraction does not correspond well to the local bedrock geochemistry (Tables 7, 9 and 10).

Table 10. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Suomussalmi study area (Kianta moraine).

Suomussalmi								
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	70,11	73,00	54,70	2,25	50,76	53,07	49,62	1,07
TiO2	0,78	1,08	0,68	0,06	1,02	1,08	0,97	0,03
Al2O3	13,86	27,20	12,40	1,53	19,79	20,61	18,61	0,72
Fe2O3	4,64	8,74	3,64	0,70	10,54	11,87	9,29	0,78
MnO	0,07	0,49	0,05	0,04	0,09	0,12	0,08	0,01
MgO	1,88	2,90	0,90	0,38	5,21	5,84	4,68	0,36
CaO	3,00	3,59	2,34	0,24	1,60	1,81	1,26	0,14
Na2O	3,03	5,40	1,50	0,60	1,80	2,12	1,38	0,19
K2O	2,37	2,87	1,42	0,20	3,88	4,11	3,27	0,24
P2O5	0,11	0,48	0,00	0,06	0,16	0,20	0,11	0,02
n	135				17			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	51	744	17	60,8	126	301	87	39,6
Pb	24	39	18	2,9	12	24	5	4,0
Ni	41	63	29	6,4	85	107	68	10,0
Co	25	73	14	5,9	30	53	24	6,8
Cu	27	66	9	10,9	134	635	57	102,5
n	135				35			

In the fine fraction of tills in Kuusamo (drumlin) Si has been strongly and Ca slightly enriched but in the case of Ti, Fe, Na and trace elements there is no remarkable enrichment. Concentrations of Ti, Al, Fe, Mn and Mg are at lower level when compared to the other study areas (Tabels 7, 8 and 11). It is obvious that concentrations of Ti, Mg and Mn have the lowest values of all the study sites and only in the tills of Suomussalmi (Kianta moraine) these concentrations are almost at the same level. There is no significant enrichment with trace element content. In comparison with Archaean gneiss province, the concentrations of elements in the fine fraction are at the same level with the present study material (Tables 7 and 8). Only Si (5 %) and Ca are slightly higher and Al has lower concentrations in the tills of the present study material. Geochemical results of fine fraction of till provide a good correlation when comparing to the geochemical distribution of Archaean gneisses (Tables 7 and 8). Aluminium, Fe, Mg, K, Ti, Mn and trace elements have been enriched in the clay fraction of the till samples of the Kuusamo drumlin area. The clay fraction of till is degraded by Si, Na and Ca. Silicon has especially low concentrations in the clay fraction of till. Zink has the lowest concentration compared to the concentrations of other study areas (Table 9). In the clay fraction Zn and Co have two times higher and Ni tree times higher and Cu seven times higher concentration values than with the Archaean gneiss province. The concentration of elements in the clay fraction does not correspond well to the local bedrock geochemistry (Tables 7, 9 and 11).

Table 11. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Kuusamo study area (drumlin).

	Kuusamo							
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	70,68	73,00	68,30	1,05	55,06	55,91	54,21	1,20
TiO2	0,68	0,87	0,07	0,14	0,83	0,85	0,81	0,03
Al2O3	13,24	14,30	12,00	0,44	18,89	19,56	18,22	0,95
Fe2O3	4,25	5,36	3,86	0,31	8,31	8,38	8,25	0,09
MnO	0,06	0,07	0,05	0,01	0,10	0,10	0,09	0,01
MgO	1,62	2,10	0,90	0,26	4,80	4,81	4,78	0,02
CaO	3,41	3,79	2,85	0,20	2,81	2,89	2,73	0,11
Na2O	3,38	4,90	2,40	0,51	2,75	2,83	2,68	0,11
K2O	2,27	2,63	2,06	0,13	3,64	3,66	3,62	0,03
P2O5	0,08	0,15	0,00	0,06	0,13	0,13	0,13	0,00
n	45				2			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	36	52	29	5,37	108	147	95	21,97
Pb	23	32	18	2,48	25	32	20	4,67
Ni	39	53	22	8,53	92	108	79	10,84
Co	24	33	13	3,55	27	34	22	4,67
Cu	31	80	16	19,51	158	200	133	25,09
n	45				5			

The fine fraction of tills in Kuivaniemi (cover moraine) Si and Na have been enriched strongly and also the content of Mg is rather high. High contents of Fe and Mg are due to Fe-and Mn-oxide concentrations existing in these tills. Ti, Al, Mn and P are depleted when compared to the other study areas (Tables 7 and 8). Zink and Cu have been slightly enriched in the fine fraction of till which is connected with the Fe- and Mn oxides. The consistency of elements is parallel with the Archaean gneiss province (Tables 7, 8 and 12). The clay fraction of the cover moraines of Kuivaniemi has been enriched with Fe, Al, Mg, K, Ti, Mn, P, Cu, Ni and Zn. Particularly Zn, Ni and Cu have high concentrations in the clay fraction of till. Silicon, Na, Ca, Pb and Co have been depleted in the clay fraction of the till (Table 9 and 12). There are some exceptionally high concentrations of Al (29,5 %), Fe (18,0 %) and Si (43,6 %) in the fine fraction sample of Käärmeaapa, pit 184 (50 cm). The sample is from leaching zone of podzol. The distribution of chemical element does not correlate with the one of local bedrock (Tables 7, 9 and 12).

Table 12. The arithmetic mean, variation and standard deviation of the chemical elements in he fine and clay fractions in the Kuivaniemi study area (cover moraine).

Kuivaniemi								
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	67,67	69,90	43,60	4,23	46,99	47,47	46,51	0,68
TiO2	0,89	1,03	0,83	0,04	1,13	1,17	1,09	0,06
Al2O3	14,19	29,50	13,00	2,70	18,59	19,01	18,17	0,60
Fe2O3	5,94	18,00	4,90	2,11	13,51	13,63	13,38	0,18
MnO	0,08	0,15	0,06	0,02	0,13	0,14	0,13	0,01
MgO	2,54	3,40	1,60	0,49	6,44	6,59	6,30	0,21
CaO	2,88	3,31	1,72	0,27	1,65	1,66	1,65	0,01
Na2O	3,57	4,45	2,50	0,47	1,47	1,58	1,35	0,16
K2O	2,63	2,87	1,26	0,27	3,83	3,95	3,72	0,16
P2O5	0,13	0,62	0,04	0,10	0,24	0,24	0,24	0,01
n	37				2			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	80	106	56	13,4	169	188	160	11,2
Pb	33	98	21	13,7	18	27	14	5,2
Ni	47	60	34	7,2	114	129	94	14,3
Co	25	113	16	15,4	38	45	35	4,2
Cu	76	117	31	26,5	172	196	143	21,7
n	37				5			

The fine fraction of tills in Kaaresuvanto (Pulju moraine) Si and K have been depleted and Ti, Al, Fe, Mg, Ca, Na and P have been enriched when compared to the other study sites (Tables 7 and 8). Magnesium, Ca and P have the highest concentrations off all the study areas (Tables 7, 8 and 13). In comparison with other study sites an abundance of trace elements are at an average level but concentrations of Zn, Ni, Co and Cu are remarkably higher than with the Archaean gneiss province. The consistency of elements in the fine fraction of the till in Kaaresuvanto (Pulju moraine) does not correspond quite well with the Archaean gneiss distribution of elements (Tables 7, 8 and 13). Quite the contrary the distribution of elements corresponds much more with the distribution of the Greenstone belt (Kittilä, Jerisjärvi). The distribution of chemical elements points out quite clearly the effect of the Greenstone belt of Kiiruna, Sweden and local micagneiss (Ambros 1980). The last ice movements have occurred from S-N and WSS-ENN directions and this may explain these results. In the clay fraction of Pulju moraine samples of Kaaresuvanto have been enriched with Fe, Mg, Al, K, Ti, Cu, Zn, Ni and Co (Tables 9 and 13). Aluminium and Pb have the lowest concentrations in the clay fraction off all the study areas and the highest Mg concentration. Silicon, Ca, Na, P and Pb have been depleted in the clay fraction of the till. There is a high content of Zn (245 ppm) in the fine fraction sample of Kaaresuvanto, pit 363 (190 cm). As earlier mentioned, the distribution of chemical element in the clay fraction of the till does not correlate that of the local bedrock (Tables 7, 9 and 13).

Table 13. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Kaaresuvanto study area (Pulju moraine).

Kaaresuvanto								
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	62,63	64,00	60,40	1,01	47,48	48,84	44,64	1,67
TiO2	1,06	1,16	0,99	0,06	1,20	1,31	1,14	0,06
Al2O3	14,85	15,80	14,10	0,47	17,91	19,26	17,19	0,81
Fe2O3	6,88	7,57	6,14	0,47	13,18	14,75	12,63	0,89
MnO	0,09	0,10	0,08	0,01	0,10	0,11	0,10	0,00
MgO	3,44	3,80	3,00	0,31	7,27	7,96	6,23	0,65
CaO	4,75	5,08	4,44	0,20	2,27	2,67	1,41	0,50
Na2O	4,02	5,30	3,20	0,58	1,71	1,92	1,19	0,30
K2O	1,95	2,09	1,75	0,11	3,17	3,29	3,05	0,10
P2O5	0,22	0,27	0,15	0,05	0,21	0,24	0,19	0,02
n	13				5			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	66	245	38	54,6	118	137	92	15,6
Pb	22	26	17	3,1	11	12	10	0,8
Ni	49	69	30	12,9	105	124	83	16,0
Co	35	47	22	7,0	36	37	34	1,5
Cu	49	112	13	35,9	151	182	90	39,5
n	13				6			

In the fine fraction of Northern Inari (a.k.a Ahvenjärvi, Sevettijärvi, Suojanperä and Pyhävaara) (Sevetti moraine) Si and K have been depleted and Si achieves the lowest concentration off all the study areas (Tables 7 and 8). In comparison with other study sites Fe and Mn have been strongly enriched and both have the highest concentrations off all the study sites (Tables 7, 8 and 14). Also Al, Ti, Mg, Ca and P have been enriched in the fine fraction of till but Na concentrations are fairly low. All trace elements have high concentrations and particularly Zn, Ni and Cu are very anomalous. All chemical elements are present in lower concentrations than in general in the Archaean gneiss province. The distribution of chemical elements corresponds to the chemical distribution of Greenstone belt areas (a.k.a Kittilä and Jerisjärvi). This provides an indication that there is more mafic volcanite/greenstones and sulphide mineralizations occurring in the same area than is known at the present time (cf., Koljonen *et al*. 1992). Iron, Al, Mg, K, Ti, Mn, Cu, Zn, Ni,

Table 14. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Inari study area (Sevetti moraine).

			Inari					
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation				
SiO2	61,77	66,80	51,75	2,46	47,51			
TiO2	1,00	1,59	0,09	0,25	1,22			
Al2O3	15,87	19,80	13,70	1,17	20,34			
Fe2O3	8,19	11,55	5,57	1,36	13,28			
MnO	0,12	0,18	0,01	0,03	0,13			
MgO	3,15	4,60	1,70	0,64	5,23			
CaO	4,50	6,69	2,16	1,23	2,60			
Na2O	2,85	4,70	1,40	0,55	1,83			
K2O	1,99	2,90	1,09	0,31	2,92			
P2O5	0,16	0,37	0,03	0,07	0,14			
n	97				1			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	113	453	61	54,9	347	1838	173	309,6
Pb	34	188	12	31,0	86	996	15	169,8
Ni	60	105	31	13,1	131	264	84	42,2
Co	40	51	27	5,3	46	84	26	14,4
Cu	86	310	20	44,1	642	1589	174	377,6
n	97				39			

Pb and Co have been enriched in the clay fraction of the till samples of Inari Sevetti moraine area (Table 14). Especially Zn and Cu have been strongly enriched in the clay fraction. The clay fraction of till is degraded by Si, Na, Ca and P. The effect of weathering crust in the clay and fine fraction samples of Inari area are clearly observed. There are very high concentrations in the fine fraction samples of Seurujärvi, pit 523 (250 cm) Zn (453 ppm), Pb (188 ppm); Suojanperä, pit 517 (80 cm) Cu 310 ppm). It is possible to observe high contents in the clay fraction of Seurujärvi, pit 523 (250 cm) Zn (1838 ppm), Pb (996 ppm) and Ahvenjärvi, pit 504 (150 cm) Cu (1589 ppm) and Ahvenjärvi, pit 510 (160 cm) Ni (264 ppm). The distribution of chemical element does not correlate that of the local bedrock (Tables 7, 9 and 14).

5.2.2 Areas of Svecokarelian schists and gneisses

The study area of Ylikiiminki (longitudinal moraine ridge, end moraine and marginal moraine) is situated in the geochemical province of Svecokarelian schists and gneiss as defined by Koljonen and co-author (1992).

Mineralogy

In the clay fraction of tills of Ylikiiminki (longitudinal moraine ridge, end moraine and marginal moraine) the rock-forming minerals are quartz, plagioclase, amphibole and microcline (Table 5 and Figs 26a,b, c).

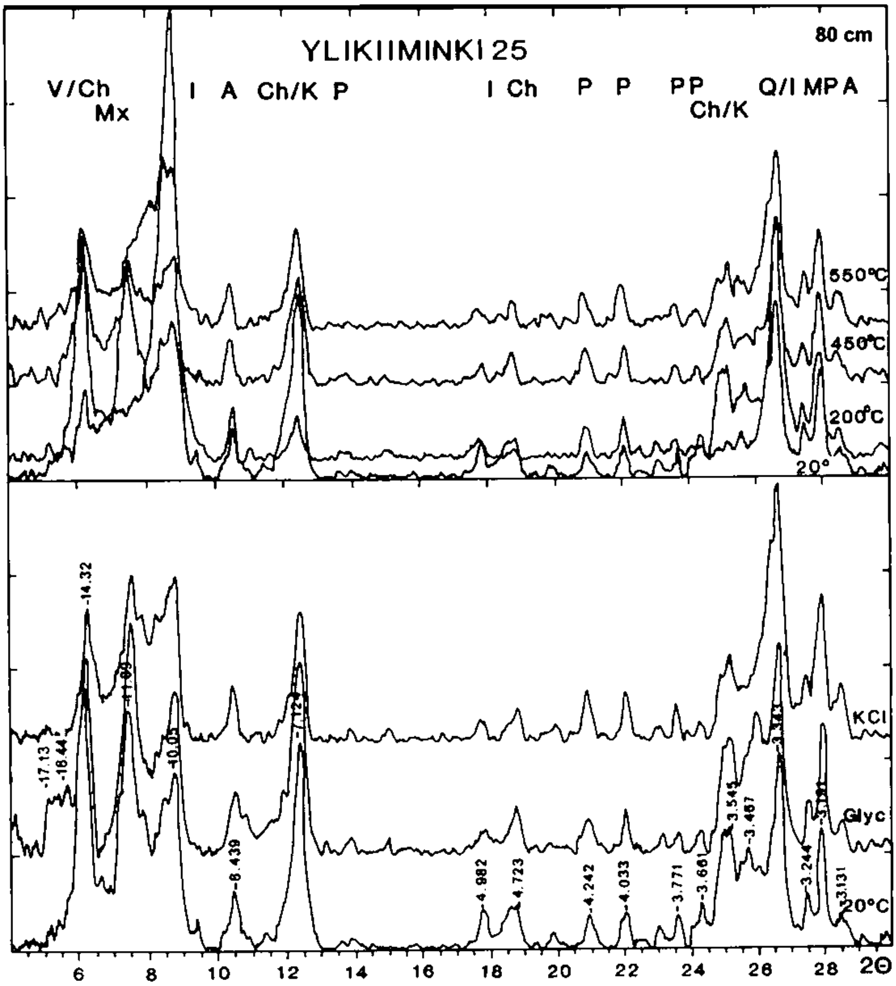

Fig. 26a. X-ray diffraction diagrams of the clay fraction of the till from the Ylikiiminki area, Torviselkä (end moraine), pit number 25, depth 80 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

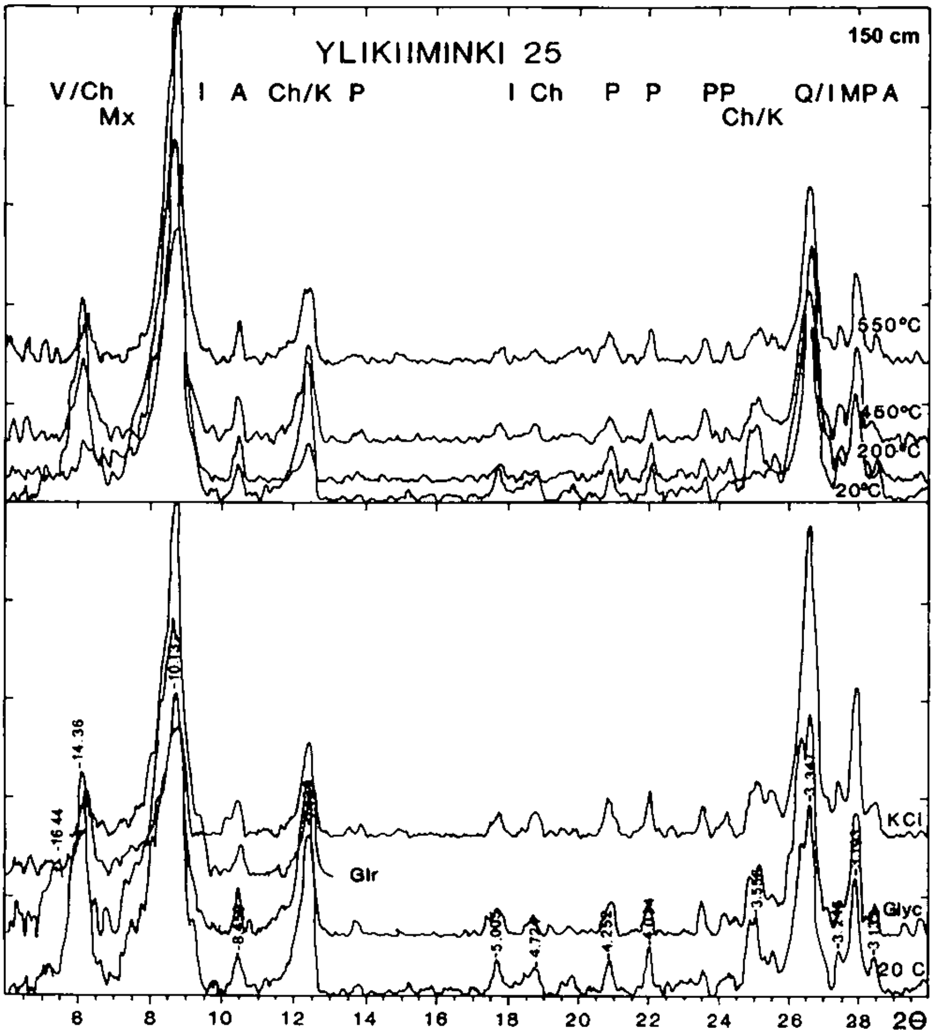

Fig. 26b. X-ray diffraction diagrams of the clay fraction of the till from the Ylikiiminki area, Torviselkä (end moraine), pit number 25, depth 150 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation, Glyc= ethylene glycol treatment and Glr= glycerol treatment.

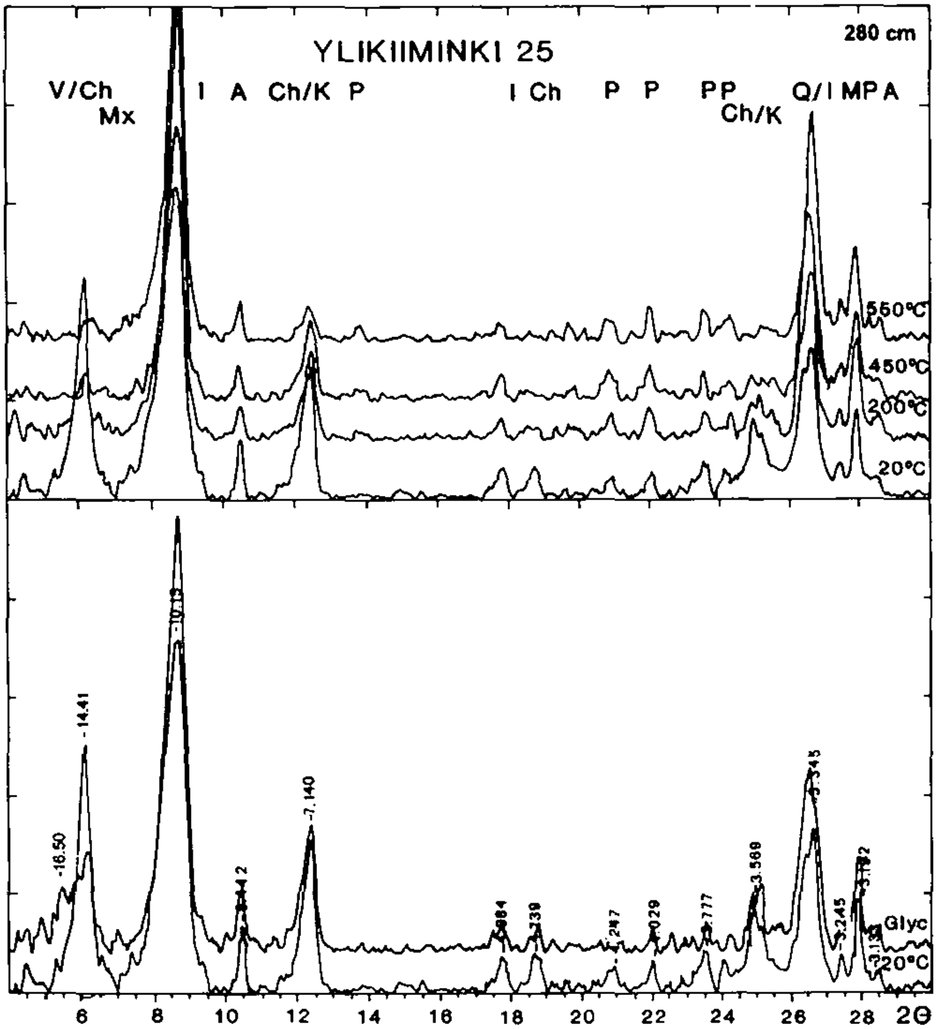

Fig. 26c. X-ray diffraction diagrams of the clay fraction of the till from the Ylikiiminki area, Torviselkä (end moraine), pit number 25, depth 280 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz and Glyc= ethylene glycol treatment.

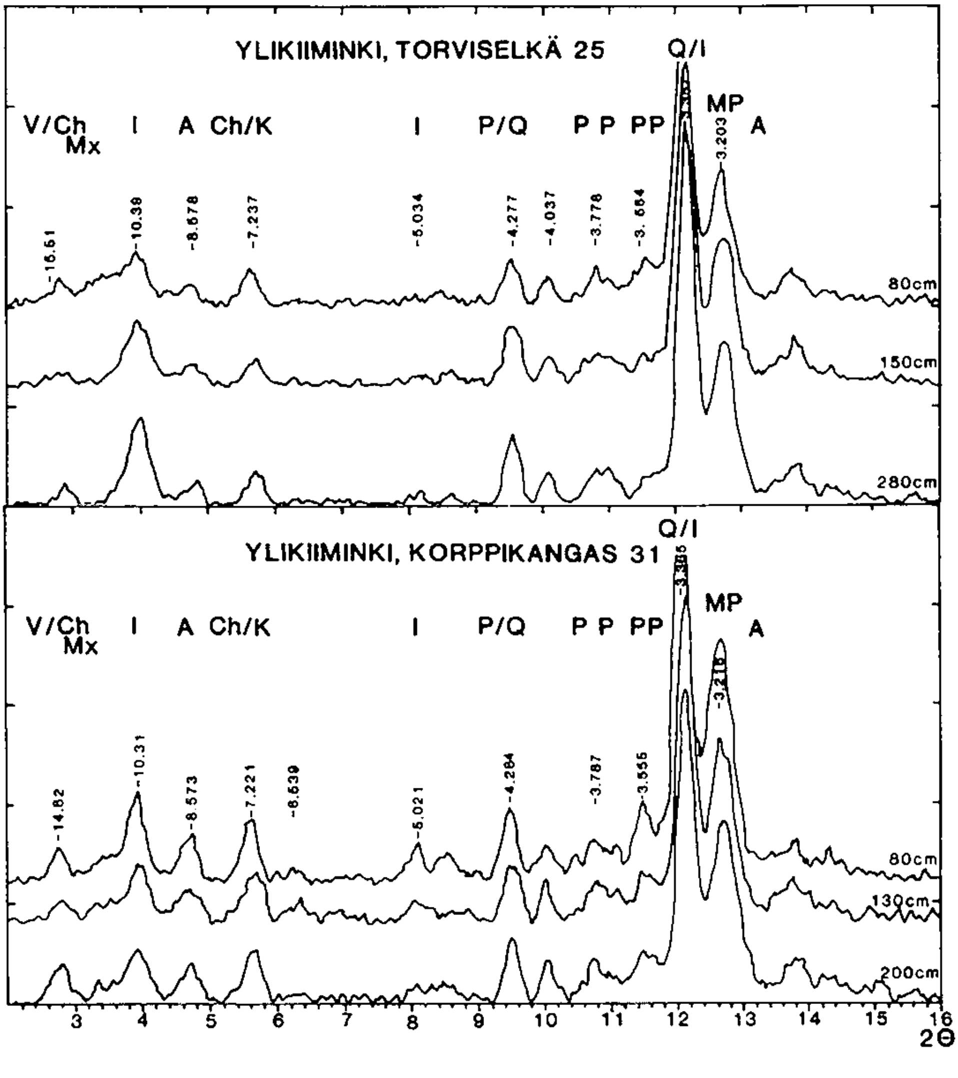

Fig. 26d. X-ray diffraction diagrams of the fine fraction of the till from the Ylikiiminki area, Torviselkä (end moraine), pit number 25 (depths 80 cm, 150 cm and 280 cm) and Korppikangas (end moraine), pit number 31 (depths 80 cm, 130 cm and 200 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

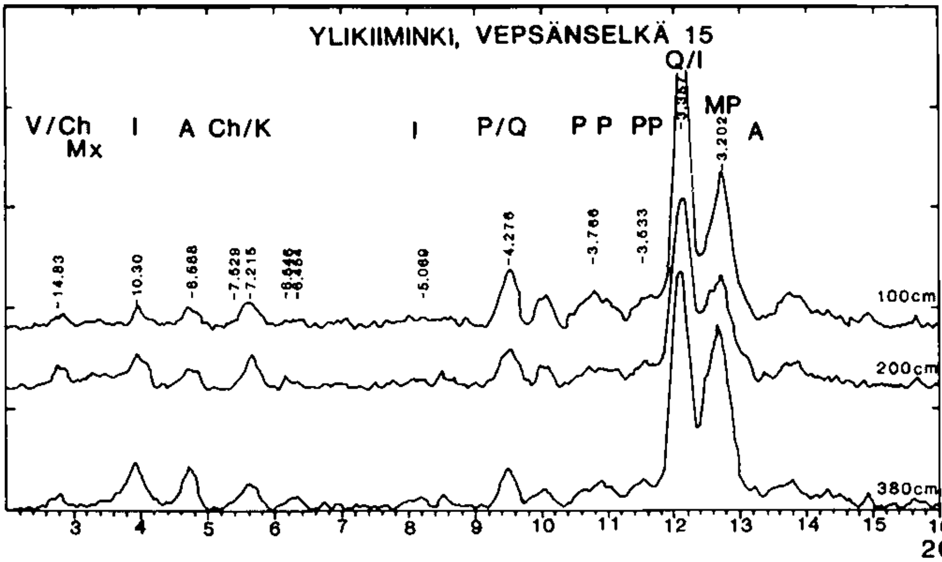

Fig. 26e. X-ray diffraction diagrams of the fine fraction of the till from the Ylikiiminki area, Vepsänselkä (longitudinal moraine ridge), pit number 15 (depths 100 cm, 200 cm and 380 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

Amphibole and microcline are minor components. Most abundant minerals are illite, vermiculite and chlorite. Both illite types are present, but trioctahedral is more common (Table 3). Dioctahedral illite is more abundant in the tillsamples of Korppikangas (end moraine), Vepsänselkä (longitudinal moraine ridge) and Puutturi (longitudinal moraine ridge). There is Mg- and Fe-rich chlorite in almost equal amounts. There are also moderate quantities of mixed-layer clay minerals in the surface samples (Fig. 26a). After ethylene glycol treatment part of the 14 Å peak shifts to 16 Å and it confirms the presence of swelling-lattice vermiculite as a minor component (Figs 26a,b, c). Glycerol treatment did not affect to the 14 Å peak and it points out that smectite is not present in these samples (Fig. 26b). In the basis of thermal analyses one can observe that samples of Ylikiiminki are strongly dehydrated between 120 EC and 190 EC in the study site of Ylikiiminki (Fig. 27). This is typical of vermiculite and mixed-layer minerals. Because XRD-graphs are pointing out that the amount of mixed-layer minerals is not great in the deeper samples, these reactions are due to vermiculite and swelling-lattice vermiculite (Figs 26a,b and c).

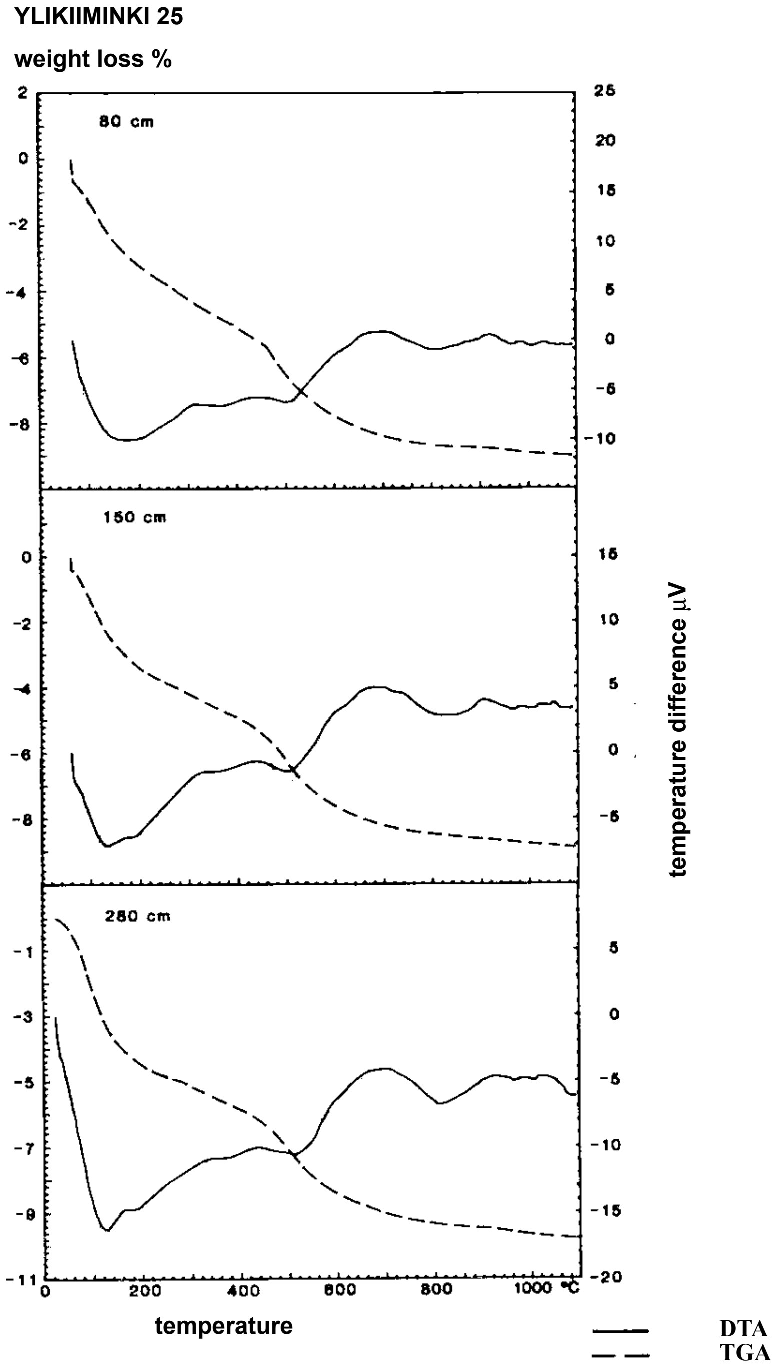

Fig. 27. Differential Thermal (DTA) and Thermogravimetric (TGA) graphs of the clay fraction of the till from the Ylikiiminki area, Torviselkä (end moraine), pit number 25 (depths 80 cm, 150 cm and 280 cm).

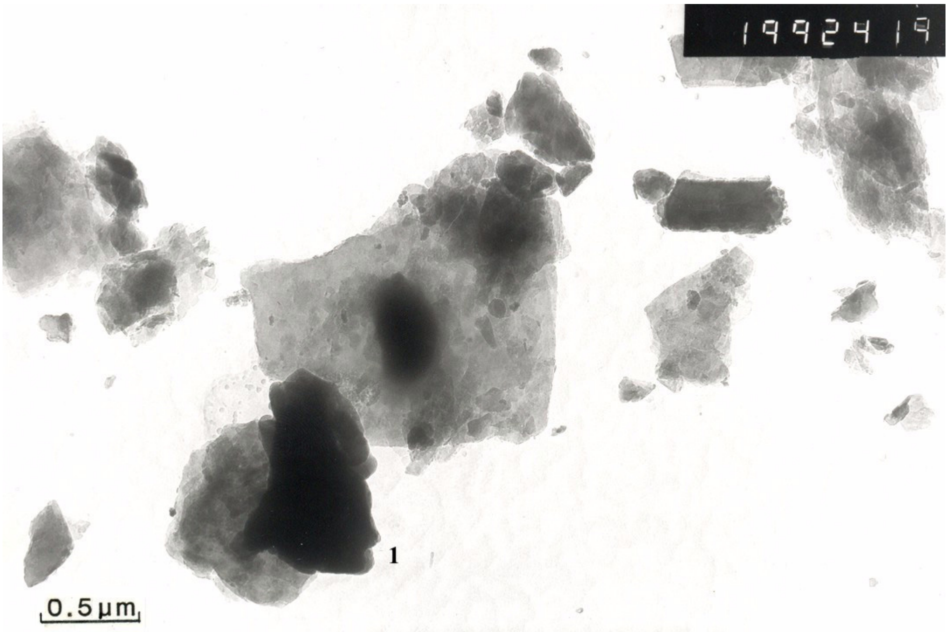

Fig. 28. TEM-photograph of clay fraction: Ylikiiminki, Torviselkä (end moraine), pit number 25, depth 280 cm. Light colored crystals are illite (Si, Al Fe, K and Mg) and dark colored crystal (1) is kaolinite (Si, Al and Fe) Identification is based on chemical elements (EDS) that are presented between parentheses.

The dehydroxylation peak at 500 EC is due to illite and chlorite, because on the basis of XRD, there is no kaolinite in the samples of Ylikiiminki. But very small amounts of kaolinite were detected, which was identified by TEM/EDS (Fig. 28). The faint endo- and exothermic reactions between 700 EC and 1000 EC are also due to illite, chlorite and vermiculite. The total loss of weight varies from 8.8 % to 9.8 % (see Fig. 27 and Table 4). Low weight loss values are due to generally low clay fraction content. In the fine fraction the most abundant minerals are quartz, palgioclase, microcline and amphibole (Figs 26d and e). There are small amounts of chlorite, illite and vermiculite, but they exist only as minor components. In the samples of Korppikangas (end moraine) there is a moderate amount of illite (Fig. 26d), but in the samples of Vepsänselkä (longitudinal moraine ridge) secondary minerals are minor components (Fig. 26e). Both fractions provide a good correlation with that of the local bedrock material, especially the fine fraction of the till. A low amphibole content in the clay fraction is due to the weathering of these minerals into clay minerals.

Geochemistry

The fine fraction of tills of the Ylikiiminki area (longitudinal moraine ridge, end moraine and marginal moraine) is quite high in Si as compared to other areas. In contrast to this the Fe content is quite low. Magnesium, Al and Ca contents are at intermediate level.

Table 15. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Ylikiiminki study area (longitudinal moraine ridge, end moraine and marginal moraine).

	Ylikiiminki							
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	68,79	73,90	45,10	3,90	49,12	49,76	48,32	0,73
TiO2	0,81	0,97	0,36	0,01	1,08	1,12	1,06	0,03
Al2O3	14,09	21,90	11,80	1,89	19,35	19,74	19,01	0,37
Fe2O3	4,77	12,31	2,84	1,81	11,48	11,99	11,08	0,47
MnO	0,08	0,55	0,05	0,05	0,10	0,10	0,10	0,00
MgO	1,99	10,40	0,70	1,00	4,94	5,15	4,79	0,19
CaO	2,98	11,30	1,50	0,95	1,58	1,68	1,38	0,17
Na2O	3,61	5,65	0,80	0,72	1,64	1,83	1,38	0,24
K2O	2,52	3,50	1,40	0,30	3,93	4,16	3,74	0,21
P2O5	0,25	5,98	0,03	0,61	0,16	0,19	0,14	0,03
n	119				3			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	63	274	22	34,8	225	599	126	82,4
Pb	25	62	0	10,4	23	63	11	10,0
Ni	35	98	13	10,9	105	151	66	18,5
Co	18	94	5	9,7	33	57	22	6,6
Cu	36	238	2	30,3	181	307	65	44,4
n	119				31			

The general distribution of elements in the fine fraction correlates the best with the geochemical province of Svecokarelian schists and gneiss off all the study material (Tables 7,8 and 15). There are some high concentrations in the fine fraction samples of end moraine of Kiviharju (longitudinal moraine ridge), pit 50 (30 cm) Al (21,9 %); Kiviharju (marginal moraine), pit 51 (80 cm) Zn (274 ppm); Vepsänselkä (longitudinal moraine ridge), pit 17 (40 cm) Fe (12.31 %); Puutturi 102 (80 cm) (longitudinal moraine ridge) P (5,98 %) and Puutturi, pit 102 (170 cm) Cu (238 ppm). These samples are from the leaching zone of podzol, except the till of Puutturi, which is rinsed out by water. In the clay fraction of tills of Ylikiiminki Fe, Al, Mg, K, Ti, Mn, Cu, Zn, Ni and Co have been enriched (Table 15). Silicon, Na, Ca, P and Pb have been depleted in the clay fraction of the till. In the clay fraction of end moraine of Korppikangas (end moraine), pit 31 (80 cm) there are high values of Zn (599 ppm), Cu (307 ppm) and Ni (151 ppm). This sample represent leaching zone of podzol. The distribution of chemical element in the clay fraction does not correlate with that of the local bedrock (7, 9 and 15).

5.2.3 Granitoid area of central Lapland

The study sites of Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) and Aavasaksa (ground moraine) are located in the geochemical province of Granitoid area of Central Lapland as defined by Koljonen and co-author (1992).

Mineralogy

Along with the Kuusamo site (drumlin), rock-forming minerals are the most abundant minerals in the clay fraction of tills of Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines). Plagioclase, quartz and amphibole are exceptionally high content and microcline is present as minor component (Table 5 and Fig. 29a). Illite, chlorite and vermiculite are the most common clay minerals. Illite is usually trioctahedral type (Table 3). Dioctahedral illite is more abundant in the tillsamples of Peltojärvi (Rogen moraine) and Kuusivaara (Rogen moraine). According to Soveri and Hyyppä (1966) the tills in the granitic bedrock areas contain less illite than the tills in the areas of other bedrock type. The predominance of illite in the Kemijärvi granite area is contradictory to this observation. Mg-rich chlorite type is more common than Fe-rich chlorite (Fig. 29a). Mixed-layer clay minerals, swelling-lattice vermiculite and kaolinite exist in small amounts. Swelling-lattice vermiculite was detected by ethylene glycol treatment and vermiculite by KCl- and heat treatment (Fig. 29a). Kaolinite was identified by TEM/EDS. The samples of Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) are strongly dehydrated < 260 EC (Fig. 30). This is due to dehydration of illite, vermiculite and swelling-lattice vermiculite. Typical dehydroxylation reaction for chlorite and illite occur when samples are heated to 500 EC. In DTA- analyses quartz has an endothermic reaction at 574 EC when α-quartz change into β-quartz. In the range between 800 EC and 1100 EC there occurs clear exothermic reactions, which are due to change of illite, chlorite, vermiculite and swelling-lattice vermiculite to olivine, mullite and enstatite and/or quartz. The total weight loss varies from 4.9 % to 8.5 %, which is one of the lowest of all samples in this study (see Fig. 30 and Table 4). It is due to a high content of rock-forming minerals. Also the most common clay mineral, illite, contains less water than other clay minerals. Thermogravimetric analyses show that in the tills of the Granitoid area the total weight loss is low when comparing to the tills of other bedrock areas (Table 4). This is due to a low quantity of clay minerals and a higher content of primary minerals. Also the weathering rate of these tills is low (not very mature tills). In the fine fraction the most abundant minerals are quartz, palgioclase and microcline (Figs 29b,c and d). There are small amounts of amphibole, illite, chlorite, mixed-layer clay minerals and vermiculite. In the sample of Peltojärvi (Rogen moraine) there are moderate amounts of illite and chlorite (Fig. 29b). Both fractions correlate quite well with the mineral composition of the granitoids.

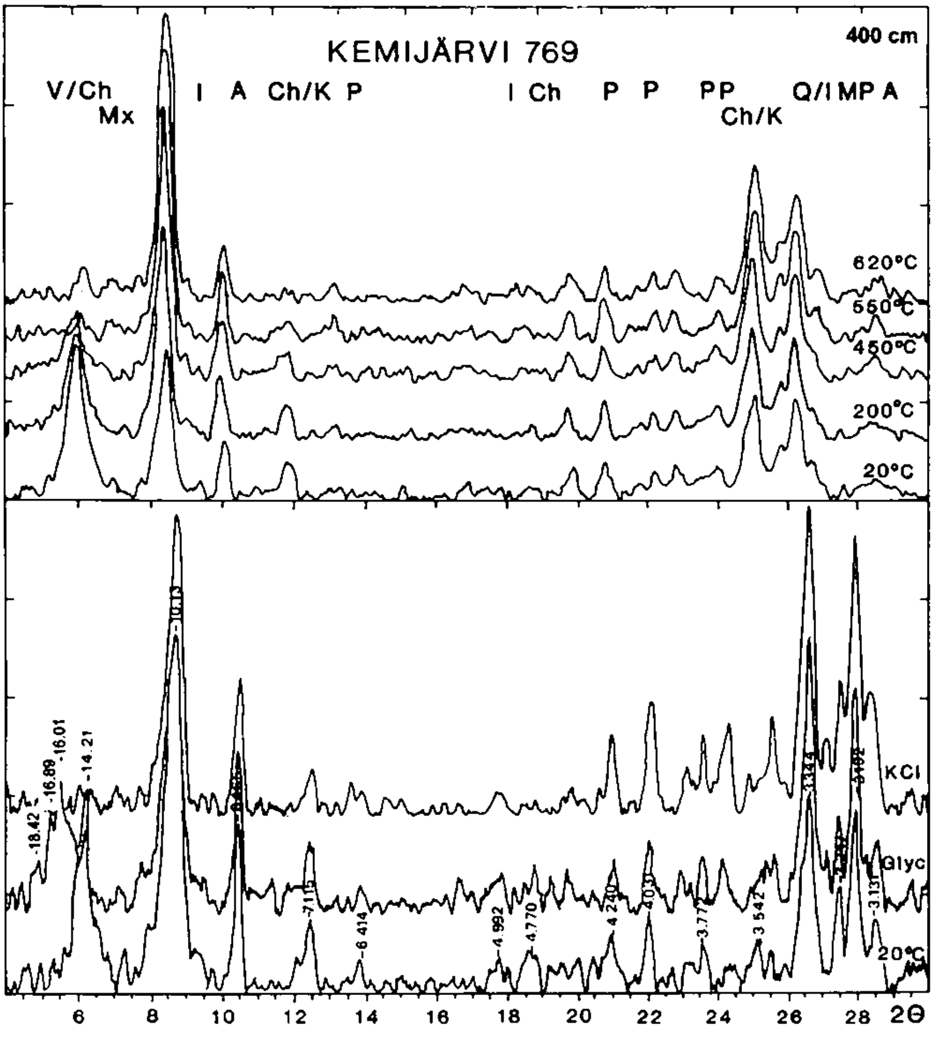

Fig. 29a. X-ray diffraction diagrams of the clay fraction of the till from the Kemijärvi area, Luusua (hummocky moraine), pit number 769, depth 400 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

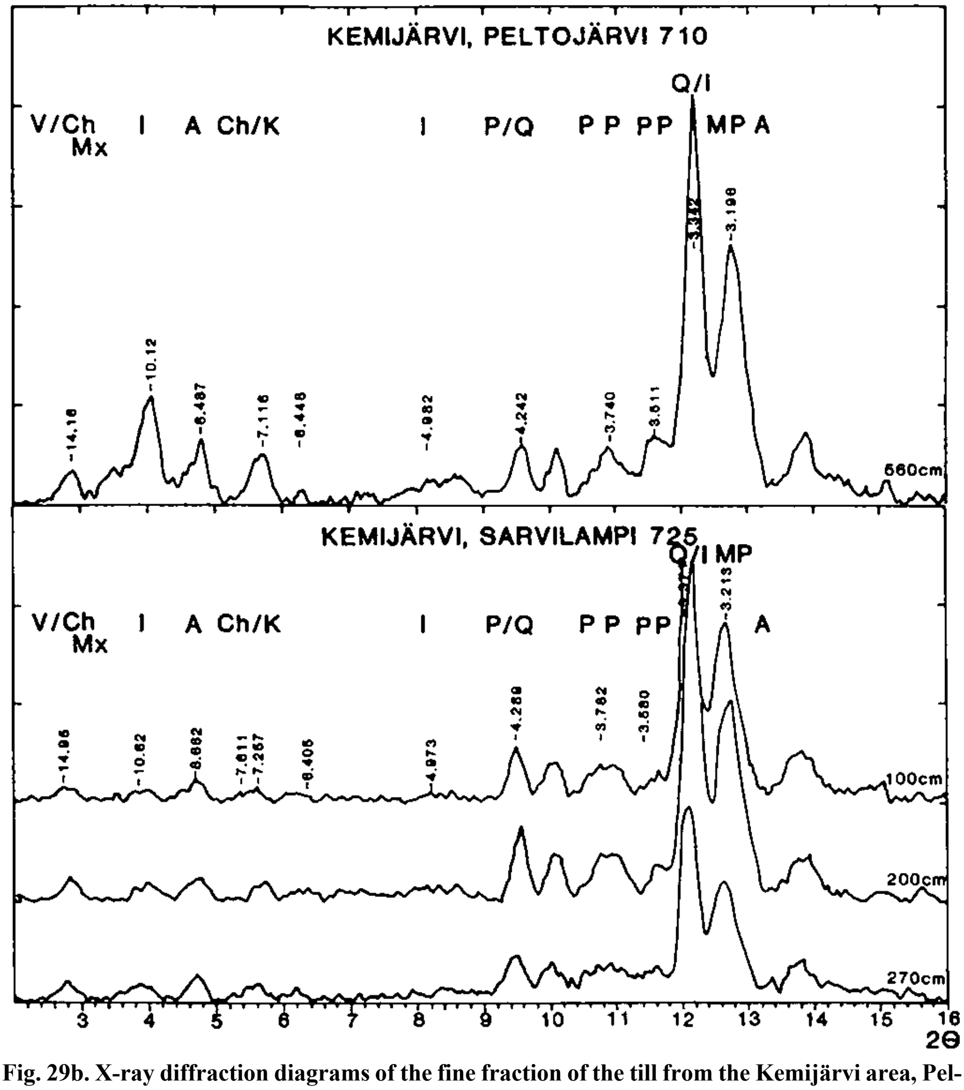

Fig. 29b. X-ray diffraction diagrams of the fine fraction of the till from the Kemijärvi area, Peltojärvi (Rogen moraine) pit number 710, depth 560 cm and Sarvilampi (ablation hummocky moraine) pit number 725 (depths 100 cm, 200 cm and 270 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

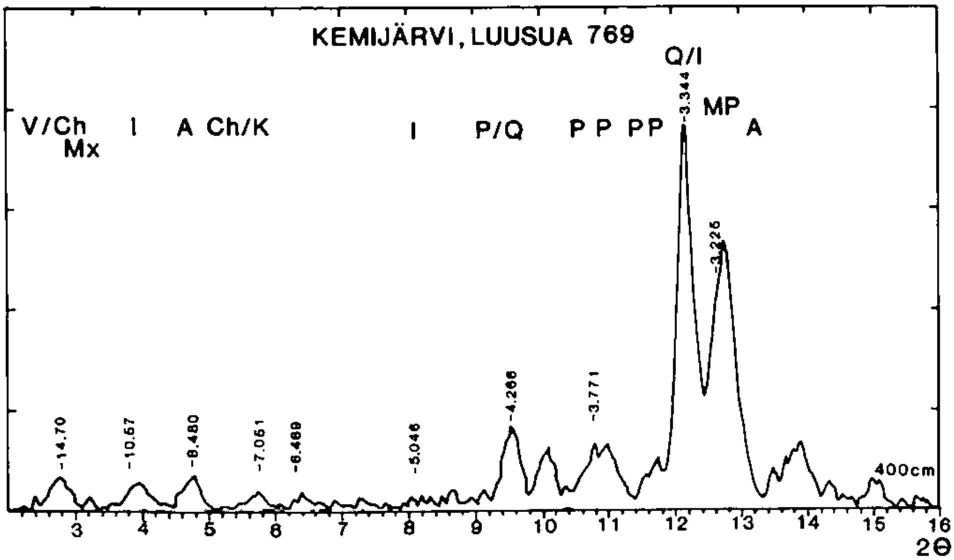

Fig. 29c. X-ray diffraction diagrams of the fine fraction of the till from the Kemijärvi area, Luusua (hummocky moraine), pit number 769, depth 400 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

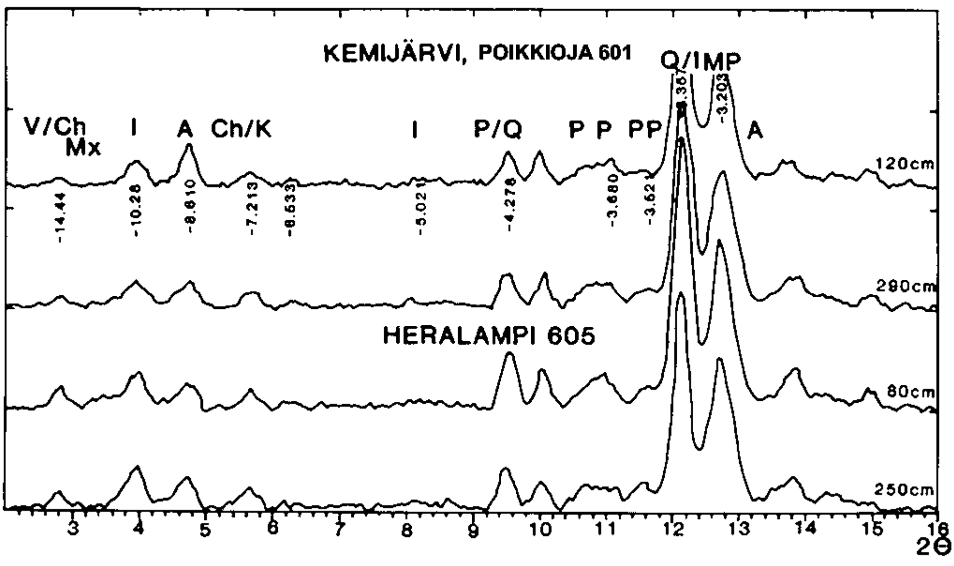

Fig. 29d. X-ray diffraction diagrams of the fine fraction of the till from the Kemijärvi area, Poikkioja (Rogen moraine), pit number 601 (depths 120 cm and 290 cm) and Heralampi, pit number 605 (depths 80 cm and 250 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

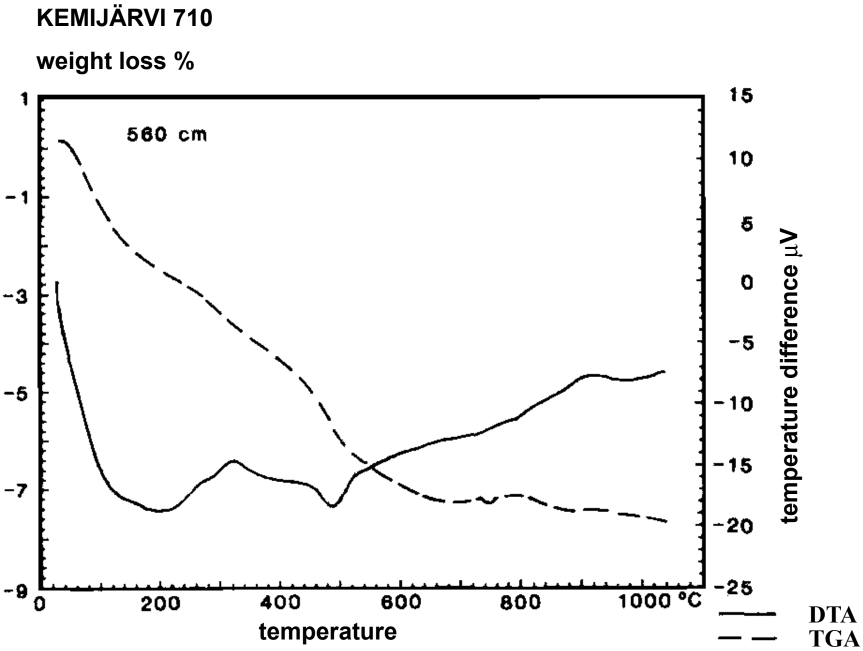

Fig. 30. Differential Thermal (DTA), Thermogravimetric (TGA) and Derivative Differential Thermal (DDTA) graphs of the clay fraction of the till from the Kemijärvi area, Peltojärvi (Rogen moraine), pit number 710, depth 560 cm.

Clay minerals are the most abundant minerals in the clay fraction of the tills of Aavasaksa (ground moraine) (Table 5 and Fig. 31a). Swelling-lattice vermiculite, vermiculite, mixed-layer clay minerals and illite are playing the main role. Vermiculite is identified on the basis of its strong 14.60-14.00 Å peak, which shifts to 10 Å after heating to 450–550 EC or with saturation with KCl. The samples of Aavasaksa (ground moraine) show a basal reflection at 14 Å, which shifts to 16 Å after ethylene glycol treatment. This is, due to swelling-lattice vermiculite (Fig. 31a). Illite is mainly trioctahedral type (Table 3). Chlorite is a minor component and it is usually Mg-rich type, but Fe-rich chlorite is also present. In the tills of Aavasaksa (ground moraine) there is no sign of kaolinite on the basis of XRD-graphs, thermal analysis or TEM/EDS. Rock-forming minerals are present in moderate quantities in following order: plagioclase, quartz, microcline and amphibole. The dehydration of the samples of Aavasaksa (ground moraine) takes place between 80 EC and 250 EC. Instead the dehydroxylation is very faint, indicating a low content of the clay minerals (Fig 32 and Table 4). The total loss of weight varies from 6.6 % to 8.0 %, which is one of the smallest of all samples in this study along with Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) and Kuusamo (drumlin) (see Figs 30, 18 and 32). In the fine fraction the most abundant minerals are quartz, plagioclase, microcline and amphibole (Fig. 31b). There are small amounts of illite, chlorite and mixed-layer clay minerals, but they exist only as minor components. Both fractions correlate quite well with the mineral composition of the granitoids.

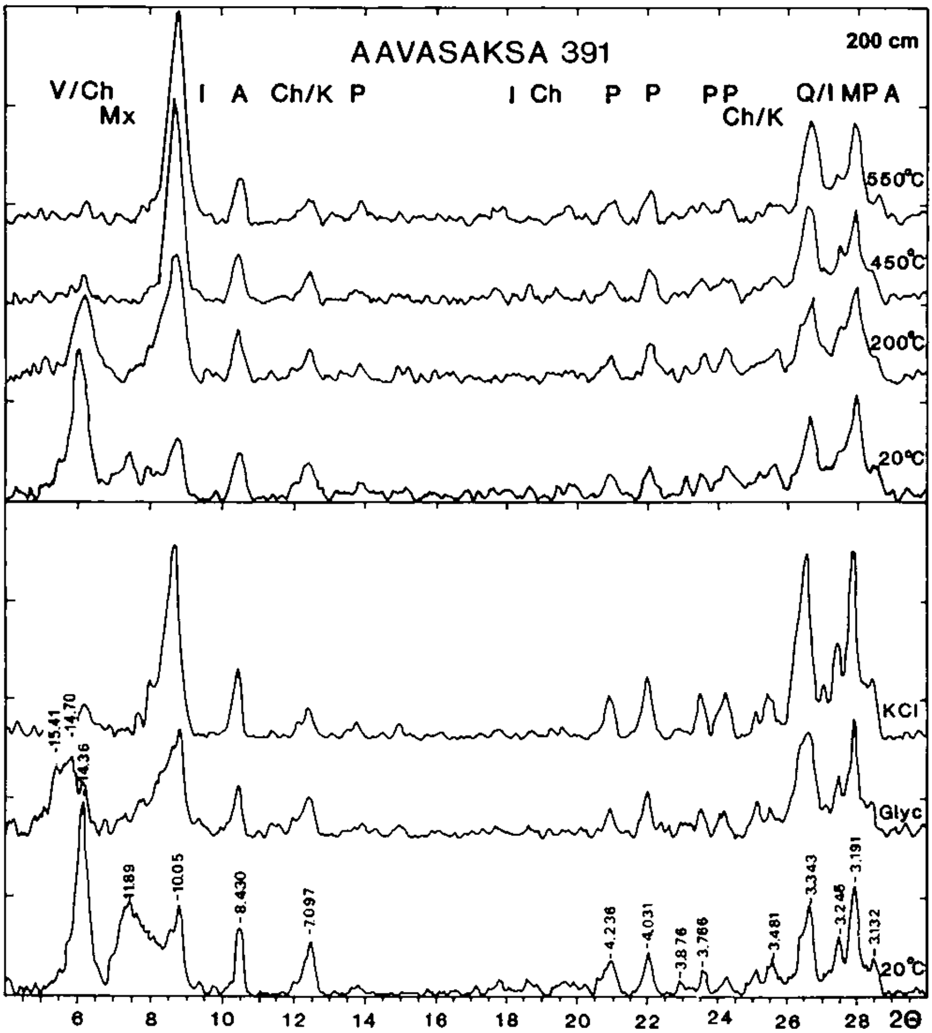

Fig. 31a. X-ray diffraction diagrams of the clay fraction of the till from the Aavasaksa area (ground moraine), pit number 391, depth 200 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

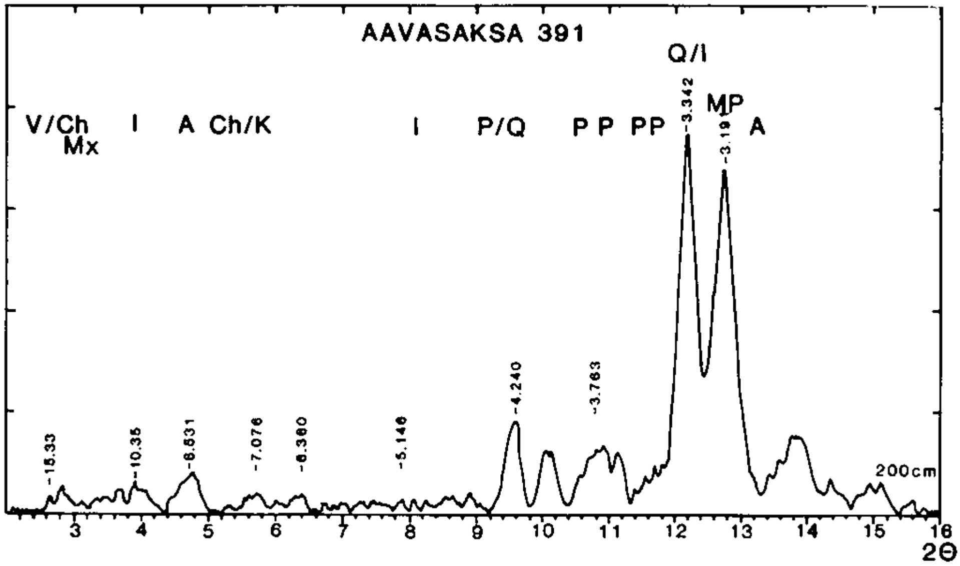

Fig. 31b. X-ray diffraction diagrams of the fine fraction of the till from the Aavasaksa area (ground moraine), pit number 391, depth 200 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

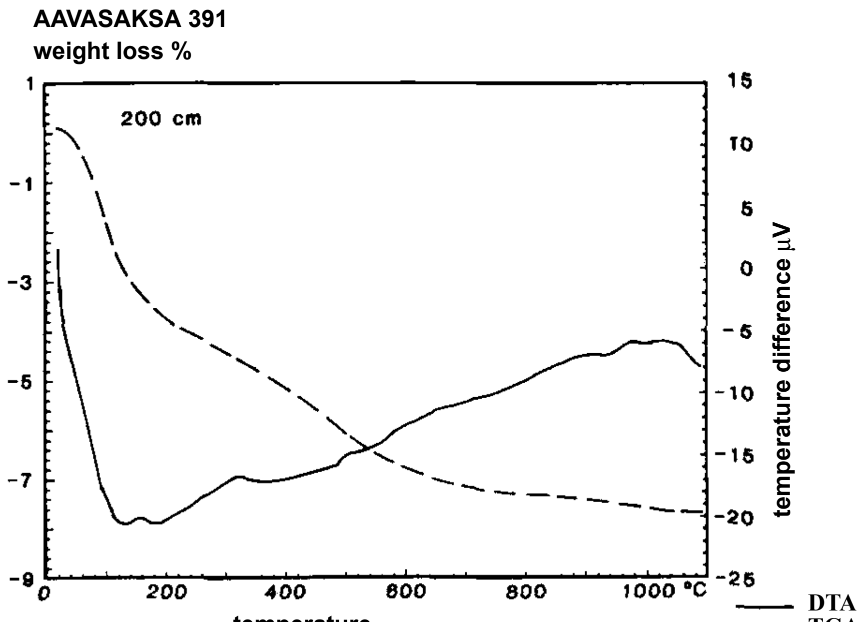

Fig. 32. Differential Thermal (DTA) and Thermogravimetric (TGA) graphs of the clay fraction of the till from the Aavasaksa area (ground moraine), pit number 391, depth 200 cm.

Geochemistry

In comparison with other study sites, in the fine fraction of tills in Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) Si, Ca, Na, and K have been enriched and concentrations of Al and Fe have been depleted. Aluminium, Mn, and Mg get the lowest concentrations off all the study material. Also Ti and P have quite low concentrations. There is no remarkable difference with the concentrations of trace elements (Table 8 and 16). The results of the geochemical province of the Granitoid area of Central Lapland correlate quite well with the present study material, although concentrations of Si and Ca are higher in present study material (Tables 7,8 and 16). In the clay fraction of tills of Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) Al, Fe, K, Mg, Ti, P, Mn, Cu, Zn, Ni and Co contents are higher than in the fine fraction (Table 16). Silicon, Ca, Na and Pb have been depleted in the clay fraction of the till. Compared to other study material Si, Na and K have the highest concentrations and Ti, Fe, Mn, and Mg the lowest concentrations in the clay fraction of till. There are some high concentrations in the fine fraction samples of the Rogen moraine of Poikkioja, pit 602 (150 cm) Al (18,2 %); longitudinal moraine ridge of Hanhikoski, pit 750 (200 cm) Fe (10,13 %), Mg (6,0 %) and Rogen moraine of Kuusivaara, pit 731 (330 cm) Ni (200 ppm). Also, in the clay fraction of the samples of the Rogen moraine of Heralampi, pit 608 (290 cm) Cu (314 ppm) and in the ablation moraine sample of Sarvilampi, pit 725 (200 cm) Zn (440 ppm) they are exceptionally high. The sample of the longitudinal moraine ridge of Hanhikoski is a silty till containing a high clay content and the sample of the longitudinal moraine ridge of Kuusivaara is from a sandy till layer containing plenty of weathered dark minerals. The sample of Sarvilampi is from sandy till, which consist of a lot of Fe-Mn-concentrations. The distribution of chemical elements of the clay fraction does not correlate with that of the local bedrock (Tables 7, 9 and 16).

In comparison with other study sites, in the fine fraction of tills in Aavasaksa (ground moraine) Si, Ca, Na, K and P have been enriched (Table 8 and 17). Along with the results of Kemijärvi (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines), concentrations of Na and K achieve one of the highest values off all the study material. Manganese and Mg have been depleted in these tills and as well concentrations of trace elements. As in the case of Kemijärvi, the distribution of chemical elements of the fine fraction correlates quite well with the geochemical province of Granitoid area (Tables 7,8 and 17). Iron, Mg, Al, K, Ti, Mn, Cu, Zn, Ni and Co have been enriched in the clay fraction of the till samples of the Aavasaksa ground moraine area (Table 17). The clay fraction of till is degraded by Si, Na, Ca, P and Pb compared to fine fraction. Cu and Ni achieve the lowest concentrations when comparing with other study material. In the fine fraction sample Aavasaksa (ground moraine), pit 398 (150 cm) have very high Si (41,4 %), Fe (38,1 %) and P (2,03 %) contents and exceptionally low Al (8,8 %) content. This sample is from the till layer with a Fe-concentration. The distribution of chemical element of the clay fraction does not correlate with that of the local bedrock (Tables 7, 9 and 17).

Table 16. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Kemijärvi study area (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines).

Kemijärvi								
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO_2	68,54	71,60	58,10	2,19	56,16	56,53	55,62	0,48
TiO_2	0,87	1,14	0,69	0,12	0,93	0,96	0,89	0,04
Al_2O_3	13,81	18,20	12,80	0,96	18,78	19,36	18,41	0,51
Fe_2O_3	4,98	10,13	3,85	0,94	7,59	7,96	7,21	0,37
MnO	0,07	0,15	0,05	0,02	0,08	0,08	0,08	0,00
MgO	1,93	6,00	1,00	0,72	3,46	3,66	3,20	0,23
CaO	3,20	4,15	2,24	0,37	2,56	2,61	2,48	0,07
Na_2O	3,76	5,80	2,60	0,59	3,15	3,16	3,12	0,03
K_2O	2,67	3,41	1,83	0,38	4,31	4,36	4,27	0,05
P_2O_5	0,15	0,28	0,03	0,05	0,16	0,18	0,14	0,02
n	104				3			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	46	98	26	12,7	185	440	77	83,4
Pb	28	99	10	11,8	18	35	4	7,4
Ni	42	200	18	24,5	78	126	50	18,7
Co	20	53	5	7,4	34	72	18	9,5
Cu	27	86	11	13,3	146	314	50	64,0
n	104				53			

Table 17. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Aavasaksa study area (ground moraine).

	Aavasaksa							
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	65,05	69,30	41,30	5,29	50,32	51,25	49,65	0,83
TiO2	0,92	1,06	0,73	0,08	1,27	1,32	1,19	0,07
Al2O3	14,14	15,70	8,80	1,34	17,26	17,82	16,23	0,90
Fe2O3	7,26	38,10	4,88	6,63	12,47	13,16	11,92	0,63
MnO	0,08	0,09	0,07	0,01	0,14	0,16	0,13	0,01
MgO	2,03	3,70	1,10	0,55	5,48	5,70	5,02	0,39
CaO	3,51	4,20	2,42	0,47	2,50	2,65	2,38	0,14
Na2O	3,86	6,20	1,70	0,81	2,47	2,60	2,26	0,18
K2O	2,92	3,31	1,72	0,29	3,89	3,93	3,85	0,04
P2O5	0,27	2,03	0,08	0,38	0,23	0,23	0,22	0,01
n	24				3			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	53	184	29	31,8	145	182	119	19,1
Pb	21	32	0	6,7	18	24	13	3,3
Ni	41	215	24	43,8	70	89	54	11,8
Co	23	45	9	7,2	31	42	24	5,0
Cu	22	95	4	19,1	108	182	50	36,3
n	24				14			

5.2.4 Greenstone belts in northern Finland

The study areas of Kittilä (ground moraine), Jerisjärvi (cover moraine) and Pulju (Pulju moraine) are situated in the geochemical province of Greenstone belts in Northern and Eastern Finland as defined by Koljonen and co-author (1992).

Mineralogy

In the clay fraction of the tills in Kittilä (ground moraine) the most abundant minerals are illite, vermiculite, kaolinite and swelling-lattice vermiculite (Table 5 and Figs 33a,b). Mixed-layer minerals are also present in some small quantities. Illite occurs dominantly as diocthedral type (Table 3) and the reason for this is possibly that the biotite in the Kit-tilä

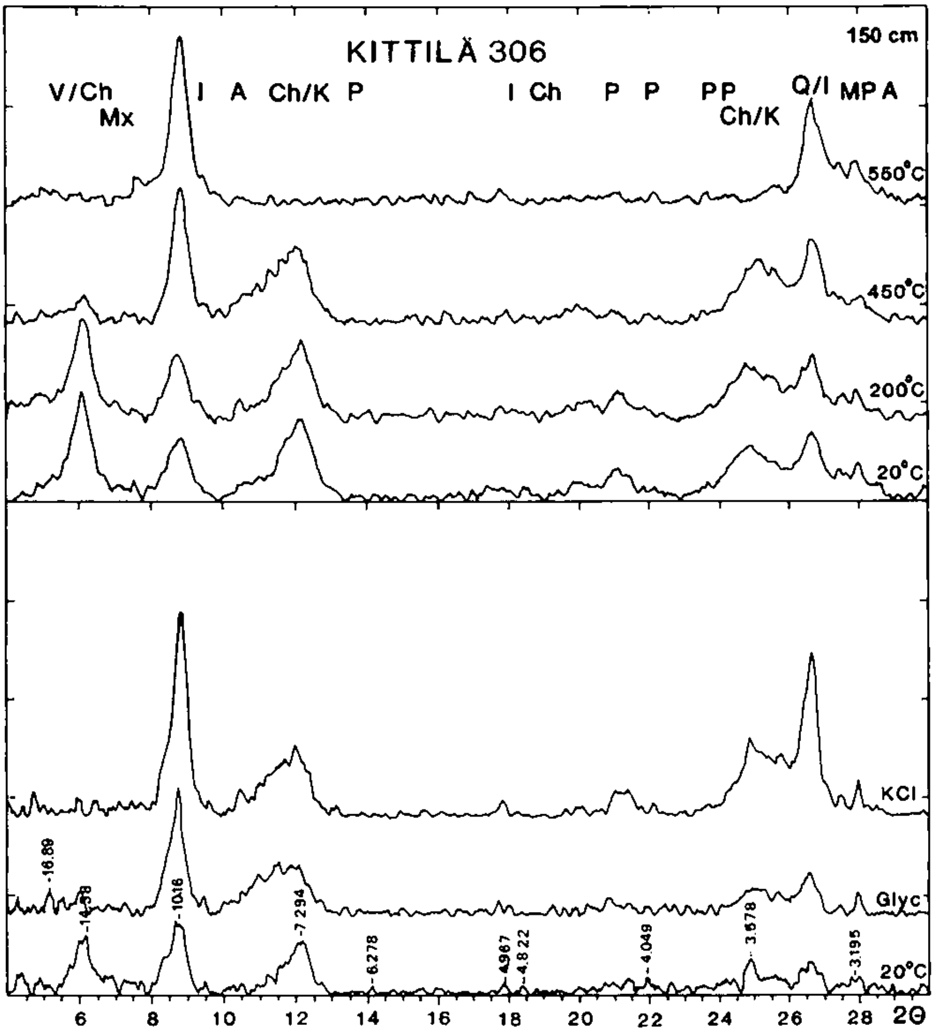

Fig. 33a. X-ray diffraction diagrams of the clay fraction of the till from the Kittilä area, Sukseton (ground moraine), pit number 306, depth 150 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

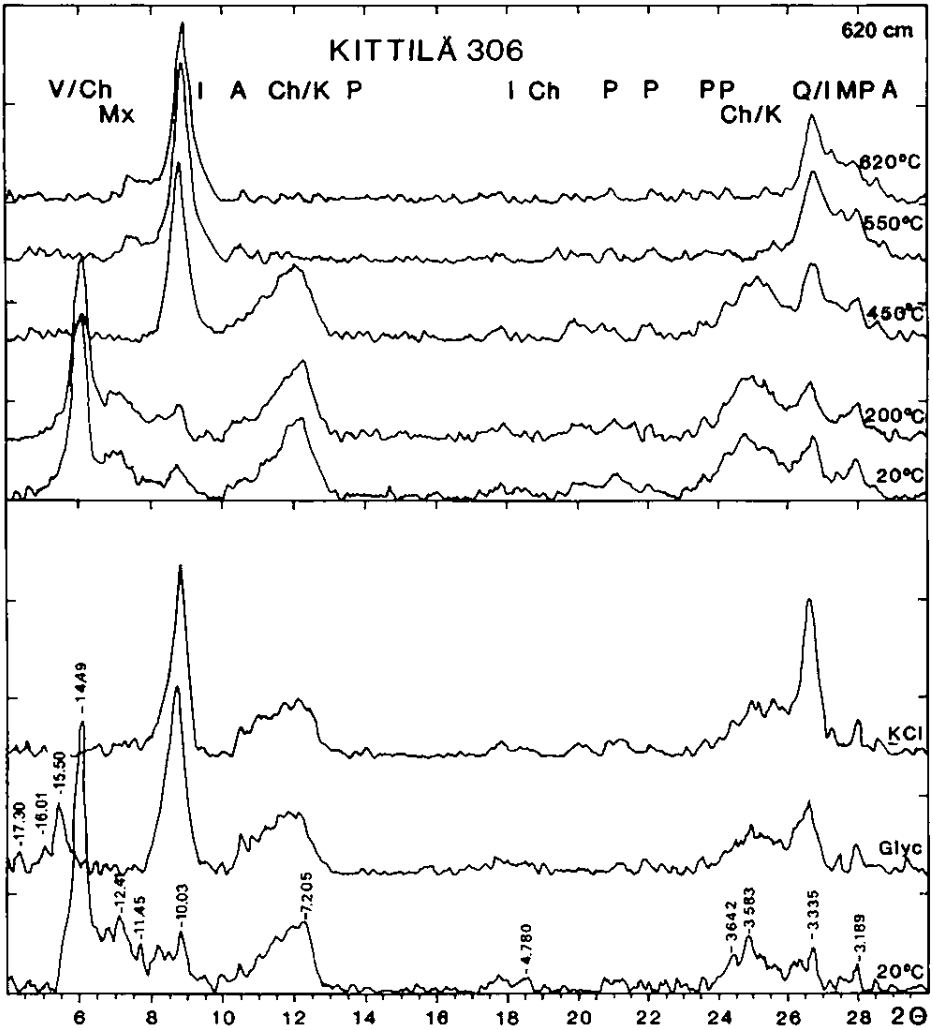

Fig. 33b. X-ray diffraction diagrams of the clay fraction of the till from the Kittilä area, Sukseton (ground moraine), pit number 306, depth 620 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

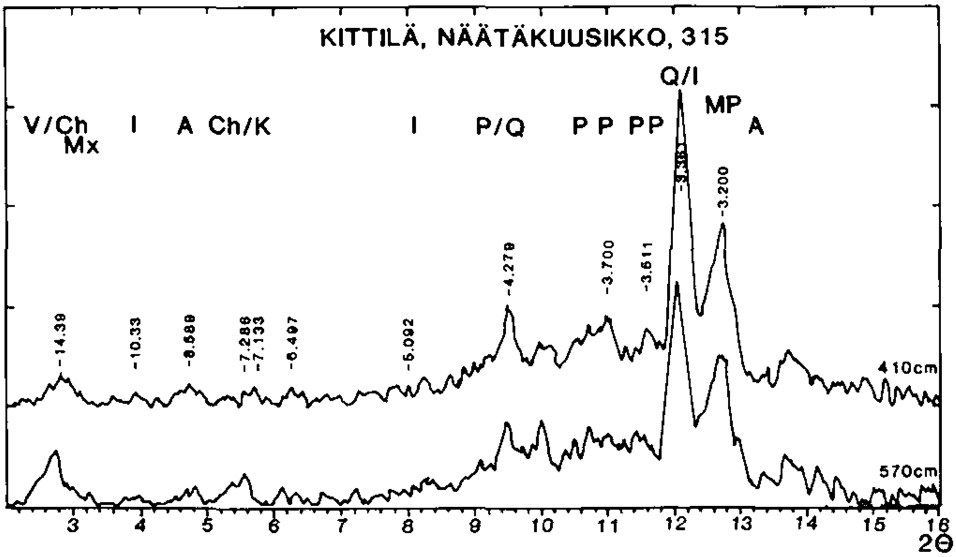

Fig. 33c. X-ray diffraction diagrams of the fine fraction of the till from the Kittilä area, Näätäkuusikko (ground moraine), pit number 315 (depths 410 cm and 570 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

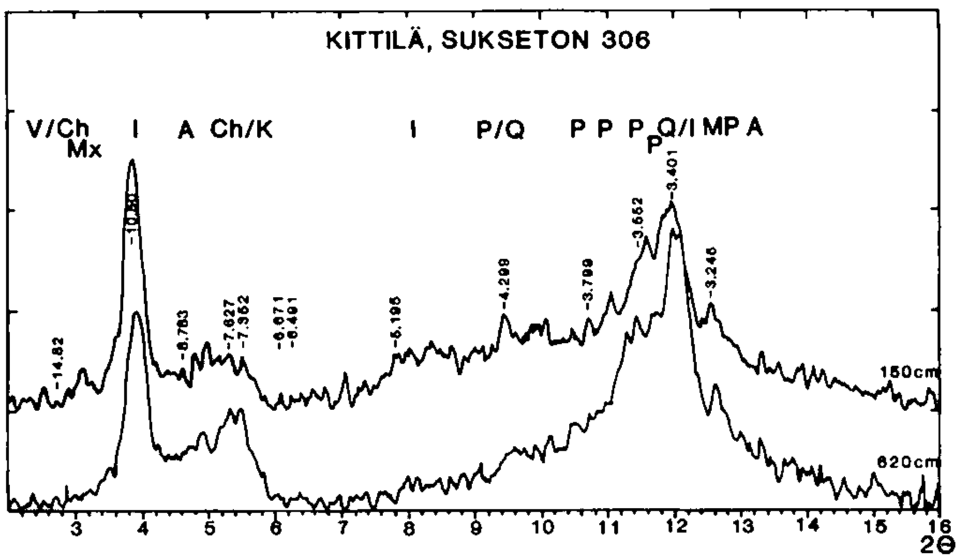

Fig. 33d. X-ray diffraction diagrams of the fine fraction of the till from the Kittilä area, Sukseton (ground moraine), pit number 306 (depths 150 cm and 620 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

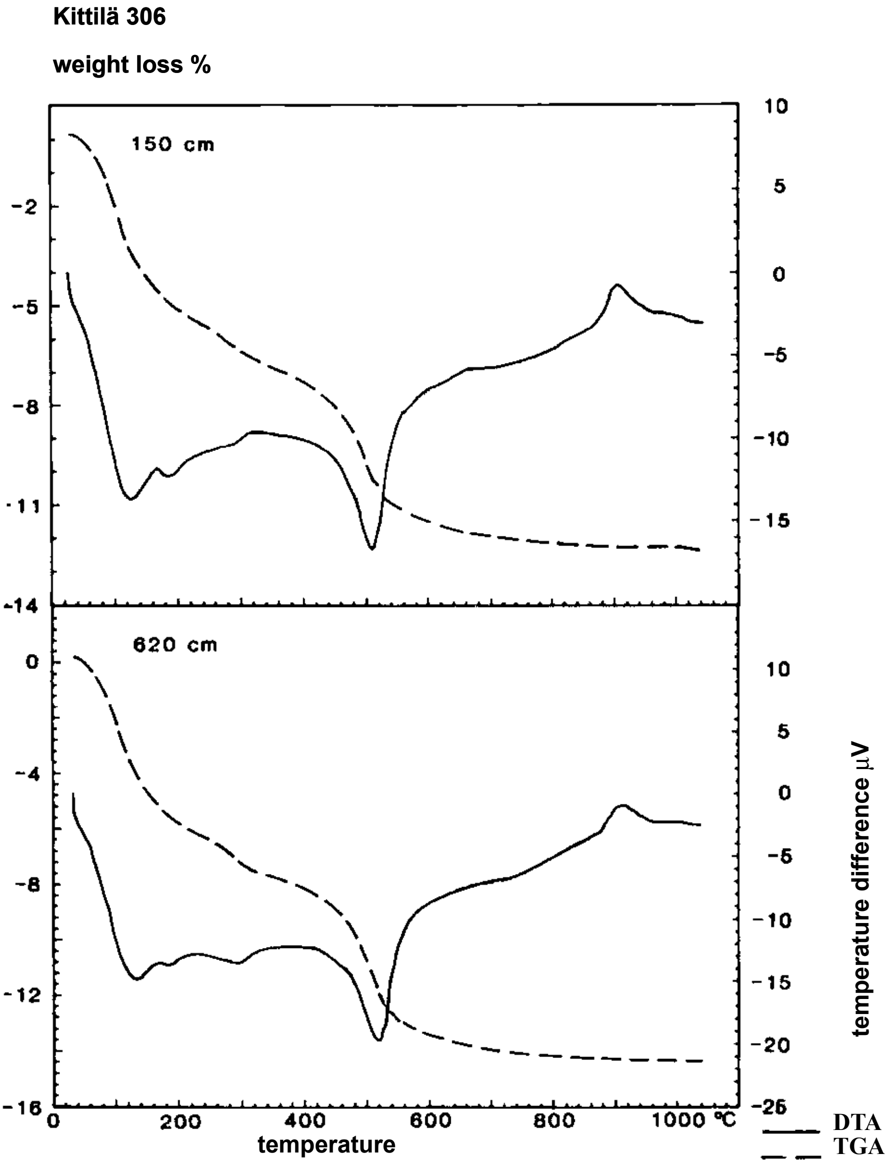

Fig. 34. Differential Thermal (DTA), Thermogravimetric (TGA) and Derivative Differential Thermal (DDTA) graphs of the clay fraction of the till from the Kittilä area, Sukseton (ground moraine), pit number 306 (depths 150 cm and 620 cm).

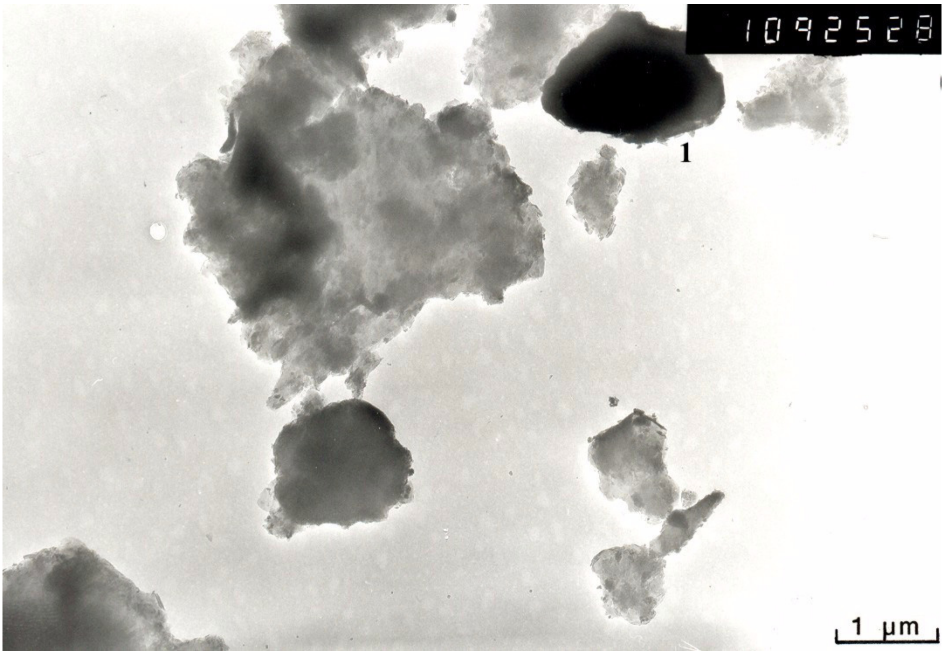

Fig. 35. TEM-photograph of clay fraction: Kittilä, Sukseton (ground moraine), pit number 306, depth 620 cm. Light colored crystals are kaolinite (Si, Al and Fe) which are Fe-pigmentated. Dark colored crystal (1) is plagioclase (Si, Al, Fe and Na) Identification is based on chemical elements (EDS) that are presented between parentheses.

area has been predominantly altered into vermiculite and not illite during long-continued chemical weathering in preglacial time. Muscovite rather has been altered to illite (cf., Peuraniemi *et al.* 1996, 1997). No chlorite can be detected. This is due to weathering of chlorite, which has transformed to mixed-layer clay minerals and vermiculite (cf., Droste 1956, Droste & Tharin 1958, Bhattacharya 1962). Kaolinite was identified by basal reflections at about 7.16 Å (001) and 3.57 Å (002). Transmission electron micrographs show that the size of kaolinite flakes is mainly of the order of 0.5-1 µm and flakes are poorly developed (Fig. 35). These kaolinite flakes can be seen in the micrographs of Kittilä. Usually kaolinite flakes were rounded in shape and containing small inclusions of hydrous iron oxides. These oxides of iron give the kaolinite flakes a dark appearance (These oxides are poorly crystalline or totally amorphous, because they produce no peaks in X-ray studies). One can see here a remarkable difference from other study areas, because rock-forming minerals exist only in small amounts. Plagioclase, microcline and amphibole occur in very low quantities or are totally destroyed by chemical weathering in the clay fraction of the till in the Kittilä area. All samples from the Kittilä area (ground moraine) are strongly dehydrated between 80 EC and 260 EC (Fig. 34). This is typical for vermiculite and mixed-layer minerals. There is a weak endothermic reaction at about 300-320 EC suggesting the presence of goethite. Strong dehydroxylation occurs between 400 EC and 600 EC, which is typical to kaolinite. The top of an endothermic peak is at 520 EC. This suggests that kaolinite is perhaps not well-crystalline, because dehydroxylation occurs at a lower temperature than for well-crystallized kaolinite (~600 EC). Also, chlorite and illite shows similar dehydroxylation reaction types, but not as strong as kaolinite. A strong exothermic reaction occurs at 900 - 950 EC, which is due to kaolinite. This reaction also indicates that kaolinite is poorly crystallized, because it occurs at lower temperature as that for well-crystallized kaolinite. Thermogravimetry provides a good measure of the contents of water-bearing secondary mineral phases (clay minerals + iron oxides) in the samples studied (cf., Velde 1992). The total weight loss varies from 12.4 % to 15.4 %, which is the highest of all samples in this study (see Fig. 34 and Table 4). This demonstrates that the amount of the secondary clay minerals and iron oxides in tills is higher in the area of the preglacial weathering crust and the former ice divide of central Finnish Lapland than elsewhere. Also XRD-graphs confirm that kaolinite, vermiculite, swelling-lattice minerals and illite are present in these samples (Figs 33a,b). In the fine fraction of the till the most abundant minerals are quartz, plagioclase/microcline (Fig. 33c,d). There are very small amounts of amphibole, illite, kaolinite, mixed-layer clay minerals and vermiculite, but they exist only as minor components. In the samples of Sukseton the most dominant minerals are illite, quartz and plagioclase (Fig. 33d). There is also a moderate amount of kaolinite. The influence of weathered bedrock is clearly seen in both fractions.

The study area of Jerisjärvi (cover moraine) is situated in the northern part of the Greenstone belt. It is also in the area of weathered bedrock and the former ice divide zone. The mineralogy of this area resembles strongly the till mineralogy of Kittilä (ground moraine). Most abundant minerals in the clay fraction of till are vermiculite, kaolinite, illite and swelling-lattice vermiculite (Table 5 and Figs 36a,b). Likewise in the tills of Kittilä (ground moraine), illite is mainly diocthedral type (Table 3) e.g., muscovite type and it is due to the preglacial weathering process. Main rock-forming minerals are in the following order: quartz, amphibole, plagioclase and microcline. It seems to be obvious that the amount of a weathered bedrock matter is not as strong as in the tills of Kittilä (ground moraine), because there is a moderate quantity of amphibole present. Also, the rate of weathering of these tills is not as strong as in the tills of Kittilä. After glycerol treatment there is no effect to the 14 Å peak and it points out that there is no smectite present. DTA- graphs of Jerisjärvi (cover moraine) samples show a strong double endothermic peak between 80 EC and 200 EC (Fig. 37). This is due to the existence of vermiculite, which is confirmed also by XRD - graphs (Figs 36a,b). The main dehydroxylation peak at 500 EC fits well with kaolinite. This point out that kaolinite is not well-crystallized. In 900 EC occurs a moderate exothermic reaction, which also confirms the existence of kaolinite. This reaction also indicates that kaolinite is poorly crystallized, because it occurs at lower temperature as that for well crystallized kaolinite. The total loss of weight varies from 11.6 % to 13.0 % (see Fig. 37 and Table 4). In the fine fraction the most abundant minerals are quartz, plagioclase, microcline and amphibole (Fig. 36c). There are very small amounts of secondary minerals.

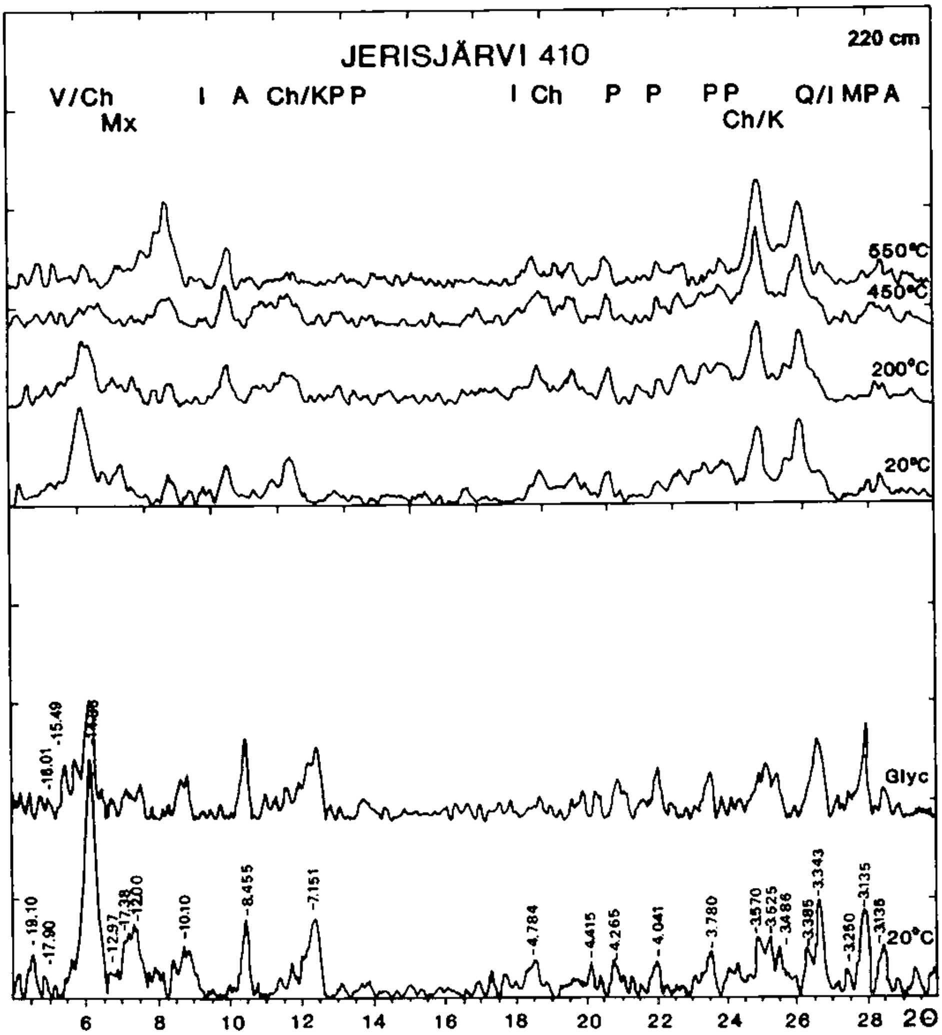

Fig. 36a. X-ray diffraction diagrams of the clay fraction of the till from the Jerisjärvi area (cover moraine), pit number 410, depth 220 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz and Glyc= ethylene glycol treatment.

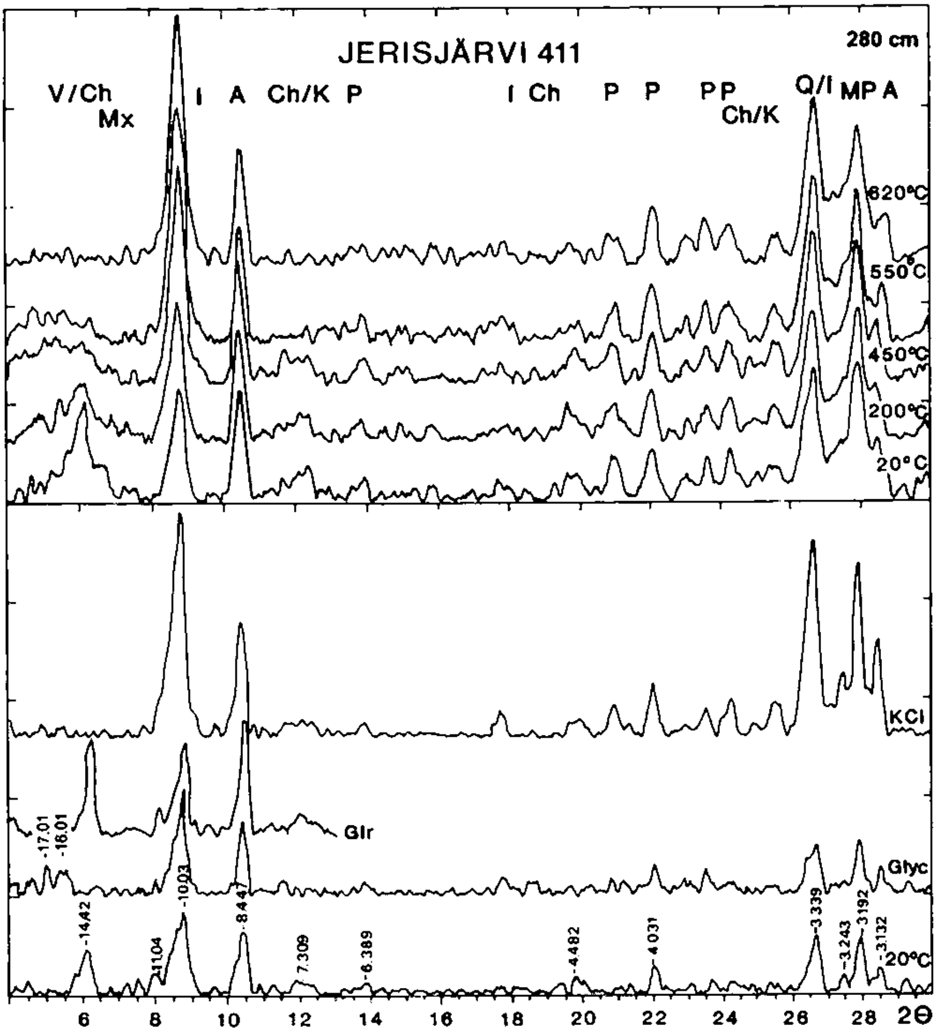

Fig. 36b. X-ray diffraction diagrams of the clay fraction of the till from the Jerisjärvi area (cover moraine), pit number 411, depth 280 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation, Glyc= ethylene glycol treatment and Glr= glycerol treatment.

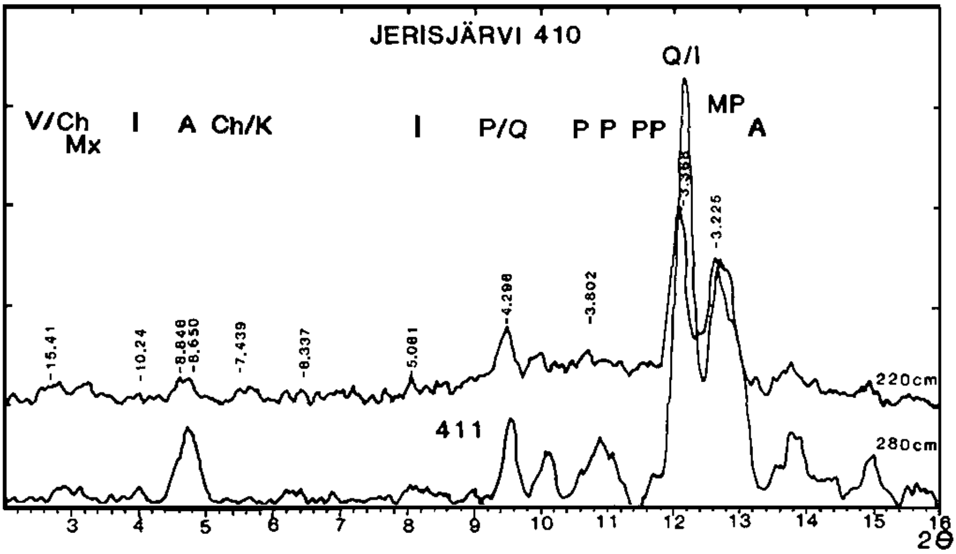

Fig. 36c. X-ray diffraction diagrams of the fine fraction of the till from the Jerisjärvi area (cover moraine), pit number 410 (depths 220 cm and 280 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

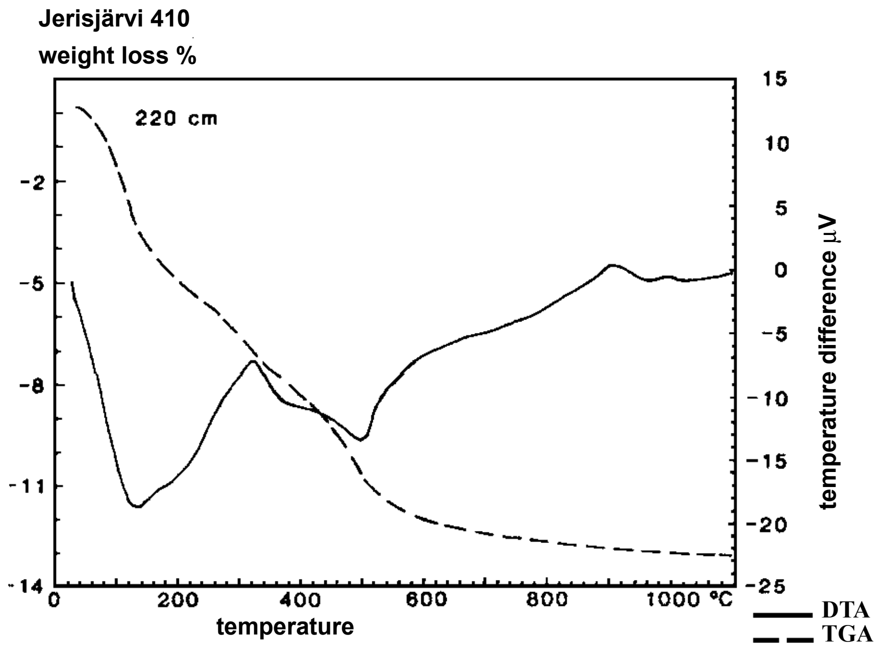

Fig. 37. Differential Thermal (DTA), Thermogravimetric (TGA) and Derivative Differential Thermal (DDTA) graphs of the clay fraction of the till from the Jerisjärvi area (cover moraine), pit number 410, 220 cm.

In the clay fraction of the tills in Pulju (Pulju moraine) swelling-lattice vermiculite, vermiculite, kaolinite and illite are the most abundant minerals and illite is totally of trioctahedral type (Tables 3, 5 and Fig. 38a). Swelling-lattice vermiculite is a dominant mineral and it is common in all the till samples.

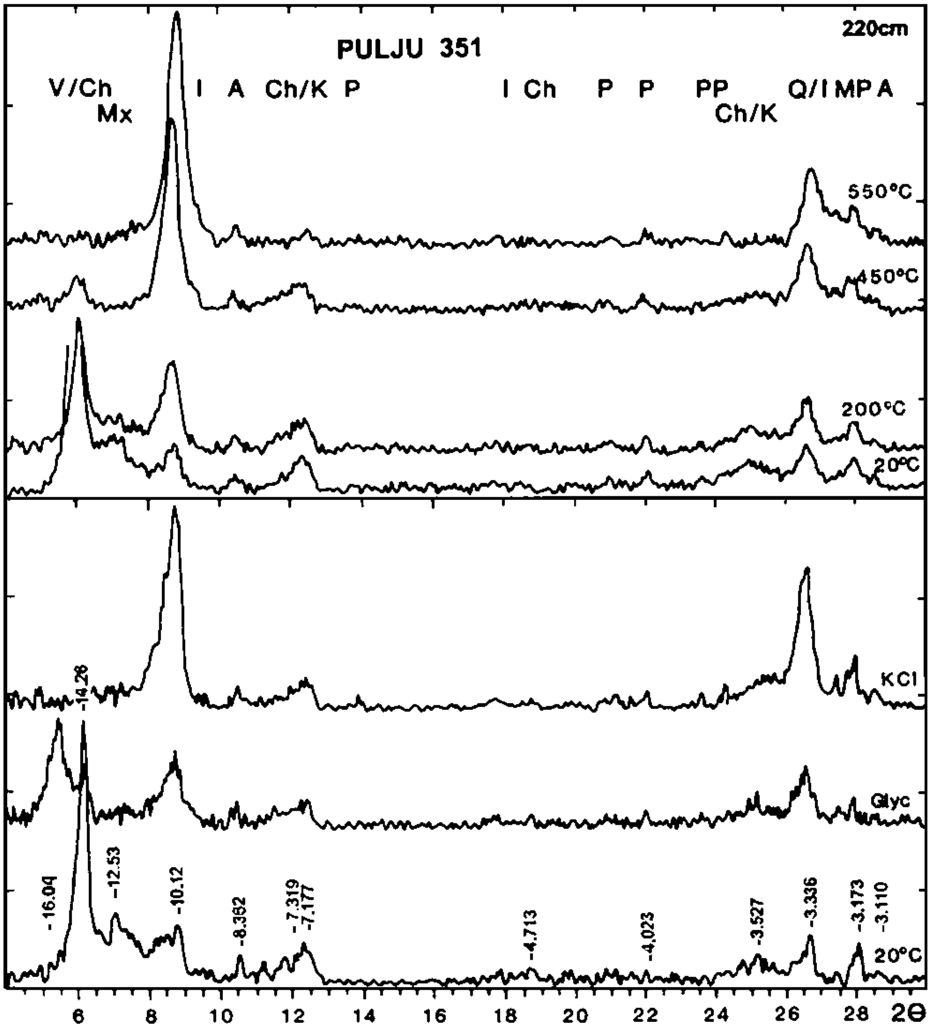

Fig. 38a. X-ray diffraction diagrams of the clay fraction of the till from the Pulju area (Pulju moraine), pit number 351, depth 220 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

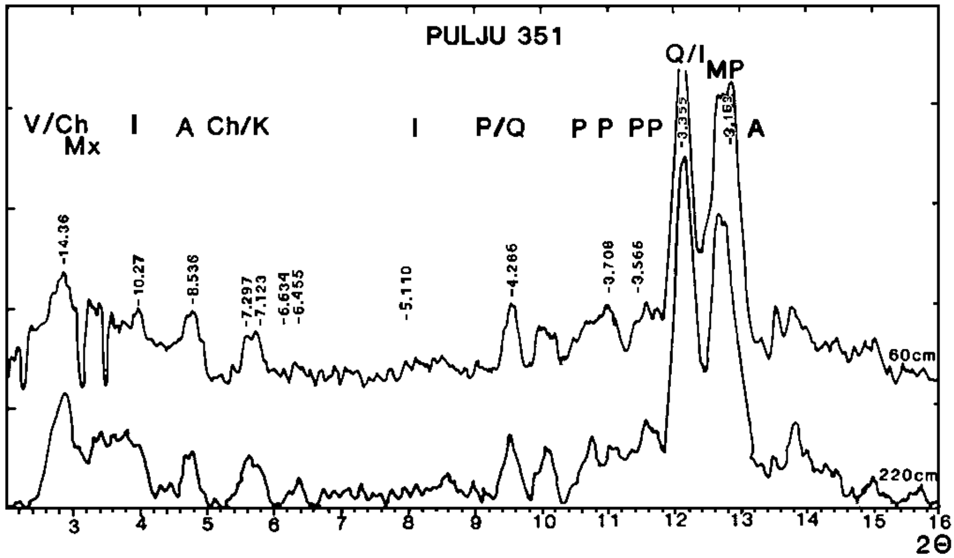

Fig. 38b. X-ray diffraction diagrams of the fine fraction of the till from the Pulju area (Pulju moraine), pit nubmer 351 (depths 60 cm and 220 cm). V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline and Q= quartz.

Rock forming minerals are in the following order: quartz, plagioclase, microcline and amphibole. DTA- graphs of Pulju samples show a strong double endothermic peak between 70 EC and 200 EC (Fig. 39). This is due to the existence of vermiculite, which is confirmed also by XRD - graphs (Fig. 38a). The main dehydroxylation peak at 500 EC fits well with kaolinite; the existence of which was confirmed also by XRD - graphs. At920 EC occurs a moderate exothermic reaction, which confirms the existence of kaolinite. Kaolinite, illite and mixed-layer clay minerals exist in moderate amounts. The total loss of weight varies from 7.8 % to 13.3 % (see Fig. 39 and Table 4). In the fine fraction the most dominant minerals are quartz, plagioclase, microcline and kaolinite/ chlorite/vermiculite (Fig. 38b). There are also some moderate amounts of amphibole, illite, mixed-layer minerals. The influence of weathered bedrock and/or maturity of the tills are maybe causing this.

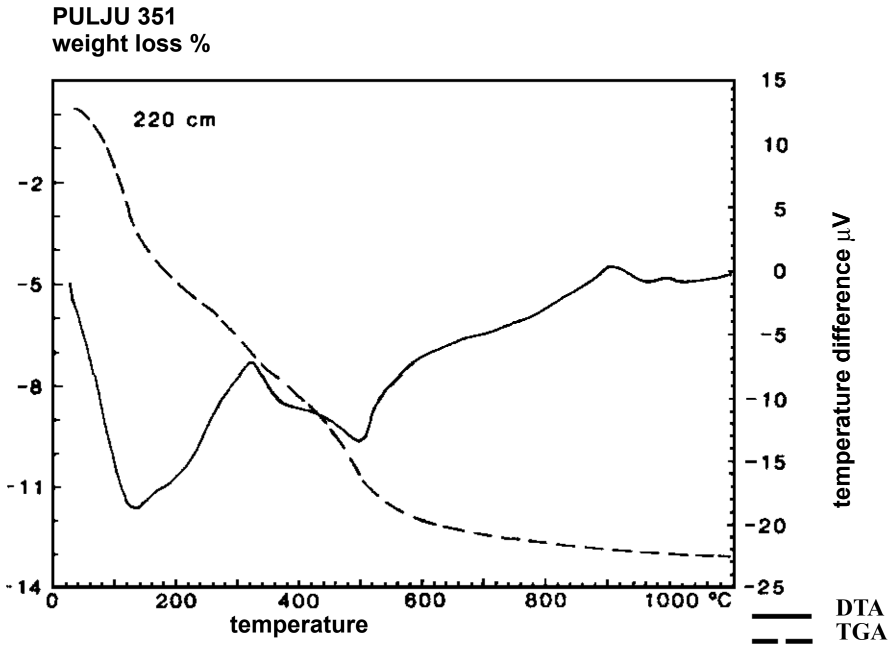

Fig. 39. Differential Thermal (DTA and Thermogravimetric (TGA) graphs of the clay fraction of the till from the Pulju area (Pulju moraine), pit number 351, depth 220 cm.

In the Greenstone belt area the mineralogical composition of the bedrock is correlates well with the fine fraction of till. The distribution of minerals in the clay fraction of the tills of these areas is not the same as that of the local bedrock. This is due to physical and chemical weathering of amphibole, microcline and plagioclase. The clay fraction can be best explained with the mixing of the weathering crust material into a clay fraction.

Geochemistry

In comparison with other study sites, the fine fraction of tills in Kittilä (ground moraine) has been enriched in Ti, Al and Fe and trace elements. Titanium, Ni and Co shows the highest values of the present study material. Also Mg, Mn and Ca are present in moderate concentrations. The fine fraction has been strongly depleted in Si, K and Na. Potassium (K) shows the lowest value of the present study material (Tables 7, 8 and 18). In the clay fraction of the ground moraine samples of Kittilä Fe, Al, Mg, Ti, P, Cu, Zn and Ni contents are higher than in the fine fraction (Table 18). Ti, Fe, Mn, P, Ni and Co have the highest concentrations of all the studied tills and Pb achieves the lowest value along with clay fraction of Kaaresuvanto (Pulju moraine) (see Tables 7,8,13 and 18). Silicon, Ca, Na, K, Pb and Co have been depleted in the clay fraction as compared to the fine fraction of the till. The content of Mn is at the same level in both fractions. The distribution of chemical elements in the clay fraction does not correlate with the one of local bedrock (Tables 7,9 and 18). There are very high concentrations in the fine fraction of till at Vänköselkä, pit 321 (160 cm) Zn (1096 ppm), Pb (104 ppm); Vänköselkä, pit 321 (170 cm), Fe (31,1

%), Ni (993 ppm), Cu (787 ppm); Vänköselkä 321 (320 cm) Ti (3,05 %); Mustapakula, pit 328 (410 cm) Al (29,4 %), Näätäkuusikko, pit 313 (240 cm) Mn (2,0 %) and Sieruma-selkä, pit 317 (210 cm) Co (307 ppm). These high concentrations of Zn, Cu, Ni and Co in the fine fraction are probably due to unknown sulphide mineralizations or influence of metals enriched weathering crust material.

Table 18. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Kittilä study area (ground moraine).

Kittilä								
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	61,55	69,60	41,60	4,50	38,99	41,60	35,27	2,04
TiO2	1,33	3,05	0,44	0,38	1,81	2,25	1,45	0,29
Al2O3	16,25	29,30	13,10	2,13	21,58	24,28	19,68	1,58
Fe2O3	8,86	31,10	2,95	3,76	21,32	25,78	16,47	3,18
MnO	0,17	2,00	0,03	0,23	0,17	0,23	0,09	0,05
MgO	3,00	8,30	0,70	0,74	4,45	6,02	3,19	0,86
CaO	3,63	6,60	0,03	1,01	1,08	1,52	0,62	0,25
Na2O	2,93	4,50	0,00	0,64	0,55	0,71	0,39	0,11
K2O	1,85	6,63	0,00	0,66	1,33	2,04	0,94	0,36
P2O5	0,18	1,17	0,00	0,14	0,49	0,76	0,38	0,11
n	219				11			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	107	1096	36	89,9	200	322	129	43,9
Pb	26	104	11	11,7	12	25	0	6,7
Ni	86	993	23	74,6	141	255	92	46,6
Co	49	307	15	32,1	48	78	22	12,0
Cu	76	787	10	73,0	181	320	101	53,7
n	219				34			

The fine fraction of tills in Jerisjärvi (cover moraine) have been enriched in Ti, Fe, Mn, Mg, Ca and P and depleted in Si, Al, Na and K. Titanium shows the second highest value of all the study material. In addition, Ca has quite high concentrations. The fine fraction is strongly depleted in Al and it shows one of the lowest concentration values in the present study material (Table 8). Trace elements are present in average concentrations and only Pb has a low concentration. The distribution of chemical elements of the present study material correlates passable with fine fraction distribution of the Greenstone belt province (Tables 7, 8 and 19). In the clay fraction of cover moraine samples of Jerisjärvi (cover moraine) have been enriched with Al, Fe, Mg, K, P, Cu, Zn, Ni, Co and Pb (Table 19). Silicon, Ca, Na and Ti have been degraded in the clay fraction compared to fine frac-tion. The content of Mn is at the same level in both fractions. Aluminium achieves the highest concentration value of the present study material. The distribution of chemical element does not correlate with the one of local bedrock (Tables 7, 9 and 19).

Table 19. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Jerisjärvi study area (cover moraine).

Jerisjärvi								
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	63,53	66,30	60,30	1,92	46,86	48,09	45,63	1,74
TiO2	1,31	1,69	1,07	0,23	1,27	1,28	1,26	0,02
Al2O3	13,81	14,50	13,30	0,42	22,73	23,07	22,39	0,48
Fe2O3	7,64	9,42	6,09	1,11	13,47	13,54	13,40	0,10
MnO	0,11	0,15	0,09	0,02	0,11	0,13	0,09	0,03
MgO	3,03	3,60	2,20	0,36	4,07	4,11	4,03	0,06
CaO	5,01	6,22	4,15	0,70	2,08	2,24	1,92	0,22
Na2O	3,02	3,80	2,10	0,42	1,50	1,69	1,31	0,27
K2O	1,91	2,23	1,57	0,20	2,19	2,36	2,02	0,24
P2O5	0,18	0,25	0,13	0,04	0,33	0,34	0,32	0,02
n	18				2			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	63	81	45	11,4	127	136	115	9,6
Pb	16	23	0	7,5	19	22	14	2,6
Ni	47	57	33	7,0	96	108	80	12,1
Co	33	43	19	7,5	43	68	26	15,0
Cu	44	139	19	26,7	226	326	173	54,8
n	18				6			

The fine fraction of tills in Pulju (Pulju moraine) have been enriched strongly in Si and slightly in Mg, Ca, Na and K and depleted in Fe, Al and P (Table 20). Magnesium achieves the highest concentration values of all the study material along with the tills of Northern Inari (Sevetti moraine). Also, Ca has quite high concentrations. The fine fraction has strongly depleted in Al. Trace elements are present in average concentrations and only Co has two times higher concentration than in the material of the Greenstone belt province. The geochemical province of Greenstone belts has lower Si and Co values than in the present study material. Distribution of chemical elements correlates passable with fine fraction distribution of the Greenstone belt province (Tables 7, 8 and 20). Aluminium, Fe, Mg, K, Ti, Mn, Zn, Ni and Cu have been enriched in the clay fraction of the till samples of the Pulju study area (Table 20). Zink and Ni have three times, Co two times and Cu four times higher concentrations in the clay fraction of till compared to the geochemical province of Greenstone belts (Tables 7, 9 and 20). The clay fraction of till is degraded by Si, Na and Ca, compared to fine fraction. Silicon has especially low concentrations in the clay fraction of till and the arithmetic mean is about 19 % lower than in the fine fraction of till. The distribution of chemical element in the clay fraction does not correlate with that of the local bedrock (Tables 7, 9 and 20).

Table 20. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and clay fractions in the Pulju study area (Pulju moraine).

	Pulju							
	<0,06 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation				
SiO2	63,90	64,60	63,20	0,99	44,64			
TiO2	0,82	0,85	0,78	0,05	1,31			
Al2O3	14,80	15,20	14,40	0,57	19,26			
Fe2O3	5,54	6,19	4,89	0,92	14,75			
MnO	0,08	0,09	0,08	0,00	0,10			
MgO	3,30	3,60	3,00	0,42	6,23			
CaO	3,81	3,92	3,70	0,16	1,41			
Na2O	4,15	4,30	4,00	0,21	1,19			
K2O	2,50	2,50	2,50	0,00	3,05			
P2O5	0,00	0,00	0,00	0,00	0,24			
n	2				1			
	<0,06 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	55	65	45	14,14	165	166	164	1,41
Pb	24	26	21	3,54	24	26	21	3,54
Ni	91	99	82	12,02	195	236	153	58,69
Co	34	36	32	2,83	37	40	34	4,24
Cu	31	44	17	19,09	144	187	101	60,81
n	2				2			

5.2.5 Granulite zone in Lapland

In the present study the area of Southern Inari (Sevetti moraine) (a.k.a Väylä and Valkkojärvi) is located in geochemical province of Granulite zone in Lapland as defined by Koljonen and co-author (1992).

Mineralogy

In the clay fraction of tills of Southern Inari (Sevetti moraine) (a.k.a Väylä and Valkkojärvi) the most abundant minerals are chlorite, illite and vermiculite (Table 5 and Fig. 40). Illite is mainly trioctahedral type (Table 3). Both Mg-rich - and Fe-rich chlorite is present.

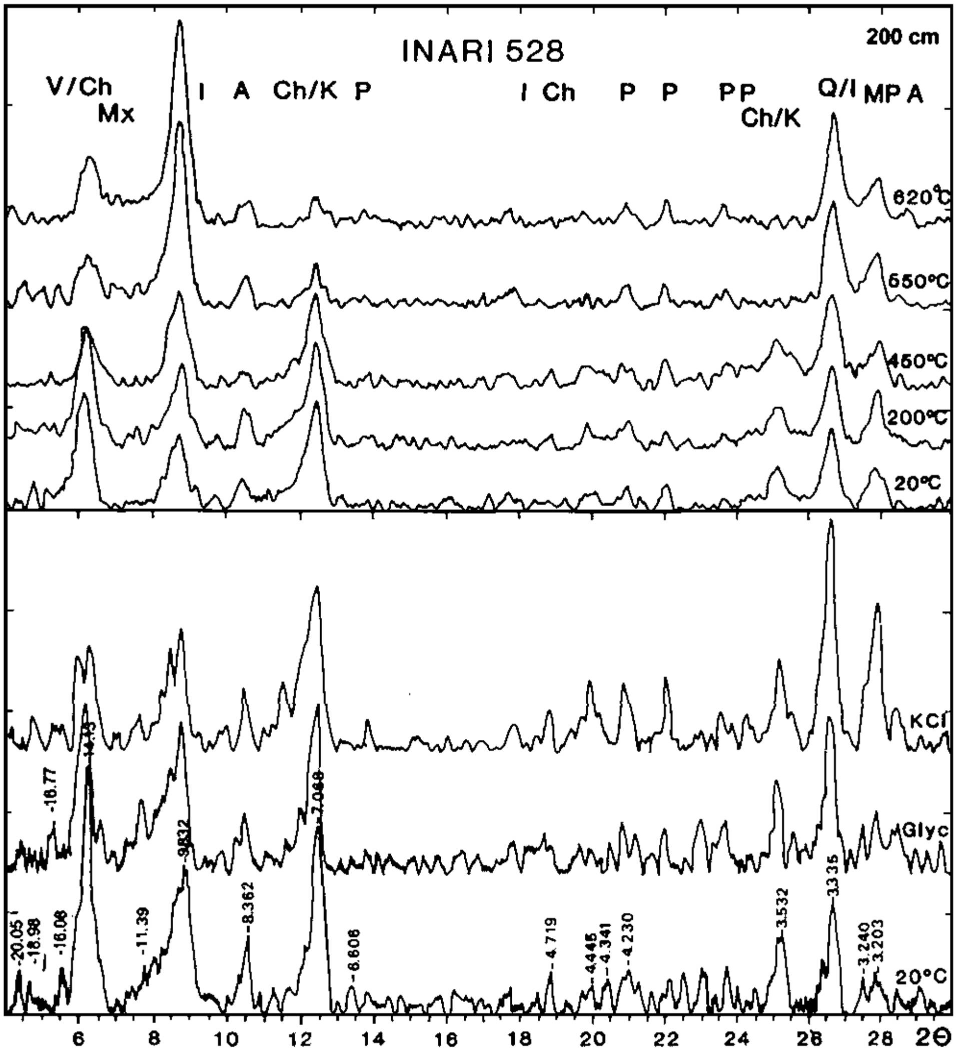

Fig. 40. X-ray diffraction diagrams of the clay fraction of the till from the Inari area, Väylä (Sevetti moraine), pit number 528, depth 200 cm. V= vermiculite/swelling-lattice vermiculite, Ch= chlorite, I= illite, Mx= mixed-layer minerals, K= kaolinite, A= amphibole, P= plagioclase, M= microcline, Q= quartz, KCl= potassium saturation and Glyc= ethylene glycol treatment.

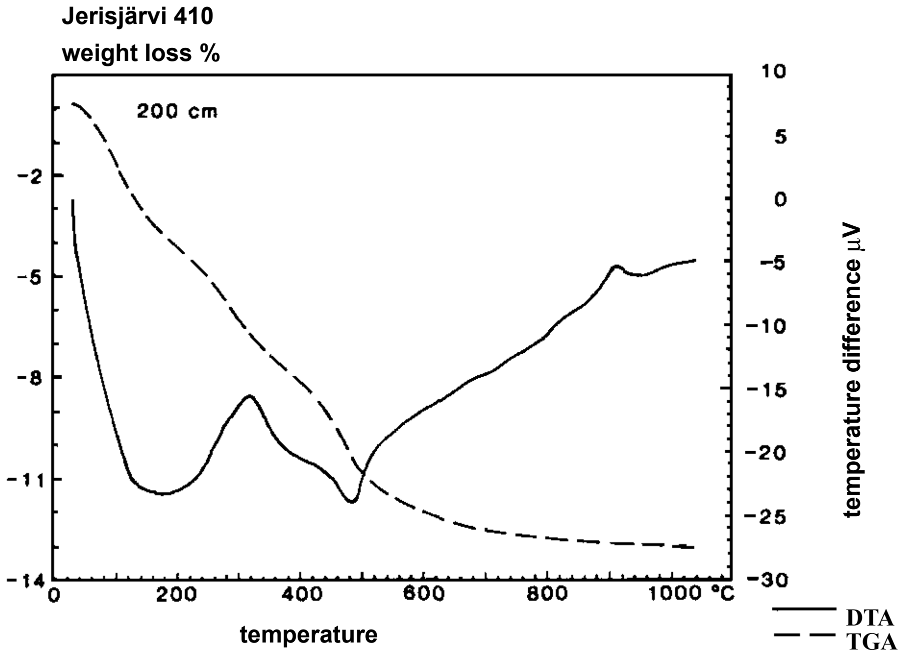

Fig. 41. Differential Thermal (DTA) and Thermogravimetric (TGA) graphs of the clay fraction of the till from the Inari area, Väylä (Sevetti moraine), pit number 528, depth 200 cm.

There is a small quantity of mixed layer clay minerals, but quartz and plagioclase are present in some greater quantities. Amphibole and microcline are minor components. Vermiculite is identified on the basis of its strong 14.00 Å peak, which shifts to 10 Å after heating to 450-550 EC and with saturation with KCl. Swelling-lattice vermiculite (after ethylene glycol treatment) and kaolinite were also detected, but in small quantities. On the basis of DTA-graphs in the study site of Inari (Sevetti moraine), one can observe that all samples are strongly dehydrated <280 EC, which are typical reactions to illite, chlorite, vermiculite and kaolinite (Fig. 41). Also, XRD-graphs confirm this conclusion (Fig. 40). A moderate loss of weight in TGA-analysis and a strong exothermic reaction between 200 EC and 360 EC in DTA-analysis is due to burning of the organic matter and reactions of amhorphic iron. An endothermic reaction is about 430-550 EC and it's strongest at 520 EC. This point out that kaolinite is not well-crystallized. At 900 EC there occurs a moderate exothermic reaction, which also confirms the existence of kaolinite. The total loss of weight varies from 8.7 % to 13.8 % (see Fig. 41 and Table 4). In the fine fraction the most dominant minerals are quartz, plagioclase/microcline, illite and chlorite/ vermiculite (Fig. 24c). There is possibly kaolinite present. The influence of weathered bedrock and/or maturity of the tills are maybe causing this. In both fractions the influence of bedrock is clearly seen. In the clay fraction amphibole and feldspars are weathered into secondary minerals but in the fine fraction the weathering rate is lower and rock-forming minerals are dominant.

Geochemistry

In comparison with other study sites in the fine fraction of tills in Southern Inari (Sevetti moraine) (a.k.a Väylä and Valkkojärvi) Fe and Al have been enriched and Si, Ca and Na have been depleted (Tables 7 and 8). Aluminium achieves the highest value of all the study material and Na achieves the lowest one. High Al content reflects the influence of weathering crust material. Other major chemical elements are at an average level. Zinc and Cu have high concentrations and other trace elements are at an average level. Present study material corresponds quite well with the average composition of the fine fraction of geochemical province of the Granulite zone in Lapland. Only Si, K and Cu have slightly higher concentrations in the samples of present study material (Tables 7 and 8). Geochemical results of fine fraction of till provided a quite good correlation when comparing to the geochemical composition of fine fraction in the Granulite belt province. For the clay fraction, there was no available chemical analyses for the main chemical elements, due to the fact that there was not enough material for analysis. Trace elements were analyzed and there is a moderate concentration of Zn, Ni and Cu (Tables 7 and 9).

5.3 Influence of preglacial weathering crust on till mineralogy and geochemistry

The study sites of Kittilä (ground moraine) and Jerisjärvi (cover moraine) are located in the former ice divide zone and in the area of the preglacial weathering crust. In these areas great amounts of weathered bedrock material are mixed into tills (Kallio *et al.* 1980, Peuraniemi *et al*. 1996, 1997, Koljonen *et al*. 1992). Kittilä and Jerisjärvi are also situated in the areas of Palaeoproterozoic mafic volcanics. Occurrences of weathering crust are also known in the study sites of Inari (Sevettijärvi and Pyhävaara (Sevetti moraine)). Although preglacial weathering crust is not known to occur in the other study areas, the mineralogical results (kaolinite) suggest that at least its influence is present in tills. Table 21 shows the arithmetic means, variations and standard deviations of the chemical elements in the fine and clay fractions of till in weathered and unweathered bedrock areas. Weathered bedrock area is represented by the study sites of Kittilä (ground moraine).

5.3.1 Mineralogy

In the tills of Kittilä (ground moraine) vermiculite, kaolinite, illite and swelling-lattice vermiculite are dominant minerals (Table 5 and Figs 33a,b). The mineralogy of tills in the Jerisjärvi area (cover moraine) resembles strongly the till mineralogy of Kittilä (Table 5 and Figs 36a,b). The most abundant minerals there are vermiculite, kaolinite, swelling-lattice vermiculite and illite. At both study sites illite exist dominantly in diocthedral type (Table 3) and the reason for this might be that the biotite in these areas has been predominantly altered into vermiculite and not illite during long-continued chemical weathering in preglacial time. Muscovite rather has been altered to illite (cf., Peuraniemi *et al*. 1996, 1997). According to Hyyppä (1983) in the preglacial weathering crust of area of Kittlä, Lonnakko, illite is present as dioctahedral type. In the preglacial weathering crust of Central Lapland has been confirmed dioctahedral illite (Islam 1996). Transmission electron micrographs show that the size of kaolinite flakes is mainly of the order of 0.5-1 µm and flakes are poorly developed (Fig. 35). Usually kaolinite flakes are rounded and include small inclusions of hydrous iron oxides. These oxides of iron give the kaolinite flakes a dark color. These oxides are poorly crystalline or totally amorphous, because they produce no peaks in X-ray study. One can see here a remarkable difference from other study areas, because rock-forming minerals exist only in small amounts. Plagioclase, microcline and amphibole occur in very low quantities or are totally destroyed by chemical weathering in the clay fraction of the till in the Kittilä area (ground moraine). Thermogravimetry provides a good measure of the contents of water-bearing secondary mineral phases (clay minerals + iron oxides) in the samples studied (cf., Velde, 1992). The total weight losses in the Kittilä area (ground moraine) are 12.4-15.4 % (see Table 4 and Fig. 34). In the tills of Jerisjärvi (cover moraine) main rock-forming minerals are in the following order: quartz, amphibole, plagioclase and microcline (Table 5 and Figs 36a,b). It seems to be obvious that the amount of a weathered bedrock manner is not as strong as in the tills of Kittilä, because there is a moderate quantity of amphibole present. Also, the rate of weathering of these tills is not as strong as in the tills of Kittilä. Thermogravimetric analyses show that the total weight loss is between 11.6-13.0 % (Fig. 37). Only in the tills of Kittilä total weight loss is greater. Kaolinite is a common clay mineral in the tills of Northern Finland. There is kaolinite in abundance also in the clay fraction of Kaaresuvanto (Pulju moraine) and Pulju (Pulju moraine). Kaolinite was detected by transmission electron micrograph (TEM) from all the study sites, except from the tills of Kuusamo (drumlin), Aavasaksa (ground moraine) and Suomussalmi (Kianta moraine). The origin of kaolinite is from recycling of fines. According to Lintinen (1995) there is a kaolinite present in the silt fraction (< 0,02 mm) of the tills of Kaapinsalmi, Suomussalmi. The bedrock in this site is composed of serpentinite and felsic volcanite. Lintinen concluded that the occurrence of kaolinite does not seem to be related to any specific lithological unit but is a feature typical of the fines of the Kuhmo tills.

In the tills of Southern Inari (Sevetti moraine) there is a fairly high total weight loss as concluded using thermogravimetric analyses (maximum 13,8 %), (Fig. 41). This supports the mineralogical analyses and in this area till consists of high amounts of clay minerals and oxides of iron (goethite and lepidocrocite). According to Koljonen and co-author (1992) in this area exists a lot of weathered bedrock material. Hence, the quantity of kaolinite is fairly low in the till in this area. The reason might be, that weathered bedrock material has not been mixed as strongly in the till matrix as in the area of Kittilä (ground moraine).

5.3.2 Geochemistry

There is a remarkable impoverishment in Si, Na and K in the fine fraction of till of the weathered bedrock area (Table 21). On the other hand these tills have been strongly enriched in Al, Fe and Mg. Also Ti, Mn, Ca and P have been slightly enriched. Zinc, Ni, Co, and Cu have been enriched at a level of two times higher in fine fraction of weathered tills and Pb has the same concentration content.

Table 21. The arithmetic mean, variation and standard deviation of the chemical elements in the fine and the clay fractions of the till in weathered and unweathered bedrock areas in the whole study area.

	unweathered bedrock				weathered bedrock			
	<0,06 mm				<0,06 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	67,43	73,90	41,30	4,28	61,55	69,60	41,60	4,50
TiO2	0,87	1,69	0,07	0,19	1,33	3,05	0,44	0,38
Al2O3	14,25	29,50	8,80	1,66	16,25	29,30	13,10	2,13
Fe2O3	5,66	38,10	2,84	2,32	8,86	31,10	2,95	3,76
MnO	0,08	0,55	0,01	0,04	0,17	2,00	0,03	0,23
MgO	2,07	10,40	0,00	0,99	3,00	8,30	0,70	0,74
CaO	3,43	11,30	1,50	0,98	3,63	6,60	0,03	1,01
Na2O	3,34	6,20	0,80	0,70	2,93	4,50	0,00	0,64
K2O	2,38	3,50	1,09	0,38	1,85	6,63	0,00	0,66
P2O5	0,34	5,98	0,00	0,73	0,18	1,17	0,00	0,14
n	594				219			
	<0,06 mm				<0,06 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	64	744	17	47,8	107	1096	36	89,9
Pb	26	188	0	14,1	26	104	11	11,7
Ni	44	215	13	17,9	86	993	23	74,6
Co	25	113	5	10,5	49	307	15	32,1
Cu	43	310	2	34,7	76	787	10	73,0
n	594				219			
	<0,002 mm				<0,002 mm			
w-%	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
SiO2	50,18	56,53	44,64	2,95	38,99	41,60	35,27	2,04
TiO2	1,08	1,32	0,81	0,13	1,81	2,25	1,45	0,29
Al2O3	19,27	23,07	16,23	1,35	21,58	24,28	19,68	1,58
Fe2O3	11,29	14,75	7,21	1,98	21,32	25,78	16,47	3,18
MnO	0,10	0,16	0,08	0,02	0,17	0,23	0,09	0,05
MgO	5,41	7,96	3,20	1,07	4,45	6,02	3,19	0,86
CaO	1,95	2,89	1,26	0,48	1,08	1,52	0,62	0,25
Na2O	1,94	3,16	1,19	0,51	0,55	0,71	0,39	0,11
K2O	3,68	4,36	2,02	0,52	1,33	2,04	0,94	0,36
P2O5	0,19	0,34	0,11	0,05	0,49	0,76	0,38	0,11
n	38				11			
	<0,002 mm				<0,002 mm			
ppm	mean	max.	min.	standard deviation	mean	max.	min.	standard deviation
Zn	203	1838	77	167,6	200	322	129	43,9
Pb	31	996	4	79,9	12	25	0	6,7
Ni	98	264	50	32,8	141	255	92	46,6
Co	36	84	18	11,0	48	78	22	12,0
Cu	248	1589	50	264,6	181	320	101	53,7
n	197				34			

According to Hiltunen (1981) and Peuraniemi (1989, 1990) trace elements such as Cu, Ni, Co, Zn and Mo have become enriched in the fine fraction of the weathering crust. The contents of trace elements differ greatly in weathered bedrock and till. The dispersion of trace element concentrations are much wider in weathered bedrock material than in till. Salminen (1975) came to the same conclusion that trace element concentrations are higher in weathered bedrock and in tills that make contact with it. Trace element concentrations are increasing in till profile with function of depth (cf., Äyräs 1979, 1982, Äyräs & Koivisto 1984, Peuraniemi 1989). According to Nurmi (1975) trace element content of fine fraction of till corresponds best in the composition of weathered bedrock. Influence of weathered bedrock is also remarkable in fine fraction of tills in Inari (Sevettijärvi and Pyhävaara), (Sevetti moraines) where there are high concentrations of Zn, Ni, Co and Cu (Table 8).

The clay fraction of weathered bedrock area has been depleted strongly not only in Si, Na and K but also in Mg and Ca. Iron, Al, Ti, Mn and P have slightly higher concentrations in the clay fraction of weathered bedrock area. Out of all the trace elements only Ni and Co have been enriched and Zn is almost at the same level as in the samples of clay fraction in unweathered bedrock area. Pb has lower concentrations in the clay fraction of tills in weathered bedrock area.

It is possible to notice that there are some very high concentrations (average and maximum) of trace elements both in the clay and fine fraction of tills in unweathered bedrock area. These exceptional values are due to the samples of Inari (Sevetti moraine). If these samples are taken out of present unweathered bedrock material of clay fraction, the trace element concentration values are following (Table 22):

Table 22. The arithmetic mean, minimum and maximum contents of trace elements in the clay fraction of till in unweathered bedrock areas in the whole study area.

Element	Mean (ppm)	Minimum-maximum (ppm)
Zn	158	124-225
Pb	17	37-247
Ni	96	70-124
Co	35	30- 40
Cu	156	105-200
n= 191		

All trace elements have been enriched in the clay fraction of weathered bedrock samples, except Pb. This also points out the exceptional geochemical character of Inari (Sevetti moraine). In the samples of Kittilä (ground moraine) high concentrations of Zn, Cu, Ni and Co in the fine fraction are probably due to unknown sulphide mineralization or influence of weathering crust material.

5.4 Influence of postglacial weathering on till mineralogy and geochemistry

5.4.1 Mineralogy

On the basis of the present study, the weathering of the primary minerals is clear. Weathering process have been the strongest in the areas of Kittilä (ground moraine) and Jerisjärvi (cover moraine). Both microcline and plagioclase have been weathered and only a very small amount of them are present in the tills of Kittilä and Jerisjärvi. Amphiboles have been weathered almost totally in the tills of Kittilä. Semi-quantitative estimation of the clay mineral content (see Table 5) shows the order of clay minerals as follows: vermiculite, chlorite, illite, swelling-lattice vermiculite, kaolinite and mixed-layer minerals. A great abundance of vermiculite is due to the weathering of Fe-chlorite and trioctahedral mica/illite into mixed-layer clay minerals and into vermiculite. Fe-rich chlorite is present in all the study areas except in the tills of Kittilä (ground moraine), Jerisjärvi (cover moraine), Pulju (Pulju moraine) and Kaaresuvanto (Pulju moraine). This metamorphic chlorite has been weathered into chlorite-vermiculite and vermiculite. Illite is classified as degraded-type (Srodon & Eberl 1984) and it is mainly trioctahedral illite. Dioctahedral type is dominant in the tills of Kittilä (ground moraine) and Jerisjärvi (cover moraine). Biotite has been weathered into trioctahedral illite and vermiculite. Muscovite has been weathered into dioctahedral illite. Also, in the tills of Ylikiiminki (Vepsänselkä, Puutturi (longitudinal moraine ridges) and Korppikangas (end moraine)) dioctahedral illite is the dominant type.

In contradistinction to earlier studies (Soveri & Hyyppä 1966, Räisänen *et al.* 1992, Lintinen 1995) swelling-lattice vermiculite is the common clay mineral in the clay fraction of northern Finnish tills. The grain size of this mineral is very small (less than 1 µm). On the basis of the studies of Righi and co-author 1997, Gillot and co-author 1999 swelling lattice-vermiculite can be a postglacial weathering product of chlorite and trioctahedral illite. Kaolinite is present in great quantities in the tills of Kittilä (ground moraine), Jerisjärvi (cover moraine), Kaaresuvanto (Pulju moraine) and Pulju (Pulju moraine) and it is present also the other study sites, except in the tills of Suomussalmi (Kianta moraine), Kuusamo (drumlin) and Aavasaksa (ground moraine). Kaolinite represents preglacial weathering product.

5.4.2 Geochemistry

Weathering, post – or preglacial has a radical effect on the mineralogy and geochemistry of till. In an oxidizing environment (above groundwater level) labile minerals are generally destroyed and their chemical constituents being carried away in a solution or scavenged by clay-sized phyllosilicates and secondary oxides and hydroxides. Clay minerals play as a scavengers and this is seen in present study material. Trace elements have especially been enriched in the clay fraction of till due to this process (cf., Rencz & Shilts, 1980). Tills rich in clay size fraction are more sensitive to weathering than coarser fractions. Weathering of amphiboles, plagioclase, microcline and mica (biotite and muscovite) produce secondary clay minerals. Further, clay minerals such as chlorite have been weathered into vermiculite, mixed-layer clay minerals and swelling-lattice vermiculite. During this physical and especially chemical weathering, chemical elements have been released from primary minerals and scavenged by clay minerals. This is especially apparent in the distribution of trace element content of clay mineral fraction of the till.

5.5 Influence of moraine type on till mineralogy and geochemistry

The present study material includes different types of moraine formations, which are located in different bedrock areas. The moraine types studied include ground moraine, cover moraine, marginal moraine, longitudinal moraine ridge, Rogen moraine, drumlin, Pulju moraine, Sevetti moraine, hummocky moraine, Kianta moraine, lee-moraine, ablation hummocky moraine, Vika moraine and end moraine. The study area has experienced several glacial cycles. The first of the Pleistocene glaciations met the loose preglacies weathering crust and consequently was responsible for a large proportion of the total erosion and till deposition. Most of the till debris commonly has been transported only a short distance during each glacial cycle. It follows that the younger tills in a sequence may contain larger amounts of reworked debris from the older tills. The matrix mode in particular may include large amounts of reworked material amongst the more or less fresh rock flour. According to the observations of to Hirvas & Nenonen (1987), Nieminen (1985), Perttunen (1977) and Lintinen (1995) redeposition of till fines is evident. The areas studied here suggest that a part of the fines of tills have been redeposited and homogenized during earlier glaciation cycles e.g., tills are multicyclic material.

Often the final granulometric composition of the till and consequently the quantitative proportion of the different minerals are related to the last quarrying or sorting process. Therefore the mineralogical composition is to a certain extent also bound to the respective moraine types. Also, Aario & Peuraniemi (1992) have noticed that tills are poor in clay fraction and enriched with rock forming minerals in the areas of active ice (e.g., drumlins and flutings) and the areas of effective glacifluvial processes (e.g., eskers). On the contrary to the former, tills are enriched with clay minerals (e.g., vermiculite, illite, chlorite ect.) and deducted by rock forming minerals in the areas of passive ice process. The experienced cycles of glacial erosion, entrainment, transportation and deposition further contribute to the total amount of the clay fraction and consequently the clay minerals.

It should also be considered that often certain minerals are bound to certain terminal grain size modes (e.g., Dreimanis & Vagners 1971). The present study concentrates on terminal grades and represents the most diluted multicyclic material. So clay fraction is also regionally most homogeneous. The granulometric maturity of the coarser grain sizes is not so high throughout. The coarser fractions also show higher variability regionally, which is partially also related to the last glacial process. The present data consequently suggest that the mineralogical composition of the coarser grain sizes can be more bound to the respective last glacial landform assemblages. Mineralogy and geochemistry of clay-poor moraine types (e.g., Sevetti moraine, cover moraine, Vika moraine) represent very local material and also reflect the composition of local bedrock. Clay-rich moraine types (e.g., ground moraine, Pulju moraine, drumlin, lee-moraine) represent mineralogically and geochemically often long-distance, multicyclic material.

6 Discussion and conclusions

The clay fraction of the till in Northern Finland is dominantly composed of clay minerals. Generally, clay minerals occur in the following order: vermiculite, chlorite, illite, swelling-lattice vermiculite, kaolinite and mixed-layer clay minerals. Mixed-layer clay minerals are mixtures of vermiculite, chlorite, illite and swelling-lattice vermiculite. Rock-forming minerals play a minor role and they are quartz, plagioclase, microcline and amphibole. In the fine fraction of the till the situation is the opposite and rock-forming minerals are the main components. Geochemical results support this matter and one can see that the geochemistry of the till reflects the mineralogical composition of both fractions. Especially, differences in the contents of Si, Ca and Na between clay fraction and fine fraction are mainly due to the amount of rock-forming minerals. Trace metals, Al, Fe, K and Na contents are higher in the clay fraction than in the fine fraction. Some clay fractions contain high Fe and Mn contents, which are caused mainly by secondary oxides of Fe and Mn.

In the clay fraction of till the contents of quartz, plagioclase, microcline and amphibole are higher in the granitic and Archaean gneiss areas than in the Greenstone Belt, Svecokarelian schists and gneiss and Granulite areas. Amphibole, microcline and plagioclase occur in very low amounts or are totally destroyed by chemical weathering in the clay fraction of till in the Kittilä area (ground moraine). Here, the influence of preglacial weathering crust is obvious. Also a high content of kaolinite is present. A moderate amount of kaolinite occurs also in the clay fraction of Kaaresuvanto (Pulju moraine), Jerisjärvi (cover moraine), Pulju (Pulju moraine) and Inari (Sevetti moraine). The material from preglacial weathering crust is mixed into the clay fraction matter. A small amount of kaolinite is also common in the tills of Kuivaniemi (cover moraine), Kemijärvi (Rogen, longitudinal moraine ridge, hummocy, lee and Vika moraines) and Ylikiiminki (longitudinal moraine ridge, end moraine and marginal moraine). Further evidence of the influence of preglacial weathering crust is that illite is of dioctahedral type in the clay fraction of tills in Kittilä (ground moraine) and Jerisjärvi (cover moraine). In all the other study areas illite is mainly of trioctahedral type. Both at Kittilä and Jerisjärvi the reason for this could be that the biotite in these areas has been predominantly altered into vermiculite and not illite during long-continued chemical weathering in preglacial time. Muscovite rather has been altered to illite (Peuraniemi *et al*. 1996, 1997). According to

Hyyppä (1983) in the preglacial weathering crust of area of Kittilä, Lonnakko, illite is present as dioctahedral type. In the preglacial weathering crust of Sodankylä dioctahedral illite has been found (Islam 1996). According to Soveri and Hyyppä (1966), the tills in the granitic bedrock areas contain less illite than the tills in the areas of other bedrock types. The predominance of illite in the Kemijärvi granite area (Rogen, longitudinal moraine ridge, hummocky, lee, and Vika moraines) is contradictory to this observation. Chlorite is altered in the weathering process into vermiculite and swelling-lattice vermiculite in these tills. This might explain why chlorite does not occur at all in the clay fraction of Kittilä, Kaaresuvanto, Jerisjärvi and Pulju.

The total amounts of secondary clay minerals and Fe-oxides were estimated from weight loss in thermogravimetric analyses. The quantities of the secondary clay mineral phases are higher in the tills of Kittilä (ground moraine), Jerisjärvi (cover moraine) and Inari (Sevetti moraine). The tills of granitic, Archaean gneiss, Svecokarelian schists and gneiss areas contain secondary phases less than the tills of the mafic volcanite (Greenstone Belt) areas (Kittilä and Jerisjärvi). The mineral composition of fine and clay fractions of the tills in Northern Inari (Sevetti moraine) suggests that there occur more mafic volcanites areas than is known today (cf., Koljonen *et al.* 1992). The fine fraction of the tills correlates quite well with the underlying bedrock in all study areas. The most abundant minerals in this fraction are rock-forming minerals and clay minerals that are playing a minor role. In the bedrock areas of Svecokarelian schist and gneiss (Ylikiiminki) and Granitoid (Kemijärvi and Aavasaksa) both fraction corresponds fairly well with local bedrock composition. In the fine fraction of the Greenstone Belt (Kittilä), Archaean gneiss (Northern Inari) and Granulite (Southern Inari) areas, the influence of preglacial weathering crust is clearly seen. The effect of local bedrock to the mineralogy of the till is obviously depending on the grain-size distribution of the till. A clay fraction is more homogeneous, weathered and far-travelled and fine fraction is more local, immature material. That is why fine fraction of the till corresponds better with the composition of local bedrock.

Geochemical results of present study material have been compared with the results of regional geochemical mapping of fine fraction of the till in Finland (Koljonen *et al.* 1992). Present material points out that the distribution of chemical elements in the clay fraction of till does not correlate with the composition of the underlying bedrock. Generally, the clay fraction of till is depleted in Si, Ca and Na and enriched in Al, Fe, Mg, K and trace elements. The lowest contents of Si, Na, Ca and K are in the clay fraction of the till in area of the Greenstone Belt (Kittilä, Jerisjärvi). In the granitoid area (Kemijärvi) Si, Na and Ca concentrations are highest. In Svecokarelian gneiss and schist areas concentration values of these elements are between the values of the Greenstone Belt and Granitoid areas. Also the influence of weathered bedrock is clearly seen in the clay fraction of Kittilä (ground moraine) and Northern Inari (Sevetti moraine) (see below). The geochemical distribution of elements in the clay fraction of the till point out that in the tills of Greenstone Belt areas Si, Na, Ca and K content are lower than in the tills of Granitoid, Archaean gneiss and Svecokarelian gneiss and schist areas. Likewise, the contents of Al, Fe Ti and P are higher in the tills of Greenstone Belt areas than in the tills of Granitoid, Archaean gneiss and Svecokarelian gneiss and schist areas. With a few exceptions, the concentration of elements of the fine fraction of the till corresponds with the underlying bedrock and with data presented by Koljonen and co-author (1992). Elemental composition of till in Kaaresuvanto (Pulju moraine) and Northern Inari (Sevetti moraine) does not correlate with the Archaean bedrock underneath. In reverse, the distribution of elements corresponds much more with the distribution of the geochemical province of Greenstone Belts (Kittilä, Jerisjärvi). Distribution of chemical elements points out quite clearly the effect of the Greenstone Belt of Kiiruna in the area of till Kaaresuvanto. Likewise, in Northern Inari, the results provide an indication that there are probably more mafic volcanites and sulphide mineralizations in the same area than is known at the present time. In the fine fraction of till at Inari (Sevetti moraine) there are exceptionally high concentrations of Fe, Al, Zn and Cu and low concentrations of Si. Also, in the fine fraction of till at Kaaresuvanto (Pulju moraine) there are high Mg and Ca concentrations, which are not typical for the tills of an Archaean gneiss area. In the fine fraction of till at Kittilä (ground moraine) there are high concentrations of Zn, Cu, Ni and Co. They are probably due to unknown sulphide mineralizations. These metals have quite low concentrations in the clay fraction of till and it is unlikely that they are originally coming from weathering crust material. These concentrations point out the special geochemical character of Kittilä, Inari and Kaaresuvanto.

In central Finnish Lapland the bedrock is covered by continuous or semi-continuous ancient weathering crust. Influence of preglacial weathering crust is especially detectable in the area of a former ice divide zone. Mineralogy of weathering crust differs from till mineralogy (e.g.,, kaolinite, halloysite, smectite ect.). Kaolinite is the key mineral in this case. It occurs in all study sites except in Suomussalmi (Kianta moraine), Aavasaksa (ground moraine) and Kuusamo (drumlin). Lintinen (1995) however, has detected kaolinite from the fine fraction of the till of Suomussalmi. Overall, the amount of kaolinite is not great, but detectable and its origin is via recycling of weathered bedrock material into till matter. In the tills of Kittilä (ground moraine), which is located in the ice divide zone, mineralogy and geochemistry of the till is strongly influenced by weathering crust material. Most common minerals are dioctahedral illite, vermiculite, kaolinite and swelling-lattice vermiculite. There are also oxides of Fe (goethite and lepidocrocite) present. Plagioclase, microcline and amphibole occur in very low quantities or are totally destroyed by chemical weathering in the clay fraction of the till. In the clay fraction of the till in Kittilä illite is present only in dioctahedral type. The reason for this can be that during long-continued chemical weathering muscovite has been altered to illite and biotite has been altered into vermiculite. Vermiculite and swelling-lattice vermiculite are present in moderate amounts. In the same kind of process chlorite has been altered into mixed-layer clay minerals (chlorite/vermiculite/illite), vermiculite and swelling-lattice vermiculite. The mineralogy of the tills of Jerisjärvi (cover moraine), Kaaresuvanto (Pulju moraine), Pulju (Pulju moraine) and Inari (Sevetti moraine) resembles strongly the till mineralogy of Kittilä (ground moraine). Chlorite is not present in the clay fraction of Kittilä, Kaaresuvanto, Jerisjärvi and Pulju. Geochemical analyses support mineralogical results. In the clay and fine fraction of till in weathered bedrock area both fractions have been impoverished of Si, Na, and K when comparing to tills of unweathered bedrock areas. Both fractions are enriched with Al, Fe and trace elements (especially Ni, Co, Cu). This is due to weathering of the plagioclase, microcline and amphibole and also enrichment of secondary clay minerals. Hiltunen (1981) and Peuraniemi (1989, 1990) found that trace elements (Cu, Ni, Co, Zn and Mo) have a tendency to be enriched in tills containing weathered bedrock material. A good example of the former is the Inari area, where both fine and clay fractions are enriched with remarkable concentrations of Zn, Ni, Co and Cu. This points out that in this area there exists a lot of weathered bedrock material and possibly weathered sulphide minerals (also Koljonen *et al*. 1992, Peuraniemi *et al*. 1996).

Postglacial weathering of minerals is a combination of mechanical crushing and chemical weathering. The rate of postglacial weathering depends also on the clay fraction content of till and mineral alterations over time. The present study material points out that the possible products of postglacial weathering might be mixed-layer clay minerals, vermiculite and swelling-lattice vermiculite. These minerals can be detected from surface samples to bottom samples (samples above groundwater level) of the clay fraction of the till in present study areas. According to Righi and co-author (1997) and Gillot and co-author (1999) smectites (beidellite) and illite-smectite are common in the E horizons of podzol (classification, INRA 1992) older than 6500 years. The number of mixed-layers decreases with the evolution of the soil, leaving a nearly pure smectite phase in the oldest soil. The present study does not confirm the presence of smectite originated by postglacial weathering in the clay fraction of the till, but the conclusion with diminishing of mixed-layers was confirmed. Mixed-layer clay minerals are composed of chlorite, illite, vermiculite and swelling-lattice vermiculite. The presence of mixed-layer minerals and swelling-lattice vermiculite play a key role in estimating the rate of possible postglacial weathering of the minerals. In the clay fraction of tills in Inari (Sevetti moraine), Ylikiiminki (longitudinal moraine ridge, end moraine, marginal moraine), Kemijärvi (Rogen, longitudinal, hummocky, lee, and Vika moraines) and Kuusamo (drumlin) mixed-layer clay minerals are more common than swelling-lattice vermiculite and in the other study areas swelling-lattice vermiculite is more common than mixed-layer clay minerals. In these areas tills are mainly poor in clay size fraction. On the other hand in the tills rich in clay size fraction (Kittilä (ground moraine), Kaaresuvanto, Pulju (Pulju moraines), Aavasaksa (ground moraine), Jerisjärvi (cover moraine), Suomussalmi (Kianta moraine) and Kuivaniemi (cover moraine)) swelling-lattice vermiculite is a common clay mineral besides vermiculite and chlorite/kaolinite. Biotite has been destroyed almost totally alterating into trioctahedral illite, illite-vermiculite mixed-layer clay minerals, vermiculite and swelling-lattice vermiculite. Also, chlorite has disappeared during the same weathering process. One can conclude that the possible postglacial weathering cycle might be as follows:

> Trioctahedral mica (biotite)+chlorite -->mixed-layer clay minerals of trioctahedral illite/chlorite/vermiculite --> vermiculite --> swelling-lattice vermiculite

Firstly, the clay fraction content of the till is one of the basic elements that effects to the rate of the postglacial weathering of tills. This is due to the fact that surface area of these clay-rich tills is much greater and more material is available to chemical weathering process. Secondly, the original composition of the till affects to the mineral composition produced by weathering. Thirdly, the more mature and older the till is, the greater amount of swelling-lattice vermiculite it has in its clay fraction. Weathering, post - or preglacial has a radical effect on mineralogy and geochemistry of till. In an oxidizing environment (above groundwater level) labile minerals are generally destroyed and their chemical constituents being carried away in a solution or scavenged by clay-sized phyllosilicates and secondary oxides and hydroxides (cf., Rencz & Shilts, 1980). Clay minerals act as scavengers and this is seen in the present study material. Trace elements especially have been enriched in the clay fraction of the till due to this process.

Influence of moraine type on till mineralogy and geochemistry depends on several factors, e.g., former ice dynamics, hydrology, hydrography, bedrock, presence of weathering crust, the regional distribution and recycling of fine-rich material. The study area has experienced several glacial cycles. According to Hirvas and Nenonen (1987), Nieminen (1985), Perttunen (1977) and Lintinen (1995) redeposition of till fines is evident. The results of this study suggest that a part of the fines of tills have been redeposited and homogenized during earlier glaciation cycles. The experienced cycles of glacial erosion, entrainment, transportation and deposition further contribute to the total amount of the clay fraction and consequently the clay minerals. Most of the till debris commonly has been transported only a short distance during each glacial cycle. It follows that the younger tills in a sequence may contain larger amounts of reworked debris from the older tills. The matrix mode in particular may include large amounts of reworked material amongst the more or less fresh rock flour. Mineralogy and geochemistry of clay-poor moraine types (e.g., Sevetti moraine, cover moraine, Vika-moraine) represent very local material and also reflect the composition of local bedrock. Clay-rich moraine types (e.g., ground moraine, Pulju moraine, Drumlin, lee-moraine) represent mineralogically and geochemically often long-distance, multicyclic material.

Often the final granulometric composition of the till and consequently the quantitative proportion of the different minerals are related to the last quarrying or sorting process. Therefore the mineralogical composition is to a certain extent also bound to the respective moraine types. One should, however, remember that when erosional landforms are concerned, the inner composition and surficial expression of the landforms are not genetically concordant. It should also be considered that often certain minerals are bound to certain terminal grain size modes (e.g., Dreimanis & Vagners 1971). The present study has been focused mainly on clay fraction, which consists entirely of terminal grades and represents the most diluted multicyclic material. So clay fraction is also regionally most homogeneous. The granulometric maturity of the coarser grain sizes is not so high throughout. The coarser fractions also show higher variability regionally, which is partially also related to the last glacial processes. The present data consequently suggest that the mineralogical composition of the coarser grain sizes (for example fine fraction) can be more bound to the respective last glacial landform assemblages.

7 Summary

The mineralogy and geochemistry of the clay and fine fractions of till in Northern Finland were studied. The study material included different moraine types as ground moraine, cover moraine, Rogen moraine, Pulju moraine, Sevetti moraine, Kianta moraine, drumlin, lee-moraine, Vika moraine, ablation hummocky moraine, hummocky moraine, marginal moraine, longitudinal moraine ridge and end moraine. These formations were situated in bedrock of different composition including Archaean gneiss, Proterozoic Schists, Granite, Granulite and Greenstone areas.

The clay fraction of the till is composed dominantly of clay minerals. Generally, clay minerals are present in the following order: vermiculite, chlorite, illite, swelling-lattice vermiculite, kaolinite and mixed-layer clay minerals. Mixed-layer clay minerals are mixtures of vermiculite, chlorite, illite and swelling-lattice vermiculite. Swelling-lattice vermiculite and kaolinite are common clay minerals in the clay fraction of the till in Northern Finland. Kaolinite is evidence of the mixing of the weathered bedrock material into the till matrix. Further evidence of the influence of weathered bedrock is the presence of dioctahedral illite, which is common in the clay fraction of the tills in Kittilä (ground moraine) and Jerisjärvi (cover moraine). An absence of chlorite in the clay fraction of Kittilä (ground moraine), Jerisjärvi (cover moraine), Kaaresuvanto (Pulju moraine) and Pulju (Pulju moraine) is one piece of evidence. Likewise, the presence of kaolinite in abundance is typical in these tills. Rock-forming minerals play a minor role in the clay fraction of the till and they are quartz, plagioclase, microcline and amphibole. In the fine fraction of the till the situation is the opposite and rock-forming minerals are the main components. Geochemical results support the mineralogical composition of both fractions. Differences in the content of Si, Ca and Na between clay fraction and fine fraction are mainly due to the distribution of rock-forming minerals and clay minerals. In the fine fraction of the till Si, Ca and Na contents are higher than in the clay fraction and the clay fraction is enriched in Al, Fe, Mg, K and trace elements. Trace metal contents increase when the grain size diminishes e.g., they are higher in the clay fraction than in the fine fraction of the till. There are some clay fraction samples (Kittilä (ground moraine), Kuivaniemi (cover moraine)), which have high Fe and Mn content. This phenomenon is probably due to the existence of secondary oxides of Fe and Mn.

In the clay fraction of till the contents of quartz, plagioclase, microcline and amphibole are higher in the granitic and Archaean gneiss areas than in the Greenstone Belt, Svecokarelian schists and gneiss and Granulite areas. Amphibole, microcline and plagioclase occur in very low amounts or are totally destroyed by chemical weathering in the clay fraction of the till in the Kittilä area (ground moraine). The till of Granitic, Archaean gneiss, Svecokarelian schists and gneiss areas contains secondary mineral phases less than tills of the Greenstone Belt (Kittilä, Jerisjärvi and Pulju) and the areas of local preglacial weathering crust (e.g., Kittilä, Jerisjärvi and Inari). The mineral composition of fine and clay fractions in the tills of Northern Inari (Sevetti moraine) corresponds to the assumptions that there occur greater amounts of mafic volcanites than modern knowledge is aware. The fine fraction of the tills correlates quite well with the underlying bedrock in all study areas. The influence of the local bedrock upon the till material is most clearly shown in the coarser fractions of the till.

Geochemical results of the present study material have been compared to the results of geochemical mapping of fine fraction of the till in Finland (Koljonen *et al.* 1992). The present material points out that the distribution of chemical elements in the clay fraction of the till does not correlate with the composition of the underlying bedrock. With a few exceptions, the concentrations of elements of the fine fraction of the till correspond with the underlying bedrock. The elemental composition in Kaaresuvanto (Pulju moraine) and Inari (Sevetti moraine) does not correspond with the geochemical composition of the underlying bedrock. Distribution of chemical elements points out quite clearly the effect of the Greenstone Belt of Kiiruna, Sweden, in the case of Kaaresuvanto. In Northern Inari results provide an indication that there occur more mafic volcanites and sulphide mineralizations in the same area than is known at the present time. In the fine fraction of till in Kittilä (ground moraine) there are high concentrations of Zn, Cu, Ni and Co. They are probably due to unknown sulphide mineralization. These concentrations point out the special geochemical character of Kittilä, Inari and Kaaresuvanto.

The present study points out that the possible products of postglacial weathering might be mixed-layer clay minerals, vermiculite and swelling-lattice vermiculite. These minerals can be detected from surface samples to bottom samples (samples above groundwater level) of the clay fraction of the till in present study areas. The present study does not confirm the presence of smectite originated by postglacial weathering in the clay fraction of the till. The rate of postglacial weathering of minerals is depending on 1) clay fraction content of the till, 2) original composition of the till, 3) the maturity and the age of the till and 4) drying and wetting of the till. The present study suggests that the possible postglacial weathering cycle might be as follows: Trioctahedral mica (biotite)+chlorite -->mixed-layer clay minerals of trioctahedral illite/chlorite/vermiculite --> vermiculite --> swelling-lattice vermiculite.

The present study has been focused mainly on clay fraction, which consists entirely of terminal grades and represents the most diluted multicyclic material. So clay fraction is also regionally most homogeneous. The granulometric maturity of the coarser grain sizes is not so high throughout. The coarser fractions also show higher variability regionally, which is partially also related to the last glacial processes. The present data consequently suggests that the mineralogical composition of the coarser grain sizes can be more bound to the respective last glacial landform assemblages.

References

Aario R (1977a) Classification and terminology of morianic landforms in Finland. Boreas 6: 87–100.

Aario R (1977b) Associations of fluitings, drumlins, hummocks and transverse ridges. Geojournal 1.6., 65–72.

Aario R (1981) Pohjois-Pohjanmaan ja Koillismaan pintamoreeneista. In: Lindroos P (ed) Pintamoreenien merkitys malmilohkarekuljetuksessa. Geologinen tutkimuslaitos, tutkimusraportti 55: 15–23.

Aario R (1984) The origin and properties of morianic landforms in northern Finland, with special reference to their potential range of use. Määräaikainen loppuraportti Suomen Akatemian tutkimusprojektista, 04-114. Oulu (in Finnish).

Aario R (1987) Drumlins of Kuusamo and Rogen-ridges of Ranua northeast Finland. In: Menzies J and Rose J (eds) Drumlin symposium. A.A. Balkema, Rotterdam, 87–101.

Aario R (1990) Glacial Heritage of Northern Finland. Excursion Guide. 3rd International Drumlin Symposium. Oulu Nordia A 1: 96.

Aario R (1990a) Morainic landforms in northern Finland. In: Aario R (ed) Glacial Heritage of Northern Finland. Excursion Guide. 3rd International Drumlin Symposium. Oulu Nordia A 1: 13–27.

Aario R (1990b) The northern ice flow area. In: Aario R (ed) Glacial Heritage of Northern Finland. Excursion Guide. 3rd International Drumlin Symposium. Oulu Nordia A 1: 57–61.

Aario R (1992) Pulju moraines and Sevetti moraines. Sveriges Geologiska Undersökning Ser. Ca 81: 7–14.

Aario R (1994) Lapin omaleimaiset moreenimuodostumat Puljumoreeni ja Sevettimoreeni (Pulju moraine and Sevetti moraine). Terra 106. 3: 258–266.

Aario R, Forsström L & Lahermo P (1974) Glacial landforms with special reference to drumlins and fluting in Koillismaa Finland. Geological Survey of Finland, Bulletin 273: 1–30.

Aario R & Forsström L (1978b) Koillismaan ja Pohjois-Kainuun deglasiaatiostratigrafia. Geologi 30: 45–52.

Aario R & Forsström L (1979) Glacial stratigraphy of Koillismaa and North Kainuu Finland. Fennia 157: 1–49.

Aario R, Pääkkönen K & Saarenketo T (1985) INQUA Commission on genesis and lithology of Quaternary deposits. Program and Abstracts. Symposium of work group 9. Oulanka August 24-25, 1985.

Aario R & Peuraniemi V (1992) Glacial dispersal of till constituents in morainic landforms of different types. Geomorphology 6: 9–25.

Aartolahti T (1974) Ring ridge hummocky moraines in northern Finland. Fennia 134: 1–21.

Afanasev AP & Evzerov VYa (1981) Sources of the material of glacial deposits of the eastern part of the Baltic Shield. In: Gorbunov, G.I. (ed) Glacial deposits and glacial history in eastern Fennoskandia. Kola Branch of the USSR Academy of Scienses. 55-62.

Ambros M (1980) Beskrivning till berggrundskartorna Lannavaara NV NO SV SO och Karesuando SV SO. Berggrundsgeologiska och geofysiska kartblad skala 1:50 000. Sveriges Geolokiska Undersökning Serie Af, 25–30.

Barshad I (1965) Thermal analysis techniques for mineral identification and mineralogical composition. In: Black CA, Evans DD, Ensminger LE, White LJ & Clark FE (eds) Methods of soil analysis. Part 1. 9: 699–742.

Bhattacharya N (1962) Weathering of glacial tills in Indiana. I. Clay minerals. Bull Geol Soc America 73: 1007–1020.

Björnbom S (1979) Clayey basal till in central and northern Sweden. Sveriges Geologiska Undersökning Årsbok 72 (15), 62 p.

Borchardt G (1989) Smectites. In: Dixon JB & Weed SB (eds) Minerals in Soil Environments. Soil Sci. Soc. Amer. Madison, Wisconsin, USA, 675–727.

Bradley WF & Grim RE (1961) Mica clay minerals. In: Brown G (ed) The X-ray identification and crystal structures of clay minerals. Mineralogical Society. London, 208–241.

Brenner T (1944) Finlands åsars vittnesbörd om ytgestaltningen hos landisen. Fennia 68:1–39.

Brindley GW (1966) Ethylene glycol and glyserol complexes of smectites and vermiculites. Clay minerals 6: 237–260.

Brindley GW & Brown G (1980) Crystal structures of clay minerals and their X-ray identification. Mineralogical Society Monograph 5: 495.

Brown G (1961) The X-ray identification and crystal structures of clay minerals. Mineralogical Society. London. 544 p.

Byström-Brusewitz AM (1975) A vermiculite clay from Junosuando Pajala county northern Sweden. Geologiska Föreningens i Stockholm Förhändlingar. 97: 286–289.

Bölviken B, Bergström J, Björklund A, Kontio M, Lehmuspelto P, Lindholm T, Magnusson J, Ottesen RT, Steenfelt A & Volden T (1986) Geochemical Atlas of Northern Fennoscandis. Scale 1:4 000 000. Mapped by the Geological Survey of Finland Norwey and Sweden in co-operation with Swedish Geological Co and the Geological Survey of Greenland, Uppsala-Espoo-Trondheim.

Chamley H (1989) Clay sedimentology. Springer-Verlag Berlin, Heidelberg, New York. 621 p.

DiLabio RNW (1989) Terrain geochemistry in Canada. In: Fulton RJ (ed) Quaternary geology of Canada and Greenland. Geogical Survey of Canada 1.

DiLabio RNW & Shilts WW (1977) Detailed drift prospecting in the southern district of Keewatin. Pap Geol Surv Can, 77–1 A: 479–483.

DiLabio RNW & Shilts WW (1979) Composition and dispersal of debris by modern glaciers Bylott Island Canada. In: Schluchter Ch (ed) Moraines and Varves. AA Balkema, Rotterdam, 145–155.

Dreimanis A & Vagners UJ (1965) Till-bedrock lithologic relationship. VII Int. Congr. INQUA. Boulder & Denver, 110–111.

Dreimanis A & Vagners UJ (1969) Lithologic relation of till to bedrock. In: Wright Jr HE (ed) Quaternary Geology and Climate. National academy of Sciences. Washington DC, 93–98.

Dreimanis A & Vagners UJ (1971a) Bimodal distribution of rock and mineral fragments in basal tills. In: Goldwait, R.P. (ed). Till, a Symposium, Ohio State University Press, 237-250.

Dreimanis A & Vagners UJ (1971b) The dependence of the composition of till upon the rule of bimodal distribution. VIII Int. Congr. INQUA Paris 1969. Etudes sur le Quaterneire dans le Monde 2: 787–789.

Dreimanis A & Vagners UJ (1972) The effect of lithology upon texture of till. In: Yatsu E & Falconer A (eds) Research Methods of Pleistocene Geomorphology, England, GeoAbstract Ltd, 66–82.

Droste JB (1956) Alteration of clay minerals by weathering in Wisconsin till. Geol Soc Amer Bull 67: 911–918.

Droste JB & Tharin JC (1958) Alteration of clay minerals in Illinoian till by weathering. Geol Soc Amer Bull 69: 61–68.

Eronen M (1974) A history of the Litorina Sea and associated Holocene events. Societas Scientiarium Fennica Commentationes Physico-Matematicae 44 1: 79–195.

Eronen M (1983) Late Weichselian and Holocene shore displacement in Finland. In: Smith DE & Dawson AG (eds) Shorelines and isostasy. Academic Press, 183–207.

Eronen M (1987) Global sea-level changes, crustal movements and Quaternary shorelines in Fennoscandia. Geological Survey of Finland, Special Paper 2:31–36

Eronen M & Haila H (1981) The highest shore-line of the Baltic in Finland. Striae 14: 157–158.

Flint R (1955) Pleistocene geology of eastern Shout Dakota. U.S. Geol. Survey Prof. Paper 262: 1–173.

Fricks CME (1906) On the occurrence of gold in Finnish Lapland. Bull. Comm. géol. Finlande 17: 35.

Gillot F, Righi D & Räisänen ML (1999) Formation of smectites and their alteration in two chronosequences of Podzols in Finland. In: Kodama H, Mermut AR & Torrance JK (eds) Clay for our future. 11th Clay conference 1997. Ottawa, Canada: ICC97 Organizing Committee, 725–731.

Gjems O (1960) Some notes on clay minerals in podzol profiles in Fennoscandia. Clay Miner Bull 4: 208–211.

Gjems O (1963) A swelling dioctahedral clay mineral of vermiculite-smectite type in the weathering horizon of podzols. Clay Miner Bull 5: 183–193.

Gjems O (1967) Studies on clay minerals and clay-mineral formation in soil profiles in Scandinavia. Medd. fra Det Norske Skogforsöksvesen 81: XXI Hf 4.

Grim RE (1968) Clay Mineralogy. Second edition, New York. 596 p.

Grim RE & Johns WmD (1955) Clay mineral investigation of sediments in the Northern Gulf of Mexico. Clays and clay minerals National Academy of sciences. National Research Council Publication 327: 81.

Graff-Petersen P (1961) Lermineralogien i de limniske jurasedimenter på Bornholm. Diss. Copenhagen 1961.

Hackman V (1910) Suomen geologinen yleiskartta. Lehti C6 Rovaniemi. Geologinen toimisto.

Hackman V (1918) Suomen geologinen yleiskartta.Vuorilajikartan selitys Lehdet C6 Rovaniemi B5, Tornio ja B6 Ylitornio, Geologinen toimisto.

Haldorsen S (1983) Mineralogy and geochemistry of basal till and its relationship to till-forming processes. Norsk Geologisk Tidsskrift 63: 15–25.

Heikkinen O & Tikkanen M (1979) Glacial flutings in northern Finnish Lapland. Fennia 157: 1–12.

Hiltunen A (1982) The Precambrian geology and scarn iron ores of the Rautuvaara area northern Finland. Geological Survey of Finland, Bulletin 318: 1–133.

Hirvas H (1991) Pleistocene stratigraphy of Finnish Lapland. Geological Survey of Finland, Bulletin 354: 123.

Hirvas H, Alfthan A, Pulkkinen E, Puranen R & Tynni R (1977) Raportti malminetsintää palvelevasta maaperätutkimuksesta Pohjois-Suomessa vuosina 1972–1976. Summary: A report on glacial drift investigations for ore prospecting in northern Finland 1972–1976. Geological Survey of Finland. Report of Investigation 19: 54.

Hirvas H & Nenonen K (1987) The till stratigraphy of Finland. Geol Surv Finland, Special Paper 3: 49–63.

Honkamo M (1984) Kallioperäkartta Pre-Quaternary rocks. Lehti Sheet 3511 Kiiminki. Suomen geologinen kartta 1:100 000. Geol Surv Finland.

Honkamo M (1986) Kallioperäkartta Pre-Quaternary rocks. Lehti Sheet 2533 Haukipudas. Suomen geologinen kartta 1:100 000. Geol Surv Finland.

Honkamo M (1988) Haukiputaan ja Kiimingin kartta-alueiden kallioperä. Kallioperäkarttojen selitykset. Lehdet 2533 ja 3511. Suomen geologinen kartta 1:100 000. Geo. Surv Finland.

Honkamo M (1989) Pohjois-Pohjanmaan vulkaniitit. Lapin vulkaniittiprojektin raportti. Summary: Volcanic rocks in northern Ostrobothnia. A report of the Lapland Volcanite Project. Geol Surv Finland, Tutkimusraportti – Rep Invest 89: 46.

Hoppe G (1952) Hummocky moraine regions with special reference to the interior of Norrbotten. Geogr. Ann. 34:1–72.

Hyvärinen H (1973) The deglaciation history of eastern Fennoscandia – recent data from Finland. Boreas 2:85–102.

Hyyppä J (1977) Kaoliinia Sodankylän Siuruanmaalla. Geologi 29, 4–5: 52–56.

Hyyppä J (1983) Suomen kallioperän preglasiaalisista rapaumista. Summary: Preglacial weathering of Precambrian rocks in Finland. Papers of the Engineering-Geological Sociaty of Finland 15 II: 1–18.

Ignatius H, Korpela K & Kujansuu R (1980) The deglaciation of Finland after 10 000 B.P. Boreas 9: 217–228.

Ihalainen P (1994) Moreenin fysikaalisten ominaisuuksien tutkimusmenetelmiä esimerkkejä Pohjois-Lapin alueelta. Summary: Methods applied in determining some physical properties of glacial tills examples from northern Fennoscandia. Acta Univ Oul A 251: 24–35.

INRA (1992) Référentiel Pédologique – Principaux sols d'Europe. INRA éditions, Paris.

Islam MR (1996) The ancient weathering crust in finnish Lapland and the recent weathring crust in Bangladesh. Acta Univ Oul A 285: 129.

Johansson P & Nenonen J (1991) Till stratigraphical studies in the Pulju area in northern Finland. Geological Survey of Finland, Special Paper 12:131–134.

Jörgensen P (1965) Mineralogical composition and weathering of some late Pleistocene marine clays from the Kongsvinger area Southern Norway. Geologiska Föreningens i Stockholm Förhändlingar 87: 62–83.

Kallio M (1980) Keski-Lapin liuskealue Itä-Kittilän ja Länsi-Sodankylän osalta. Osa II: Rakenne ja stratigrafia. Kuhmon ja Kittilän malmiprojekti raportti 29. Oulun yliopisto, 67 p.

Kallio M, Kärkkäinen N & Sarapää O (1980) Keski-Lapin liuskealue Itä-Kittilän ja Länsi-Sodankylän osalta. Osa I: Kuhmon ja Kittilän malmiprojekti raportti 28. Oulun yliopisto, 88 p.

Kapoor BS (1972) Weathering of micaeous clays in some Norwegian podzols. Clay Minerals 9: 383–394.

Kauranne LK, Salminen R & Äyräs M (1977) Problems of geochemical contrast in finnish soils. In: Prospecting in areas of glaciated terrain 1977. Inst. of Mining and Metallurgy. London. 34–44.

Kettles MI & Shilts WW (1989) Geochemistry of drift over the Precambrian Grenville Province southeastern Ontario and southwestern Quebec. In: DiLabio RNW & Coker WB (eds) Drift Prospecting. Geological Survey of Canada Paper 89–20: 97–112.

Klassen RA & Shilts WW (1977) Glacial dispersal of uranium in the district of Keewatin Canada. In: Jones JM (ed) Prospecting in Areas of Glaciated Terrain. Inst. of Mining and Metallurgy, London. 80–88.

Kodama H (1979) Clay minerals in Canadian soils: their origin distribution and alternation. Canadian Journal of Soil Science 59: 37–58.

Kodama H & Brydon JE (1968) A study of clay minerals in podzol soils in New Brunswick eastern Canada. Clay Minerals 7: 295–309.

Koljonen T, Elo S, Gustavsson N, Huhma H, Kauranne LK, Noras P, Pesonen LJ, Ruotoisenmäki T, Saltikoff B, Sillanpää M, Tanskanen H, Vaasjoki M & Vuorela P (1992) Suomen Geokemian Atlas osa 2: Moreeni. The Geochemical Atlas of Finland Part 2: Till. Koljonen T (ed). Geologian tutkimuskeskus Geological Survey of Finland, Espoo, 218 p.

Korja T, Tuisku P, Pernu T & Karhu J (1996) Field petrophysical and carbon isotope studies on the Lapland Granulite Belt: implications for deep continental crust. Terra Nova, Terra Research 8: 48–58.

Kujansuu R (1967) On the deglaciation of western Finnish Lapland. Bull. Comm. géol. Finlande 232: 98.

Kujansuu R (1972) On landslides in Finnish Lapland. Geological Survey of Finland, Bulletin 256: 22.

Kärki A (1995) Palaeoproterozoic Shear Tectonics in the Central Fennoscandian Shield Finland. Res Terrae Ser. A 10: 37.

Lagerbäck R (1988) The Veiki moraines in northern Sweden – widespread evidence of an Early Weichselian deglaciatin. Boreas 17: 469–486.

Lehtonen M, Manninen T, Rastas P, Väänänen J, Roos SI ja Pelkonen R (1985) Keski-Lapin geologisen kartan selitys. Summary and discussion: Explanation to the geological map of Central Lapland. Geol Surv Finland, Report of investigation 71: 35.

Lestinen P, Savolainen H & Lahtinen R (1996) New methods applying bedrock lithological and geochemical data to the interpretation of regional till geochemical data: a study in the Tampere-Hämeenlinna area southern Finland. Geological Survey of Finland, Bulletin 391: 37.

Linden A (1975) Till petrographic studies in an Archean bedrock area in southern central Sweaden. Striae 1: 57.

Lindsay PJ & Shilts WW (1995) A standard laboratory procedure for separating clay-sized detritus from unconsolidated glacial sediments and their derivatives. In: Bobrowsky PT, Sibbick SJ & Newell JM (eds) Drift Exploration. B.C. Ministry of Energy. Mines and Petroleum Resources Paper 1995–2: 165–166

Lintinen P (1995) Origin and physical characteristics of till fines in Finland. Geological Survey of Finland, Bulletin 379: 83.

Lundqvist J (1969) Problems of the so-called Rogen-moraine. Sveriges Geologiska Undersökning. C 648:1–32.

Lundqvist J (1974) Outlines of the Weichsel Glacial in Sweden. Geologiska Föreningens i Stockholm Förhändlingar 96: 29.

Lundqvist J (1980) The deglaciation of Sweden after 10 000 B.P. Boreas 9:229–238.

Lundqvist J (1989) Rogen (ribbed) moraine – identification and possible origin. In: Menzies J & Rose J (eds) Subglacial bedforms – drumlins, Rogen moraine and associated bedforms. Sed Geol 62: 281–292.

Lång L-O & Stevens RL (1996) Weathering variability and aluminium interlayering: clay mineralogy of podzol profiles in till and glaciofluvial deposits SW Sweden. Applied Geochemistry 11: 87–92.

MacEwan DMC (1949) Recording and interpretation of X-ray diagrams of soil clays. J Soil Sci 1:90–103.

Mackenzie R (1957) The differential thermal analysis of clays. Mineralogical Society London, 456 p.

Mackenzie R & Berggren G (1970) Oxides and hydroxides of higher-valency elements. In: Mackenzie R (ed) Differential thermal analysis. Academic Press, London, 271–302.

Markgren M & Lassila M (1980) Problems of moraine morphology: Rogen moraine and Blattnick moraine. Boreas 9: 271–274.

Matisto A (1958) Kivilajikartanselitys. Lehti D5 Suomussalmi. English summary: General geological map of Finland 1:400 000. Geologinen tutkimuslaito, 115 p.

Matisto A (1959) Suomen geologinen kivilajikartta lehti B8 Enontekiö. Geologinen tutkimuslaitos.

Matisto A (1969) Suomen geologinen kivilajikartan selitys lehti B8 Enontekiö. With an English summary. Geologinen tutkimuslaitos, 77 p.

Melkerud P-A (1983) Quaternary deposits and bedrock outcrops in an area around Lake Gårdsjön south-western Sweden with physical mineralogical and geochemical investigations Swedish University of Agricultural Sciences Reports in Forest Ecology and Forest Soils 44: 1–84.

Melkerud P-A (1984) Distribution of clay minerals in soil profiles – A tool in chronostratigraphical and litostratigraphical investigations of till. In: Königsson L-K (ed) Ten Years of Nordic Till Research, Striae 20: 31–37.
Melkerud P-A (1986) Clay mineralogical comparsions of weathering profiles associated with spurce and birch stands. Geologiska Föreningens i Stockholm Förhändlingar 107 Part 4: 301–309.
Melkerud P-A (1991) The importance of fine-textured material for chemical weathering soil formation and aluminium mobilization. In: Rosen R (ed) Chemical Weathering under Field Conditions. Swedish University of Agricultural Sciences Reports in Forest Ecology and Forest Soils 63: 119–138.
Minell H (1979) The genesis of tills in different moraine types and the glaciation in a part of central Lapland. Sveriges Geologiska Undersökning C 754:1–83.
Mäkinen J (1992) Glacial fractonation and relationships of unit weight to geochemical and mineralogical composition in the fine fraction of till. Bulletin of the Geological Society of Finland 64: 59–74.
Nevalainen R (1983) Moreenin hienoaineksen mineraalikoostumus ja kulkeutuminen Kuhmon liuskejakson alueella Kellojärvellä. Arkeeisten alueiden malmiprojekti. Oulun yliopisto raportti 8: 110.
Nevalainen R (1989) Lithology of fine till fractions in the Kuhmo greenstone belt area eastern Finland. Geolgical Survey of Finland. Special Paper 7: 59–65.
Nieminen P (1985) Moreenin hienoaineksen laatu ja sen vaikutus routimisherkkyyteen. Tampere University of Technology. Publications 34: 81.
Niini H (1968) A study of rock fracturing in valleys of Precambrian bedrock. Fennia 97 6: 60.
Niini H & Uusinoka R (1978) Weathering of precambrian rocks in Finland. Proceedings of the III International Congress IAEG 4–8 September 1978 Section 11 1: 77–83.
Nikkarinen M, Kallio E, Lestinen P & Äyräs M (1984) Mode of occurrence of Cu and Zn in till over three mineralized areas in Finland. Journal of Geochemical Exploration 21: 239–247.
Nurmi A (1975) Geochemical exploration in a glacial ice-divide region: Riikonkoski copper ore deposit Kittilä Finnish Lapland. In: Jones MJ (ed) Prospecting in areas of glaciated terrain 1975. Inst. of Mining and Metallurgy, London, 54–59.
Olsson M & Melkerud P-A (1989) Chemical and mineralogical changes during the genesis of a Podzol from till in southern Sweden. Geoderma 45: 267–287.
Peltoniemi HE (1981) Moreenin litologia ja geokemia sekä moreeniaineksen kulkeutumismatka Kuhmon luoteisosissa. Kuhmon ja Kittilän malmiprojekti. Oulun yliopisto. Raportti 48: 91.
Perttunen M (1977) The lithologic relation between till and bedrock in the region of Hämeenlinna southern Finland. Geological Survey of Finland, Bulletin 291: 68.
Peuraniemi V (1982) Geochemistry of till and mode of occurrence of metals in some moraine types in Finland. Geological Survey of Finland, Bulletin 322: 75.
Peuraniemi V (1989) Till stratigraphy and ice movement directions in the Kittilä area Finnish Lappland. Boreas 18: 145–157.
Peuraniemi V (1990) Heavy minerals in glacial material. In: Kujansuu R & Saarnisto M (eds) Glacial Indicator Traceing. Balkema, Rotterdam, 165–185.
Peuraniemi V (1991) Geochemistry of till and mode of occurrence of metals in some moraine types in Finland. Geological Survey of Finland, Bulletin 322: 75.
Peuraniemi V & Islam MR (1993) The weathering crust in the Vuotso-Tankavaara area. The first evidence on the occurrence of halloysite in Finland. Chemical Geology 107: 307–311.
Peuraniemi V, Aario R & Pulkkinen P (1996) Moreenin savifraktion mineralogiasta ja geokemiasta Pohjois-Suomessa. Geologi 48 4–5: 83–91.
Peuraniemi V, Aario R & Pulkkinen P (1997) Mineralogy and geochemistry of the clay fraction of till in northern Finland. Sedimentary Geology 111: 313–327.
Piirola J (1972) Pohjois-Suomen kuviomaista. Terra 84: 132–142.

Pulkkinen E (1985) Vuotson rapakalliosavi. Lapin tutkimusseura. Summary: Weathered bedrock of Vuotso area. The Research Society of Lapland. Year Book XXVI 1985, 41–45.

Punkari M (1996) Glacial dynamics of the northern European ice sheets. Department of Geology, Division of Geology and Palaeontology, University of Helsinki, Finland. Dissertation, 24 p.

Rencz AN & Shilts WW (1980) Nickel in soils and vegetation of glaciated terrains. In: Nrigau JO (ed) Nickel in the environment, 151–188.

Righi D, Räisänen ML. & Gillot F (1997) Clay mineral transformations in podzolized tills in central Finland. Clay Minerals 32: 531–544.

Rooksby HP (1961) Oxides and hydroxides of aluminium and iron. In: Brown G (ed) The X-ray identification and crystal structures of clay minerals. Mineralogical Society. London, 354–392.

Räisänen ML (1996) Geochemistry of podzolized tills and the implications for aluminium mobility near industrial sites: a study in Kuopio eastern Finland. Geological Survey of Finland, Bulletin 387: 72.

Räisänen ML, Tenhola M & Mäkinen J (1992) Relationship between mineralogy and the physicochemical properties of till in central Finland. Bulletin of the Geological Society of Finland 64 Part I: 35–58.

Saarnisto M, Peltoniemi H, Uusikartano K, Tuokko I & Koivumaa S (1980) Malminetsintää palvelevat maaperägeologiset tutkimukset Kuhmon Kellojärven alueella. Summary: Studies on glacial geology and lake sediments for prospecting purposes in the Kellojärvi area of the Kuhmo greenstone belt. Kuhmon ja Kittilän malmiprojektit. Oulun yliopisto raportti 39: 127.

Saarnisto M, Nevalainen, R, Peltoniemi H, Taipale K & Tuokko I (1981) Kuhmon malmiprojektin maaperägeologiset tutkimukset v. 1980. Summary: Studies in glacial geology in the Kuhmo research projekt 1980. Kuhmon ja Kittilän malmiprojektit. Oulun yliopisto raportti 44: 95.

Saarnisto M & Taipale K (1984) Influence of Kuhmo Greenstone belt (eastern Finland) upon the lithology and geochemistry of till. Striae 20: 39–44.

Saarnisto M & Taipale K (1985) Lithology and trace-element content in till in the Kuhmo granite-greenstone terrain eastern Finland. Journal of Geochemical Exploration 24: 317–336.

Salminen R (1975) Moreenin ja rapakallion geokemiallisista eroista. Julkaisematon lisensiaattityö. Turun yliopisto s. 85.

Salminen R (1980) On the geochemistry of copper in the Quaternary deposits in the Kiihtelysvaara area northern Karelia Finland. Geological Survey of Finland, Bulletin 309: 48.

Sederholm J (1913) Weitere Mitteilungen uber Bruschpalten mit besonderer Beziehung zur Geomorphologie von Fennoskandia. Bull. Comm. géol. Finlande 37: 66.

Seppälä M (1972) Pingo-like remnants in the Peltojärvi area of Finnish Lapland. Geografiska Annaler 54: 38–45.

Shaw J (1979) Genesis of the Sveg tills and Rogen moraines of central Sweden: a model of basal meltout. Boreas 8: 409–426.

Shilts WW (1971) Till studies and their application to regional drift prospecting. Can. Mining Journal 4: 45–50.

Shilts WW (1973a) Glacial dispersal of rocks minerals and trace elements in Wisconsian till southeastern Quebec Canada. In: Black RB, Goldwaith RB & Willman HB (eds) The Wisconsian Stage. Geol Soc Amer Mem, 136: 189–219.

Shilts WW (1973b) Drift prospecting: geochemistry of eskers and till in permanently frozen terrain: District of Keewatin: Northwest Territories. Geological Survey of Canada Paper 72–45: 34.

Shilts WW (1975) Principles of geochemical exploration for sulphide deposits using shallow samples of glacial drift. Can Inst Min Metall Bull 68: 73–80.

Shilts WW (1976) Glacial till and mineral exploration. In: Legget RF (ed) Glacial Till. R Soc Can Special, Publ 12: 205–223.

Shilts WW (1977) Geochemistry of till in perennially frozen terrain of the Canadian shield – application to prospecting. Boreas 5: 203–212.

Shilts WW (1980) Flow patterns in the central North American ice sheet. Nature 286: 213–218.
Shilts WW (1980) Geochemical profile of till from Longlac Ontario to Somerset Island. CIM Bulletin 73 822: 85–94.
Shilts WW (1984) Till geochemistry in Finland and Canada. Journal of Geochemical Exploration, 21: 95–117.
Shilts WW (1991) Principles of glacial dispersal and sedimentation. In: Coker WB (ed) Exploration Geochemistry Workshop. Geolgical Survey of Canada Open File 2390: 1–42.
Shilts WW (1993) Geological Survey of Canada´s contributions to understanding the composition of glacial sediments. Canadian Journal of Earth Sciences 30: 333–353.
Shilts WW (1995) Geochemical partitioning in till. In: Bobrowsky PT, Sibbick SJ & Newell JM (eds) Drift Exploration. B.C. Ministry of Energy Mines and Petroleum Resources Paper 1995–2: 149–164.
Shilts WW & Kettles IM (1990) Geochemical-mineralogical profiles through fresh and weathered tills. In: Kujansuu R & Saarnisto M (eds) Glacial Indicator Tracing. A.A. Balkema, Rotterdam, 187–216.
Shilts WW & Smith SL (1989) Drift prospecting in Appalachians of Estrie-Beauce Quebec. In: DiLabio RNW & Coker WB. Drift Prospecting. Geological Survey of Canada. Paper 89–20: 41–59.
Snäll S (1986) Weathering in till indicated by clay mineral distribution. Geologiska Föreningens i Stockholm Förhändlingar 107 Part 4: 315–322.
Snäll S, Persson Ch & Wikström A (1979) Mineralogisk undersökning av morän från ett område väster om Katarineholm. Sveriges Geologiska Undersökning C 761: 1–32.
Snäll S, Brusewiz A-M & Ålinder C (1992) Mineralogiska analys av moräner. Sveriges Geologiska Undersökning. BRAP 92005, 16 p.
Soveri U (1956) The mineralogical composition of argillaceous sediments of Finland. Ann. Sci. Fennicae., Sarja A III, 48.
Soveri U & Hyyppä JMI (1966) On the mineralogy of fine fractions of some finnish glacial tills. Valtion tekninen tutkimuslaitos. Julkaisu 113: 30.
Srodon J & Eberl DD (1984) Illite. In: Bailey, S.W. (ed) Micas. Review in Mineralogy 13. Min. Soc. Amer., 495–554.
Sutinen R (1984) On teh glacial stratigraphy in Pudasjärvi area, Peräpohjola. Striae 20: 91–94.
Taipale K, Nevalainen R & Saarnisto M (1986) Silicate analyses and normative compositions of the fine fraction of till: Examples from eastern Finland. Jour Sed Petr 56 3: 370–378.
Tanner V (1915) Studier över kvartärsystemet I Fennoskandias nordliga delar III. Bull Comm géol Finlande 38: 815.
Thorez J (1975) Phyllosilicates and clay minerals. A laboratory handbook for X-ray diffraction analysis: Lelotte G, Dison, Belgique, 579, p.
Uusinoka R (1975) A study of composition of rock-gouge in fractures of Finnish Precambrian bedrock. Societas Scientiarium Fennica Commentationes Physico-Matematicae 45 1: 1–101.
Vartiainen H & Wooley AR (1976) The petrography, mineralogy and petrochemistry of the Sokli carbonite massif, northern Finland. Geol Surv Finland, Bulletin 280, 126 p.
Velde B (1992) Inroduction to clay minerals. Chapman & Hall, London, 198 p.
Virkkala K (1952) On the bed structure of till in eastern Finland. Bulletin of the Geological Society of Finland 25: 97–109.
Virkkala K (1955) On glaciofluvial erosion and accumulation in Tankavaara area Finnish Lappland. Acta geocraphica 65:7–24.
Virkkala K (1969) On the lithology and provenance of the till of a gabbro area in Finland. VIII Int. Congr. INQUA, Paris Etudes sur le Quaternaire dans le Monde, 711–714.
Walker GF (1949a) Water layers in vermiculite. Nature. London. 163: 726.

Walker GF (1949b) Distinction of vermiculite chlorite and montmorillonite in clays. Nature, London, 164: 577.

Walker GF (1957) Reactions of expanding-lattice clay minerals with glyserol and ethylene glycol. Clay Min Bull 3: 302–313.

Walker GF (1958) Distinction of vermiculite, chlorite and montmorillonite in clays. Clay Min Bull 3: 154–163.

Walker GF (1961) Vermiculite minerals. In: Brown G (ed) The X-ray identification and crystal structures of clay minerals, 297–324.

Wiklander L & Loste E (1966) Mineralogical and physico-chemical studies of clay fractions of Swedish cultivated soil. Lantbrukshögsk Annaler 32: 439–475.

Wiklander L & Alexandrovic D (1969) Mineralogical analysis of Swedish soils. I. Brown earths and Podzols. Lantbrukshögsk Annaler 35: 895–919.

Äyräs M (1979) Kiistalan karttalehtialueen geokemiallisen kartoituksen tulokset, lehti 2743. Summary: The results of the geochemical survey in the Kiistala map-sheet area. Geologinen tutkimuslaitos. 41 p.

Äyräs M (1982) Vesmajärven karttalehtialueen geokemiallisen kartoituksen tulokset lehti 3721. Summary: The results of the geochemical survey in theVesamajärvi map-sheet area. Geologinen tutkimuslaitos, 41 p.

Äyräs M & Koivisto T (1984) Pokan karttalehtialueen geokemiallisen kartoituksen tulokset lehdet 2744 ja 3722. Summary: The results of the geochemical survey in the Pokka map-sheet area. Geologinen tutkimuskeskus, 35 p.

Ödman OH. (1937) Urbergsgeolokgska undersökningar inom Norrbottens län. English summary: On the pre-Cambrian geology of Swedish Lappland. Sveriges Geologiska Undersökning. Ser. C 426.

Ödman OH (1957) Beskrivning till berggrundskarta över urberget i Norrbottens län. Sveriges Geologiska Undersökning. Ser. Ca 41.

Ödman OH (1958) Berggrunds karta. Urberget inom Norrbottens län. Norra Bladet. Sveriges Geologiska Undersökning.