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Geochemistry of till and mode of occurrence of metals in some moraine types in Finland

by Vesa Peuraniemi

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GEOCHEMISTRY OF TILL AND MODE OF OCCURRENCE OF METALS IN SOME MORAINE TYPES IN FINLAND

by

VESA PEURANIEMI

with 71 figures and 11 tables in the text

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The areas covered by this survey represent four types of morainic landform: cover moraine, ground moraine, drumlins and Rogen moraine. All these moraines consist mainly of basal till facies. The < 0.06 mm fraction was analyzed from a total of 4441 geochemical till samples taken by percussion drilling and pneumatic drilling. The metal contents were determined by AAS after total dissolution of the samples. The mode of occurrence of the metals was studied by chemical cold-extractability studies and mineralogical investigations. The use of a scanning electron microscope equipped with an energy-dispersive X-ray spectrometer was important in identifying the ore minerals and their alteration products.

The anomalies in the till proved to be predominantly clastic and glaciogenic in all four moraine types. Sulphide minerals had been preserved unweathered in the till which had been saturated with groundwater, whereas above the groundwater level they had been weathered to variable extents, entailing alteration, most commonly to goethite. A small proportion of the sulphide grains had been preserved in the fresh state even in the superficial parts of the till deposits.

The geochemical anomalies, which can be traced up to 400–600 m from the mineralization in the direction of ice movement, are more local in the cover moraine area than in the other moraine types. Till geochemistry is highly applicable to all four moraine types when searching for indications of mineralizations and locating these.

The mode of occurrence of metals requires to be investigated in every survey of till geochemistry, and mineralogical studies are particularly important in areas where there is a thick preglacial weathering crust.

Key words: moraines, till, geochemistry, dispersion pattern, sulphides, weathering, Finland.

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To Maija-Liisa and Jussi

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INTRODUCTION

Geochemical investigations using till as a sampling medium have been done in Finland from the early 1950's. Nowadays the Geochemistry Department of the Geological Survey of Finland is doing regional mapping (Kauranne, 1975, 1980; Salminen, 1980) and the mining companies are doing detailed geochemical prospecting (Nuutilainen, 1973; Nurmi, 1975; Björklund, 1976, 1977; Kokkola & Penttilä, 1976; Kokkola & Korkalo, 1976; Puustinen, 1977). The most common metals which are sought in prospecting by using till geochemistry are copper, nickel, zinc, lead, cobalt, molybdenum, tin, tungsten, chromium and uranium.

Studies concerning the mode of occurrence of metals in till are too sparse for the present, however. Kauranne (1976) and Nurmi (1977) have studied the portion of hydromorphic component in till samples by using a cold citric acid leach. Kontas (1976 d) has used a mixture of HCl and NH_4OH when dissolving secondary molybdenum compounds in till samples. Äyräs (1979) has leached samples with HCl when determining the content of loosely bound metals.

The mineralogy of the heavy fraction of till has been studied primarily when prospecting for minerals resistant to chemical weathering, such as cassiterite and scheelite (Lehmuspelto, 1976; Nikkarinen & Björklund, 1976; Brundin & Bergström, 1977; Lindmark, 1977; Mattila & Peuraniemi, 1980). The sulphide minerals in till have been investigated very little.

Brundin (1966) has described weathered pyrite in some till samples from Central Sweden. Toverud (1977) has studied the mineralogy of the heavy fraction of such till samples from Northern Sweden that contained in their fine fraction anomalous contents of copper, zinc and lead. He observed pyrite and chalcopyrite in the samples, but not sphalerite and galena, which he concluded to have been weathered completely in the acid and oxidizing environment.

Some Canadian investigators have also described the occurrence of sulphide minerals (chalcopyrite, pyrite, pyrrhotite, sphalerite, galena, arsenopyrite) in till (Garrett, 1971; Gleeson & Cormier, 1971; Thompson, 1979; Shilts, 1980; DiLabio, 1981).

Kinnunen (1979) has elucidated the ore mineral inclusions in detrital quartz grains in till near the Ylöjärvi copper-tungsten deposit in southwestern Finland.

Pulkkinen *et al.* (1980) have studied the applicability of magnetic susceptibility of till in interpretation of geochemical anomalies.

There is evidently no description in the geochemical literature on the occurrence of molybdenite in till. It has been stated that molybdenite is weathered quite rapidly and liberated molybdenum occurs in till either as secondary molybdenum minerals, ferrimolybdite and ilsemannite, or bound to hydrous oxides of iron, or as organometallic complexes (Davy, 1973; Smith & Gallagher, 1975; Kontas, 1976 d).

Sulphide minerals also have been described in peat (Lovering, 1928; Papunen, 1966; Lett & Fletcher, 1980). There, the sulphide minerals have formed syngenetically, when metal-rich groundwaters have discharged into hydrogen sulphide-bearing bogs.

In this investigation the intention is to clear up the relation of till anomalies to underlying bedrock and the mode of occurrence of metals in till anomalies by using chemical and mineralogical studies. The survey areas have been selected so that they represent four various glaciomorphic types of till: 1. cover moraine 2. ground moraine 3. drumlin 4. Rogen moraine.

All the glaciomorphic till types are composed mainly of basal till, but surficial parts of them especially of Rogen moraines, can include considerable amounts of ablation till (Prest, 1968; Lundqvist, 1969; Aario, 1977).

These moraine types constitute together the greatest part of the Quaternary deposits of Finland and so the knowledge of their geochemical characteristics is very important both in regard to prospecting, and in regard to other geochemical surveys.

The survey areas in this investigation are Rantavaara in Ilomantsi commune, Susineva in Kalajoki commune, Kangerjärvi in Kuusamo commune and Petäjäskoski in Rovaniemi rural commune (Fig. 1). The material for this survey has been gathered during the prospecting work of Rautaruukki Oy, in the years 1976–1980.

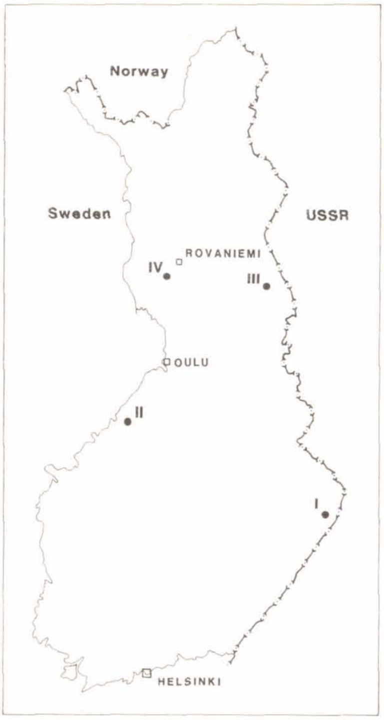


Fig. 1. The location of the survey areas. I = Rantavaara (Ilomantsi), II = Susineva (Kalajoki), III = Kangerjärvi (Kuusamo), IV = Petäjäskoski (Rovaniemi).

METHODS OF INVESTIGATION

The bedrock maps of the investigation areas are based on outcrop mapping and geophysical ground measurements done by the Exploration Department of Rautaruukki Oy. The maps of Quaternary deposits have been prepared mainly with the aid of aerial photo interpretation. The interpretation has been done with a Topcon mirror stereoscope using black and white and infrared aerial photographs (Kodak Infrared Aero Film, type 8443) at a scale of 1 : 60 000.

The till samples were taken by petrol-operated percussion drilling equipment, Partner M 100 in the investigation areas of Rantavaara, Kangerjärvi and Petäjäskoski. The diameter of the drilling rods was 25 mm. The through-flow shell bit was used as a sampler (Kauranne, 1975).

In these three investigation areas one till sample was taken from every drilling point. The aim was to take the till samples from as near the bedrock surface as possible. The drilling grid was such that the samples were taken at fifty metre intervals along lines which were two hundred metres apart (cf. Wennervirta, 1968). At interesting, anomalous places the sampling grid was made denser by reducing the line interval to 100 m and the point interval to 25 or even 10 m.

In the investigation area of Susineva sampling was done by a Tampella L 400 pneumatic drilling machine attached to a Valmet

1100 farm tractor (Wennervirta, 1973; Kokkola, 1976). The great advantage of this equipment is that it is capable of penetrating large boulders in till and of taking a sample of the bedrock surface.

At Susineva, at every drilling point is was attempted to take till samples at 1–2 metres depth interval up to the bedrock surface and also to get a sample of the bedrock. This succeeded very well. The line interval in Susineva was 50 m and point interval 20 m. In interesting places the point interval was 5–10 m. In locating the sampling lines, the boggy terrain had to be taken into account because of the heavy equipment.

In the laboratory the samples were dried and sieved. The sieves were constructed from plastic tubing and nylon screen. Thus, contamination in sample preparation was inhibited. The samples from Susineva were screened on a 0.5 mm sieve and the material passing through the sieve was analyzed chemically. The samples from Rantavaara, Kangerjärvi and Petäjäskoski were screened into three grain size fractions: < 0.06 mm, 0.06–0.25 mm and > 0.25 mm. The finest fraction was analyzed chemically. The sand fraction was separated with heavy liquid for the heavy mineral studies. Stone counts were made from the coarse fraction.

The fractions being analyzed were dissolved in a mixture of perchloric, hydrochloric, nitric and hydrofluoric acids ($HClO_4$–HCl–HNO_3–HF ratio 2:5:5:10). This is a total dissolution, in which metals bound in silicate lattices also become dissolved (Levinson, 1974; Dijkstra *et al.*, 1979). After dissolution, the mixture was evaporated to dryness and the residue was dissolved in 5 % HCl. Copper, cobalt, nickel, zinc and lead were determined by flame AAS from this solution.

For molybdenum analysis, the sample was fused with potassium pyrosulphate ($K_2S_2O_7$) and the flux was dissolved in HCl. This solution was extracted as organic chelate and molybdenum was determined by graphite furnace AAS. This method of analysis gives the total content of molybdenum in samples.

The mode of occurrence of various metals were studied by extracting the samples with weaker acids. One solvent was a mixture of ascorbic acid, $C_6H_8O_6$, and hydrogen peroxide, H_2O_2 (5 parts liquid of 1 % ascorbic acid + 2 parts 30 % hydrogen peroxide). Analysis was done with AAS. This solvent mixture dissolves the metals bound in sulphides and also the metals adsorbed to the surfaces of clay and silicate minerals but not the metals included in the lattices of silicate and oxide minerals (Smirnova *et al.*, 1968; Cameron *et al.*, 1971; Chao & Sanzolone, 1977). This method of dissolution was applied only to the till samples of the first sampling stage in the Rantavaara survey area.

The other acid used in the extraction studies was 0.1 M citric acid, $C_6H_8O_7 \cdot H_2O$. In this cold extraction method, the weakly bound metals come into solution (Nurmi, 1977). The ability of citric acid to dissolve the primary sulphides is very poor. Molybdenum was assayed by photometry and the other metals by AAS. This cold extraction method was applied to the till samples of the Rantavaara, Kangerjärvi and Petäjäskoski survey areas. All the partial dissolution studies were done on the fraction < 0.06 mm.

The mode of occurrence of various metals was investigated also by mineralogical studies, which were done on the heavy fraction of till. From every survey area, some samples were chosen, whose sand fractions (at Susineva 0.5–2 mm, elsewhere 0.06–0.25 mm) were separated in a heavy liquid. The samples from the Susineva area were separated in methylene iodide (density 3.31 g/cm^3) and the samples from other areas in tetrabromoethane (density 2.96 g/cm^3). A part of the heavy fractions was mounted in Epofix and made into polished sections or polished thin sections. These were studied with the aid of a polarizing microscope in reflected light.

The use of a scanning electron microscope (JEOL JSM-35) equipped with an energy dispersive X-ray spectrometer (EDS) was important in identifying the ore minerals and their alteration products. The accelerating voltage used was 20 keV. Both secondary and backscattered electron images were formed. Also some separate mineral grains were studied with the scanning electron microscope. The light and dark rectangular areas in SEM-images are the »footprints» of the electron beam. X-ray diffraction was also used in the identification of the silicate minerals.

Some heavy fractions of the Rantavaara till samples were analyzed chemically. Copper, zinc and lead were assayed by XRF and molybdenum by AAS.

The coarse fraction of the samples (> 0.25 mm) was washed and the rock types in it were determined.

The statistical distributions of the metal contents were determined by computer.

THE RESULTS OF INVESTIGATION IN EACH AREA

RANTAVAARA AREA

Location and topography

The survey area is situated in North Karelia in the commune of Ilomantsi, 50 km east of Joensuu (Fig. 1). The local relief is great, the absolute height above sea level varying between 152 and 192 m. The features dominating the topography are the hills *(vaarat* in Finnish) and the numerous lakes and ponds.

Bedrock and mineralizations

The bedrock of the survey area belongs to the Presvecokarelidic basement gneiss complex (Simonen, 1980). The Exploration Department of Rautaruukki Oy mapped the outcrops of the survey area, 25 km^2, in the summers 1978 and 1979. The bedrock map (Fig. 2) has been drawn on the basis of outcrop observations and magnetic and electric ground measurements.

The oldest rocks of the area are amphibolites, chlorite schists and mica gneisses, which occur as long, narrow and discontinuous horizons in the younger intrusive rocks. The area is a part of the batholith called the Ilomantsinjärvi granodiorite by Lavikainen. The main rock type is compositionally mostly granodiorite, but in places the composition varies from granite to tonalite. The major constituents of the granodiorite are plagioclase, quartz, microline and biotite. Accessories are epidote, hornblende, sphene and apatite. In the mineralized area, the feldspars are strongly sericitized and saussuritized. The colour of granodiorite varies from reddish to gray and the texture from porphyritic to equigranular. It is medium grained.

In some places, the granodiorite is clearly gneissic and in other places it is quite homo-

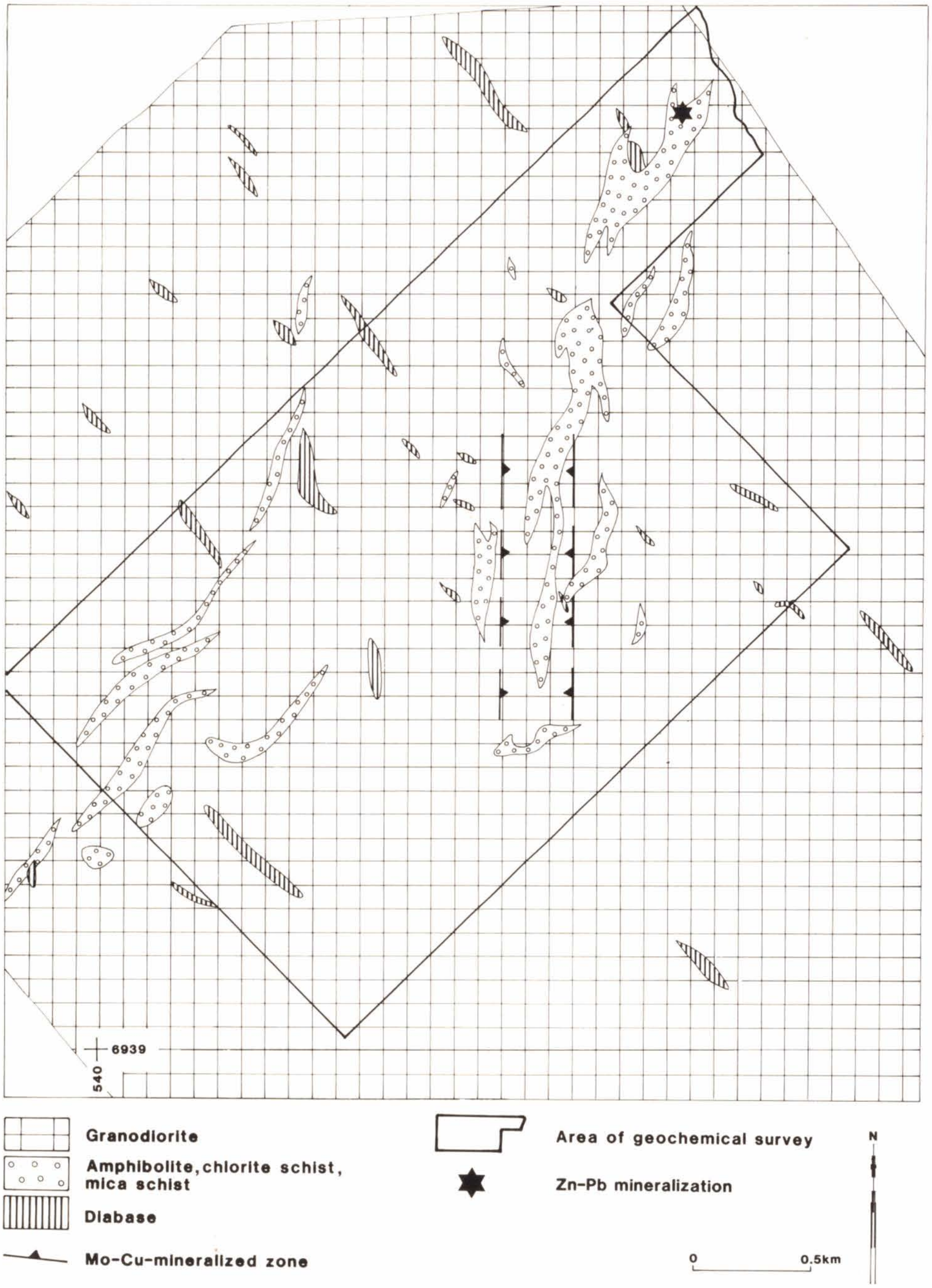


Fig. 2. Bedrock geology of the Rantavaara survey area.

geneous. It has been observed in three outcrops that granodiorite brecciates the older rocks of the area.

In the southwestern corner of the area, surrounding Lake Kuokanlampi, the strike of the bedrock is NE-SW and the dips are to the southeast. In the surroundings of Lake Paavonlampi, the strike of the bedrock is N–

S and dips are to the west. The dips are generally steep, 60–80°. The youngest rocks of the area are the Svecokarelidic metadiabase dykes, which cut the older rocks.

As a result of exploration work, several molybdenum mineralizations have been found in the area. The main ore mineral is molybdenite. Chalcopyrite and pyrite occur often in connection with molybdenite. In a few places bornite and covellite have been found. These mineralizations occur in granodiorite, especially in its quartz-rich parts, quartz veins and microcline-rich portions. Some molybdenite occurs also on fissure planes in schist horizons. The sulphide minerals are found as a sparse, fine-grained dissemination.

The Mo-Cu mineralizations resemble in many respects the Precambrian porphyry copper deposits described in the literature (Kirkham, 1972; Wolfe, 1974; Blecha, 1974; Findlay & Ayres, 1977; Schmidt, 1978; Gaál & Isohanni, 1979).

In the schist horizons, there are in places small lead-zinc-mineralizations. They contain sphalerite, galena, pyrite and chalcopyrite.

In the amphibolite, there have been found two compact pyrite mineralizations, the marginal parts of which contain pyrrhotite (cf. Saksela, 1923; Aurola & Vähätalo, 1939). In amphibolite, there also occur some small iron formations.

Some chalcopyrite dissemination has been seen in the metadiabase dykes.

Quaternary deposits

There is very scanty information in the literature about the Quaternary deposits of the survey area. Some data is included in explanations of old maps of surficial deposits (Sederholm, 1899; Frosterus & Wilkman, 1917; Berghell, 1927). The area is situated 20 km east of the First Salpausselkä complex. Thus, the Quaternary deposits of the survey area were formed in an older deglacial flow phase than the Tuoppajärvi lobe, which has been described farther north. The marginal position of the Tuoppajärvi lobe, the White Sea marginal complex, correlates plausibly with the First Salpausselkä (Rosberg, 1899; Aario & Forsström, 1978, 1979).

Figure 3 is a map of the Quaternary deposits. Besides the areal distribution of various glacial deposits, the orientations of small drumlins and striae have also been drawn. There are many small rock outcrops. Overburden is composed mainly of a gray, sandy, basal till. It contains in places sand as lenses and intercalations. On the basis of drilling and excavation data, only one till bed occurs in the area. In bog depressions, there is often sand between peat and till. Glaciofluvial deposits are not found in the area. At six percussion drilling sites, weathered bedrock has been met under till (cf. Salminen, 1980).

It is possible to get a rather reliable picture of the thickness of the overburden and its variation by examining the depth data of diamond core drilling and percussion drilling (Table 1).

When the thickness of the overburden was calculated, the share of water in the lakes was rejected. When comparing the data in Table 1, it is observed that the diamond core drilling

Table 1.

The thickness of the overburden on the basis of diamond and percussion drilling in the Rantavaara area. $\overline{X}$ = arithmetic mean, n = number of observations

	minimum m	maximum m	$\overline{X}$ m	n
Diamond drilling	0.5	9.5	3.1	19
Percussion drilling	0.1	9.8	2.3	2760

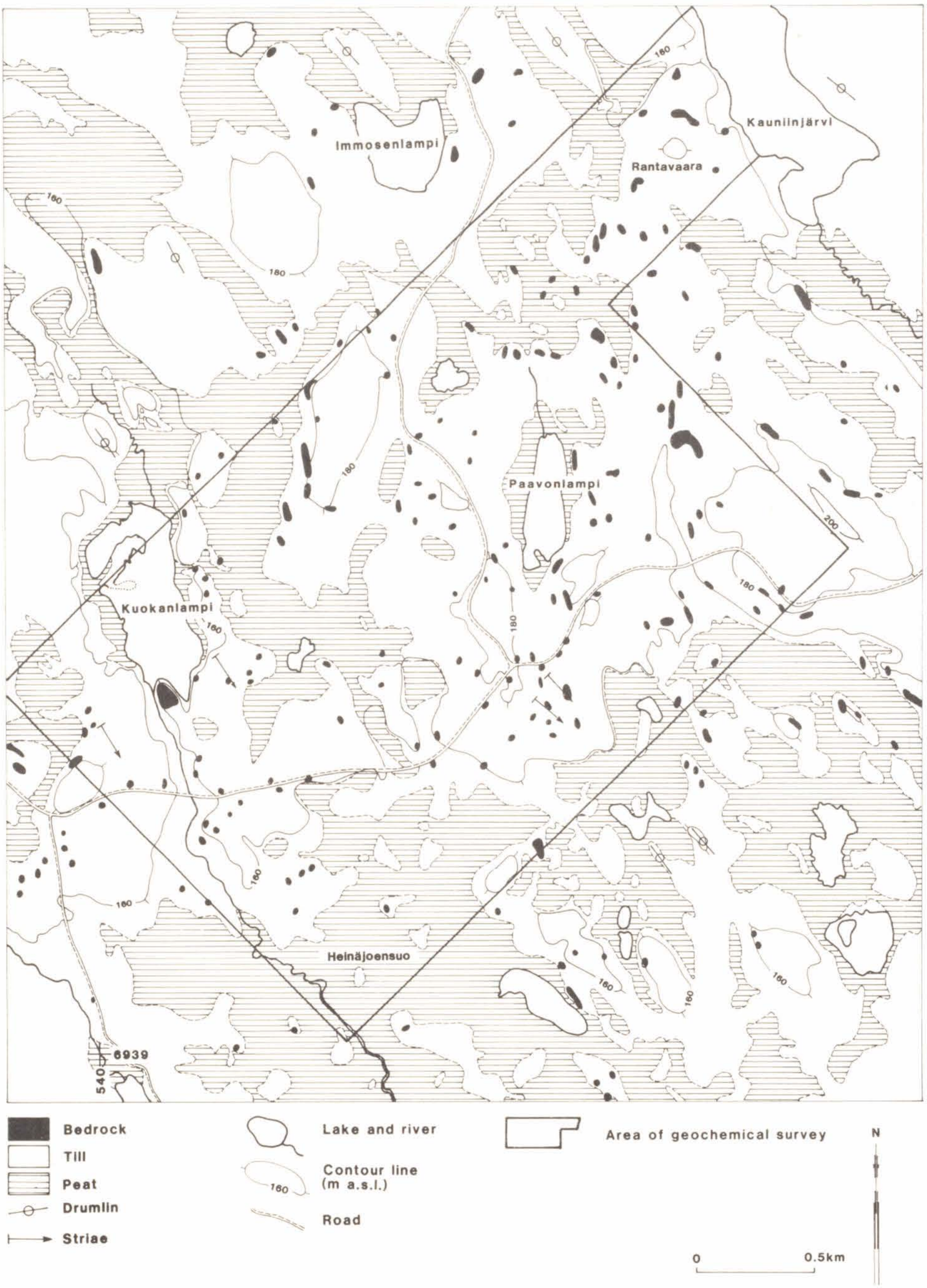


Fig. 3. Quaternary deposits of the Rantavaara survey area. The drumlins and striae indicate the general direction of ice movement. No other directions have been observed in till stratigraphy.

and percussion drilling give a rather uniform picture of the thickness of the overburden. The slightly greater arithmetic mean given by diamond drilling comes probably from the fact that the greatest part of the diamond drill holes is situated in the fracture valley of

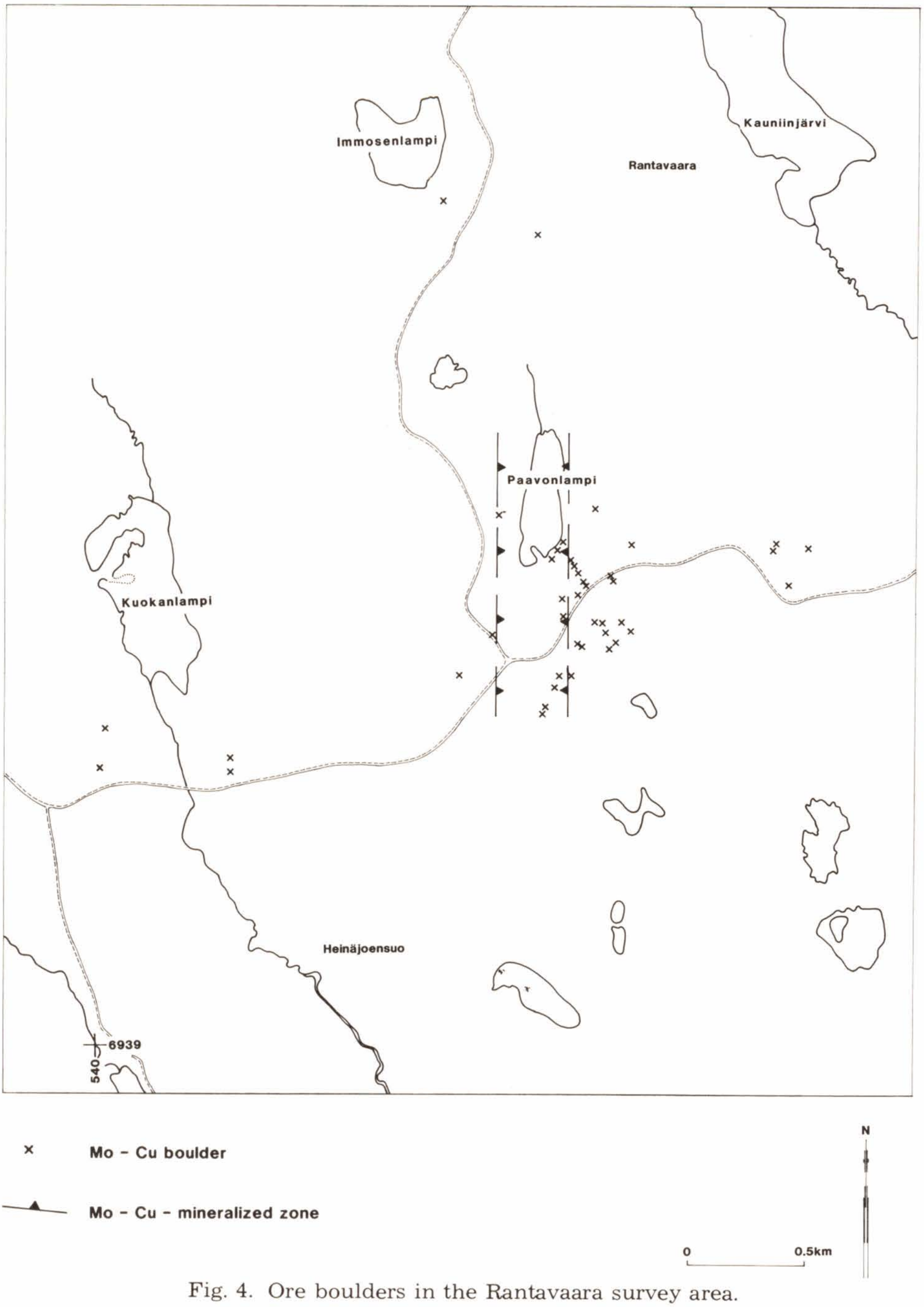


Fig. 4. Ore boulders in the Rantavaara survey area.

Lake Paavonlampi, where the percussion drill holes are also deeper than in the surroundings. So, the mean depth of the percussion drilling, 2.3 m, can be considered as a rather good value for the mean thickness of the overburden in the whole survey area. Table 1 shows also that the objective of the sampling stage in the geochemical survey, to get a sample from the basal till near the bedrock surface, has been well accomplished.

The till cover has no topography of its own, but follows the relief of the bedrock surface levelling its variation. Because of this, the area can be classified as a typical cover moraine area (Aario, 1977).

Nine striae observations have been made on the rock outcrops. The directions of these are all northwesterly, varying between 320°–335°. Also a few longitudinal morainic landforms in the marginal parts of the area follow the same direction. The map (Fig. 4), which shows the molybdenum- and copper-bearing ore boulders of the area, also shows that the ice movement has taken place from the northwest. This is correlative with the oldest ice movement directions described in the whole area of North Karelia (Rosberg, 1899; Frosterus & Wilkman, 1917; Berghell, 1927; Repo, 1957). The movement from northeast to southwest presented by Salminen (1980) has not been detected in the Rantavaara survey area.

The transport distance of the till can be estimated with the aid of the known ore boulders (Fig. 4). The greatest number of the molybdenum- and copper-bearing boulders are concentrated in the Paavonlampi subarea. When the location of boulders is compared to the mineralized zone located by outcrop observations and diamond drilling, it is seen that the boulders are either just above the mineralized zone or immediately east of it. On the basis of this, the transport distance of boulders appears to be from a few metres to about four hundred metres. Some boulders may be quite local, whereas the most distant ones have been found about a kilometre from the mineralized zone along the transport direction of the ice. The flow of ice from northwest to southeast is clearly seen in the areal distribution pattern of the boulders.

On the southwestern side of Lake Kuokanlampi there is a smaller concentration of molybdenum- and copper-bearing boulders, whose bedrock source has not yet been located.

The amphibolite horizon south of Lake Kuokanlampi contains a small pyrite mineralization. One hundred metres southeast of it, a boulder of the same type has been found. On the eastern and southeastern side of Lake Paavonlampi, a few iron ore boulders have been located. The same kind of rock has been met as a short intersection in the hole drilled in the central part of Lake Paavonlampi. In this case the boulders are transported one hundred to one thousand metres to the southeast.

Geochemistry of till

Distributions of metals

The effect of the quantity of samples on the statistical parameters of various metals was studied with the material of the Rantavaara survey area. This was possible because sampling was performed in several stages, beginning in the ore-critical area and growing wider outwards. Listed in Table 2 are the important statistical parameters of copper, molybdenum and zinc.

It is noticed that the arithmetic means of copper and molybdenum fall when the number of samples increases. On the other hand the mean value of zinc does not change noticeably when the number of samples increases. The high mean value of copper and molybdenum in the till samples of the first sampling stage ($n = 162$) is naturally caused by the fact that the samples were taken for the greatest part from the anomalous areas of Lake Paavonlampi and Lake Kuokanlampi.

Table 2.

The statistical parameters of copper, molybdenum and zinc in till at Rantavaara. X̄ = arithmetic mean, M = median, s = standard deviation, c = coefficient of variation, n = number of samples

	X̄	M	s	c	n
Cu ppm	67	38	141	2.1	162
	63	42	91	1.4	1294
	48	33	75	1.6	2760
Mo ppm	6	1	18	3.0	162
	3	1	18	4.3	1294
	3	1	11	3.7	2760
Zn ppm	64	58	35	0.5	162
	70	62	41	0.6	1294
	66	59	38	0.6	2760

The second sampling stage (n = 1294) included that whole area, where mineralizations were found by diamond drilling. The great part of the samples of the third sampling stage (n = 2760) is from Heinäjoensuo, south of the Paavonlampi–Kuokanlampi area, where no mineralizations have been found.

As to copper, the fall of the mean value might also be explained by the fact that the bedrock in the Paavonlampi–Kuokanlampi area contains clearly more schist inclusions and metadiabase dykes than the bedrock in the Heinäjoensuo area. The normal copper content of the schists and metadiabases is many times higher than the copper content of the granodiorite (Salminen, 1980). The mean content of copper in till in the whole area, 48 ppm, is a little lower than generally in the area of North Karelia (Kauranne *et al.*, 1977; Kauranne, 1980; Salminen, 1980). The mean content of copper in the Paavonlampi–Kuokanlampi sub-area, 63 ppm, corresponds well to the means presented for till in the granite gneiss and granite areas of North Karelia (*op. cit.*).

The mean content of molybdenum in the Earth's crust is 1 ppm (Kuroda & Sandell, 1954). Various surficial soils contain an average of 2 ppm molybdenum (Davy, 1973). Little information exists about the distribution of molybdenum in till on a regional scale. It has been determined only in detailed prospecting for molybdenum ores (Kauranne, 1958; Canney *et al.*, 1961; Ek & Toverud, 1976; Kokkola & Penttilä, 1976; Kontas, 1976 a–c; Äyräs,

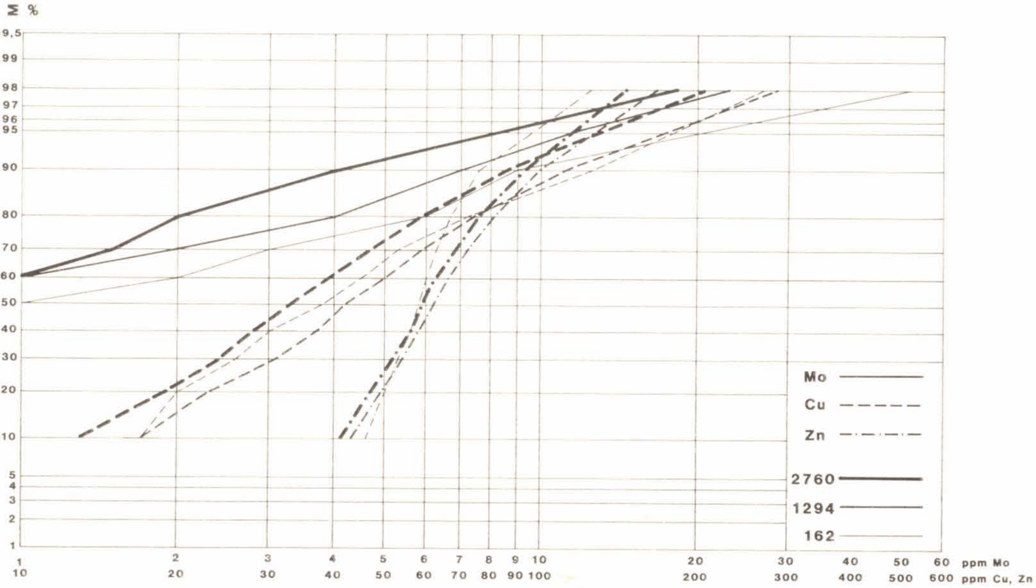


Fig. 5. Cumulative frequency distributions of molybdenum, copper and zinc in till at Rantavaara. 162 = the first sampling stage, 1294 = the second sampling stage, 2760 = the third sampling stage.

1979). On the basis of these studies, the background content of molybdenum in till is 1–2 ppm, so the molybdenum content of till in the Rantavaara area is on the average somewhat higher than the regional background.

The mean content of zinc is at the same level as in till of North Karelia (Kauranne, 1980).

The total distribution of metals can be evaluated best on the basis of cumulative frequency distributions (Tennant & White, 1959; Lepeltier, 1969; Sinclair, 1976). In Fig. 5 are presented the cumulative frequency curves of copper, molybdenum and zinc separately for each sampling stage. It is observed that not even the major increase in the number of samples and the widening of the sampling area to some extent have any great influence on the general picture of the distributions. The form and slope of the curves are about the same for the various numbers of samples.

The distribution of molybdenum is most strongly positively skewed. That is shown also by the coefficient of variation in Table 2 (Levinson, 1974). Similarly, the distribution of copper is clearly positively skewed. On the other hand, zinc is nearly normally distributed. However, zinc also has anomalous values. This is indicated by the bending of the zinc curves in their upper parts to the right, towards the higher values.

The anomaly threshold for all metals has been selected as the 80 percentile of the cumulative frequency distribution. Anomalies have been divided into several classes by using as limiting values the 90, 95 and 98 percentiles. The limiting values have been determined from the frequency curves of the second sampling stage.

The areal distributions of various metals are presented as symbol maps in Figs. 6–8.

The anomalies of molybdenum, copper and zinc are located in the same areas within broad limits, but in details there are many differences. The broadest and strongest molybdenum anomaly is situated mainly on the southern side of Lake Paavonlampi. In its northern part, it begins from the eastern shore of Paavonlampi. The anomaly is quite coherent and has clearly marked boundaries. Its length is 1200 m; its breadt in the northern part is 50 m, in the central part 350 m, and in the southern part 550 m. The longitudinal axis of the anomaly is north–south. The peak values appear along the whole anomaly: in the northern part 210 ppm, in the central part 196 ppm and in the southern part 125 ppm.

Copper correlates quite highly with molybdenum in the Paavonlampi area. High copper values also occur along the whole length of the anomaly. The highest copper content in the northern part is 872 ppm, in the central part 1710 ppm, and in the southern part 1510 ppm.

The anomaly pattern of zinc in the Paavonlampi area is wider and more dispersed than that of molybdenum and copper. Also in detail the anomalous zinc contents are not found in those samples which have high molybdenum and copper. The intensity of zinc anomaly is quite low, the maximum value being 432 ppm.

When the location of the Paavonlampi molybdenum-copper anomaly is compared to the mineralized zone and ore boulders (Fig. 4) some interesting inferences can be made. In the first instance, the molybdenum-copper anomaly is right above the mineralized zone and is parallel to it. The anomaly reaches in its southern part 100–300 metres east of the mineralized zone. Secondly, most of the Mo-Cu-boulders are located in the eastern part of the till anomaly and east of it. So, the boulders are transported slightly farther from the source than the molybdenum-copper anomaly of till fines. The till anomaly can be regarded practically as local, the distance of transport being mostly some metres to some tens of metres.

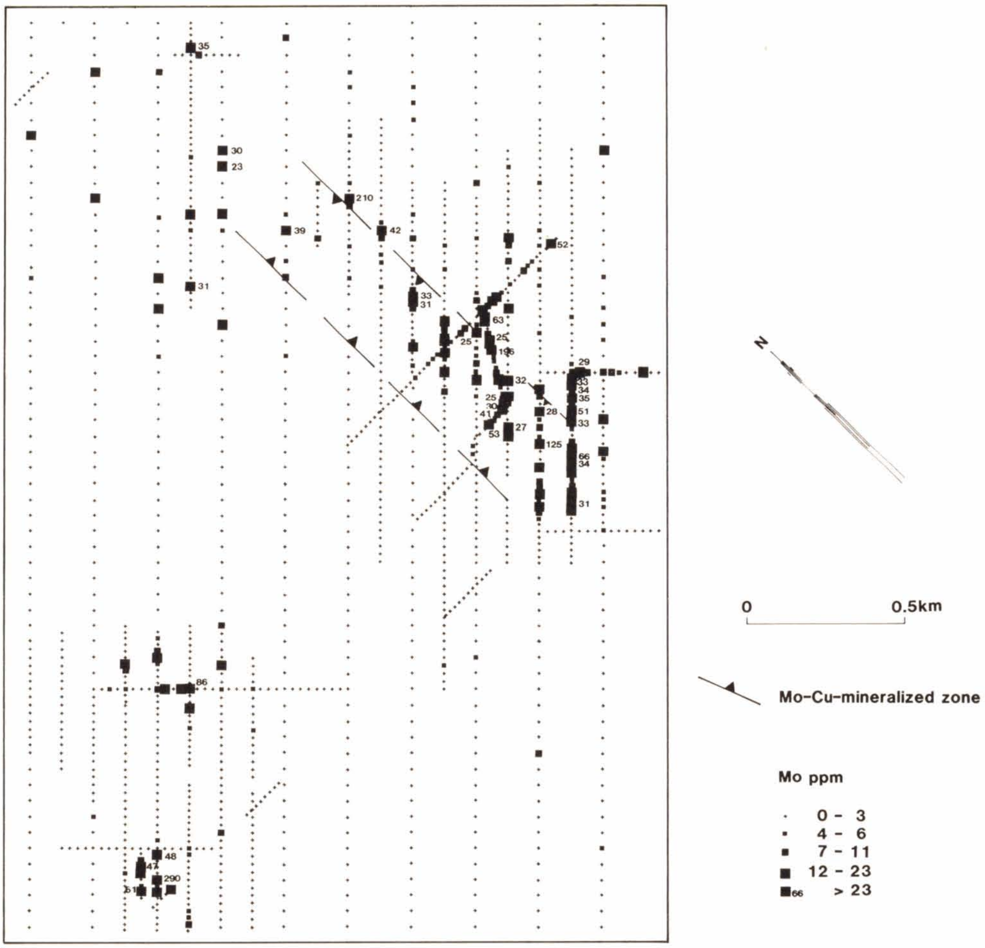


Fig. 6. Symbol map of the areal distribution of molybdenum in till at Rantavaara.

On the eastern and southwestern side of Lake Kuokanlampi there are two other coherent molybdenum anomalies. The eastern anomaly is 300 m long and 100 m wide. Its longitudinal axis is oriented in a northwest–southeast direction. The highest molybdenum value in the anomaly is 86 ppm. In detail, the anomaly might be divided into two parts. The northerly part contains also anomalous copper and zinc contents. The highest zinc value in till in the whole survey area, 1040 ppm, occurs in this anomaly. The maximum content of copper in the anomaly is 235 ppm. The source of this Mo-Cu-Zn anomaly has not been found with the aid of diamond drilling. On the nearby granodiorite outcrop have been found some narrow veins containing molybdenite and chalcopyrite. The source of the zinc anomaly is probably associated with the amphibolite horizon along the northwestern side of the anomaly (Fig. 2).

The molybdenum anomaly on the southwestern side of Lake Kuokanlampi is 300 m long and 100 m wide, the longitudinal axis being in a north–south direction. In this anomaly there are many high values, e.g. the highest molybdenum content of the whole survey area, 290 ppm. Some of the anomalous

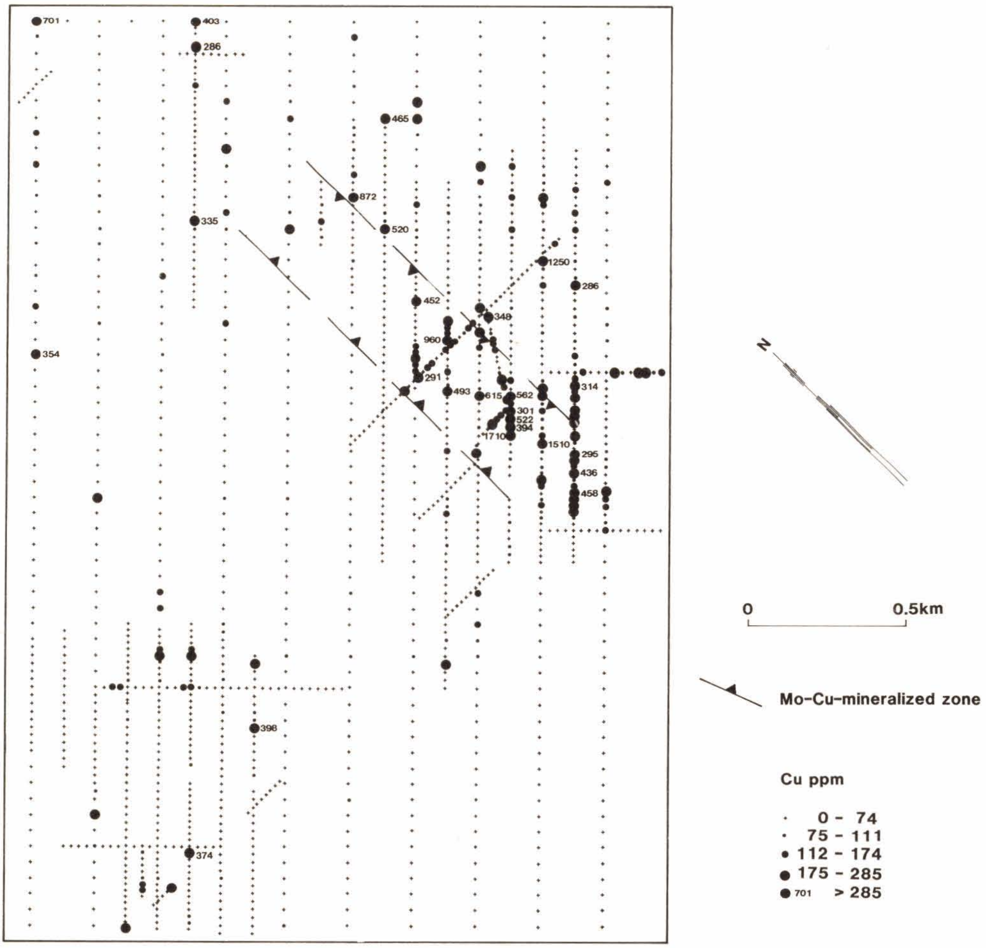


Fig. 7. Symbol map of the areal distribution of copper in till at Rantavaara.

samples are composed of sorted sand. These probably represent sand occurring as intercalations and lenses in till. Only on the western border of the anomaly does copper rise above background (maximum 220 ppm), so that it may be regarded as a pure molybdenum anomaly. Its source in the bedrock is unsolved for the present. One hole was drilled just under the anomaly. Both granodiorite and amphibolite in the drill core contain some tens of ppm molybdenum, which can be regarded lithogeochemically anomalous, but which don't suffice to explain the till anomaly.

To the north of Lake Paavonlampi there are scattered anomalous contents of molybdenum and copper. On the outcrops of the same area there have been found disseminations of molybdenite and chalcopyrite.

In the northeastern corner of the survey area (Fig. 9) there is a zinc anomaly (maximum 425 ppm). Sphalerite and galena were seen there on one amphibolite outcrop. The till anomaly implies however, that the lead-zinc mineralization occurs over a broader area.

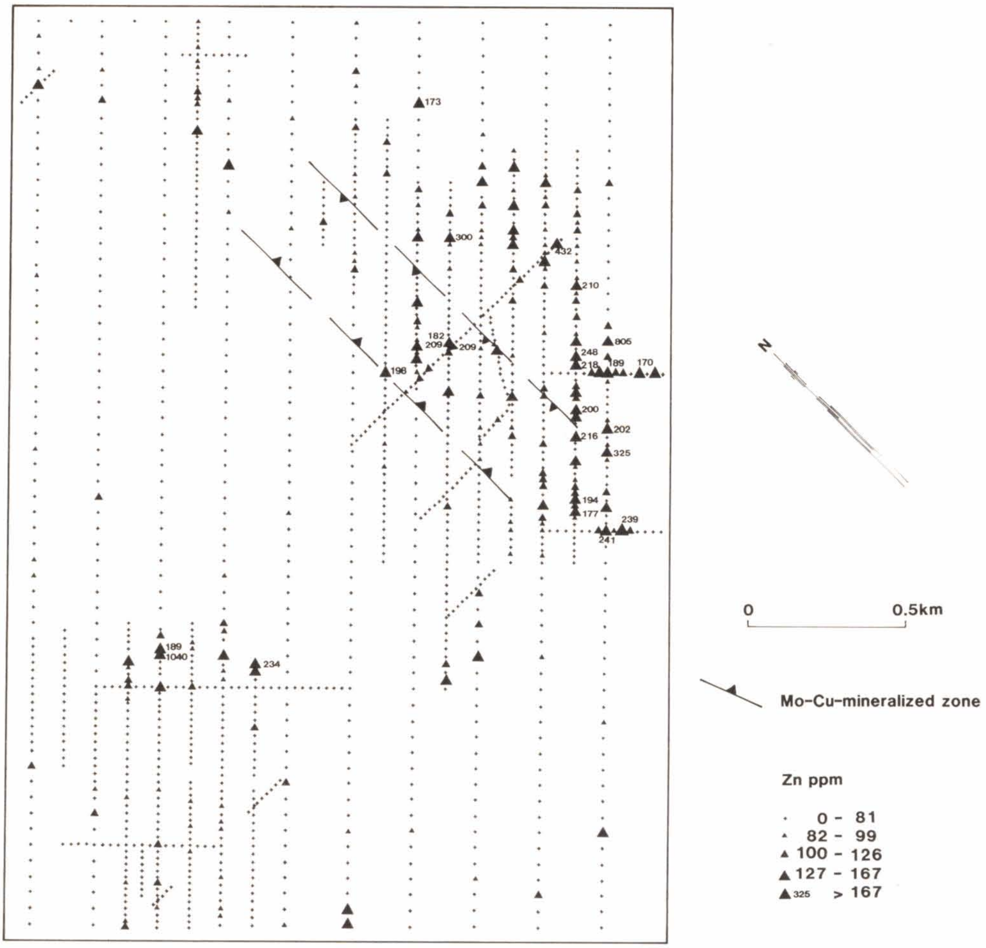


Fig. 8. Symbol map of the areal distribution of zinc in till at Rantavaara.

Mode of occurrence of metals

Chemical studies

The cold-extractable metals were determined on 47 samples using a citric acid leach. These included primarily anomalous samples, but some background samples were used also. The results are presented as diagrams in Fig. 10, so that the total content of each metal is as abscissa and the cold-extractable part in percentage from the total content as ordinate.

All the analyzed metals have a minor cold-extractable component. For copper it is on the average 13 %, for molybdenum 21 % and for zinc 4 %. So it can be said that dispersion in the survey area has been mechanical for the greatest part. Only in a few samples do cold-extractable copper and molybdenum occur more abundantly. Examples are sample number 5420, which has 701 ppm total copper and 331 ppm (47 %) cold-extractable copper; number 7768, which has 210 ppm total molybdenum and 158 ppm (75 %) cold-extractable molybdenum; number 7966, which has 66

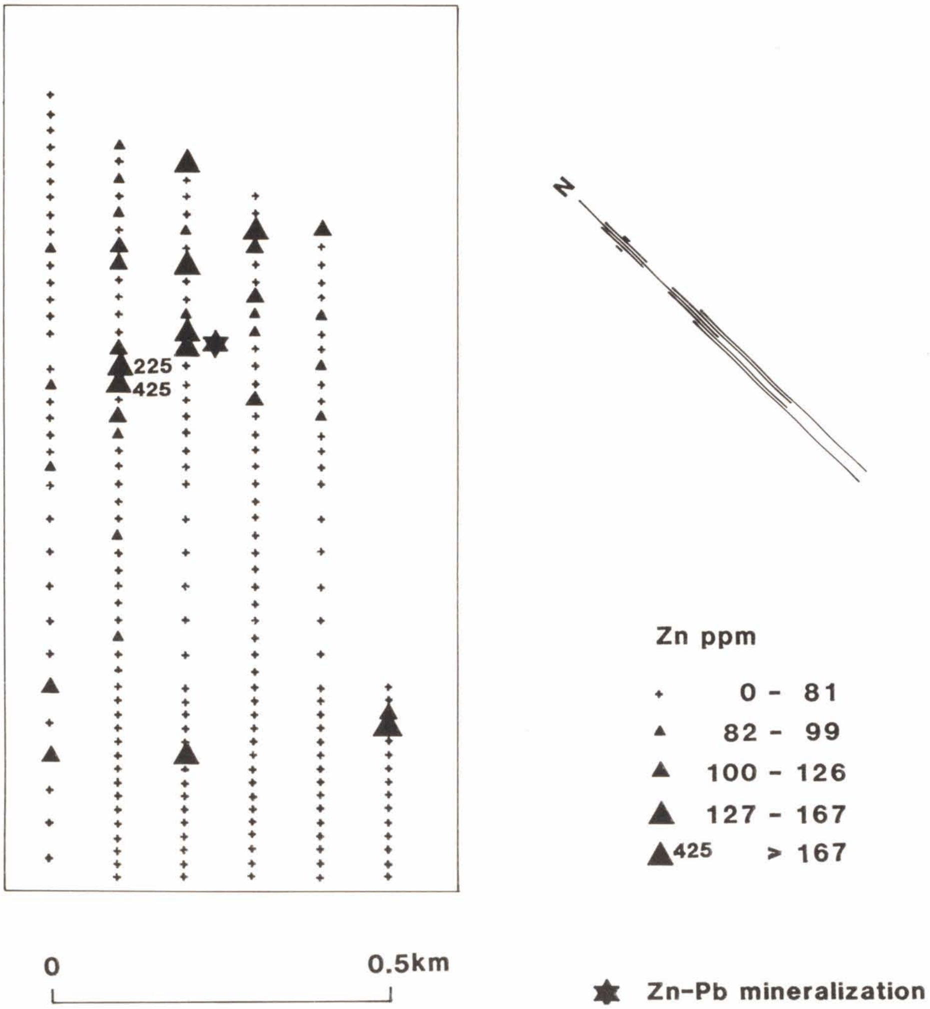


Fig. 9. Symbol map of the areal distribution of zinc in till in the northeastern part of the Rantavaara area.

ppm total molybdenum and 53 ppm (80 %) cold-extractable molybdenum; number 8008, which has 290 ppm total copper and 160 ppm (56 %) cold-extractable copper and both 35 ppm total molybdenum and 35 ppm (100 %) cold-extractable molybdenum. So in some places of the area, hydromorphic dispersion has formed anomalies.

To determine the share of metals bound to sulphides, 30 samples were leached with a mixture of ascorbic acid and hydrogen peroxide. In diagrams in Fig. 11 the total content of each metal is as abscissa and the sulphide-bound part in percentage from the total content as ordinate.

The share of the cold-extractable component of each metal has increased compared with the leaching with citric acid. The strongest increase is for molybdenum, of which 71 % of the total content on the average has been dissolved in the mixture of ascorbic acid-hydrogen peroxide. The corresponding ratio per cent for copper is 31 % and that for zinc 15 % on the average. This indicates clear-

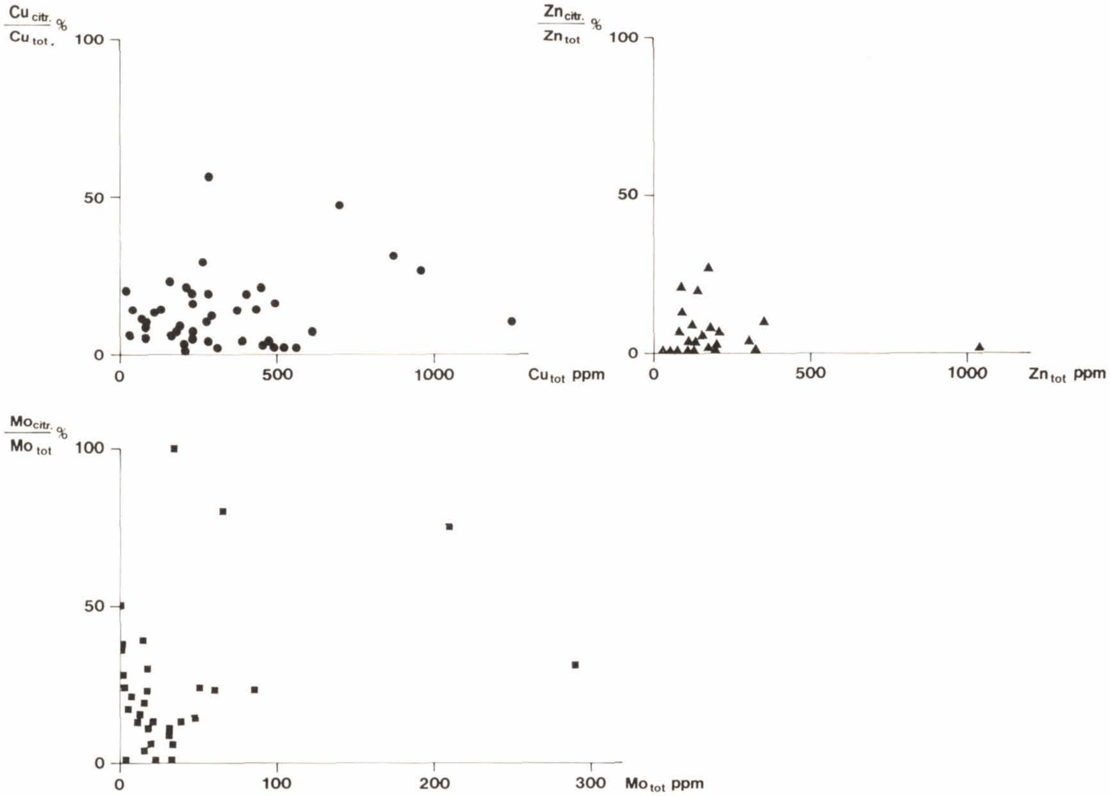


Fig. 10. Citric acid soluble metals in till at Rantavaara.

ly that the metals also occur in till in sulphide form (Peachey & Allen, 1977).

The quite low ratio per cents of copper and zinc may arise in part from the fact that chalcopyrite and sphalerite are not always dissolved completely in the mixture of ascorbic acid-hydrogen peroxide (Olade & Fletcher, 1974; Chao & Sanzolone, 1977). In addition the low ratio per cent of zinc is explained by the fact that the greatest part of the total zinc content can be included in silicates. This is supported by the results from one sample in which zinc is strongly anomalous (432 ppm); 73 % (315 ppm) of its tötal content dissolved in the ascorbic acid hydrogen peroxide mixture.

Mineralogical studies

Mineralogical studies were done only on those samples whose fine fraction contained anomalous contents of copper, molybdenum and/or zinc. The amount of the heavy fraction (>2.96 g/cm^3) in the samples was 0.4–12.8 %. Sample 5420 (depth 1.8 m; 701 ppm Cu, 1 ppm Mo and 73 ppm Zn in the fine fraction), which was collected in the northern part of the survey area, contains much chalcopyrite and pyrite. The sulphides are sharp-edged and unweathered (Figs. 12–13). The surprising feature of this sample is that it contains abundant molybdenite (Figs. 14–15), although the molybdenum content of the fine fraction was normal. The molybdenite is also fresh. It

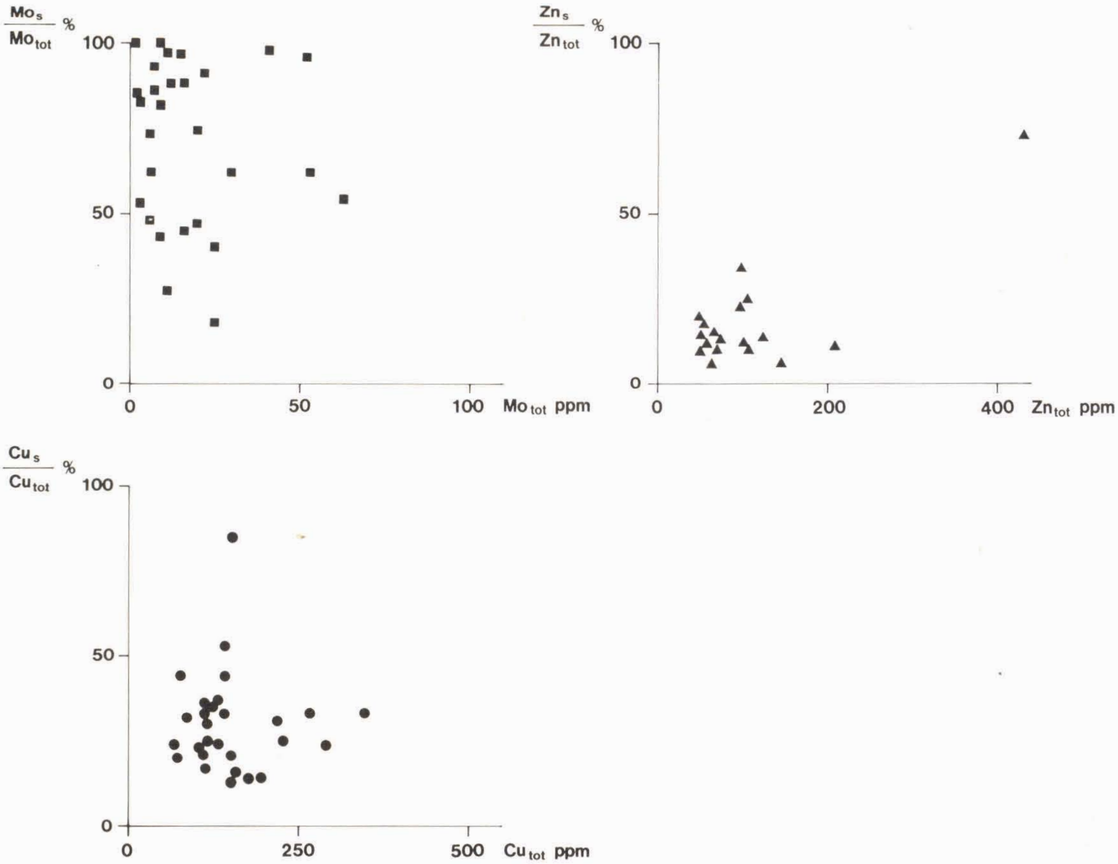


Fig. 11. Ascorbic acid-hydrogen peroxide soluble metals in till at Rantavaara.

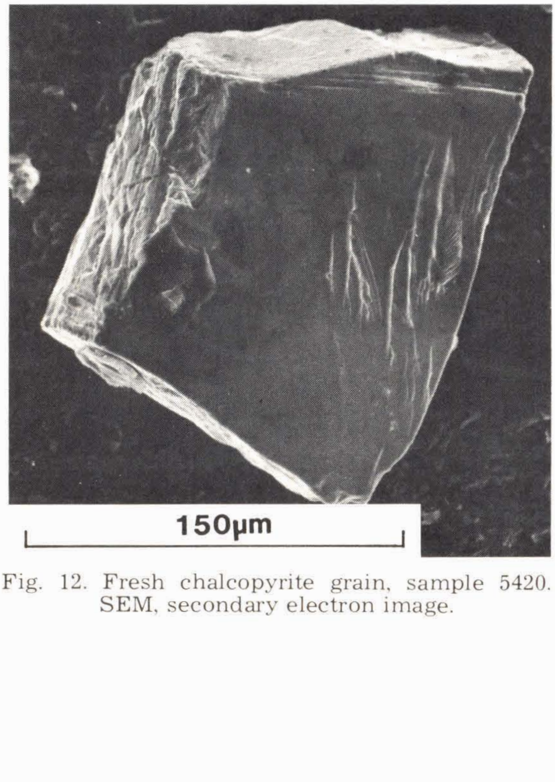


Fig. 12. Fresh chalcopyrite grain, sample 5420. SEM, secondary electron image.

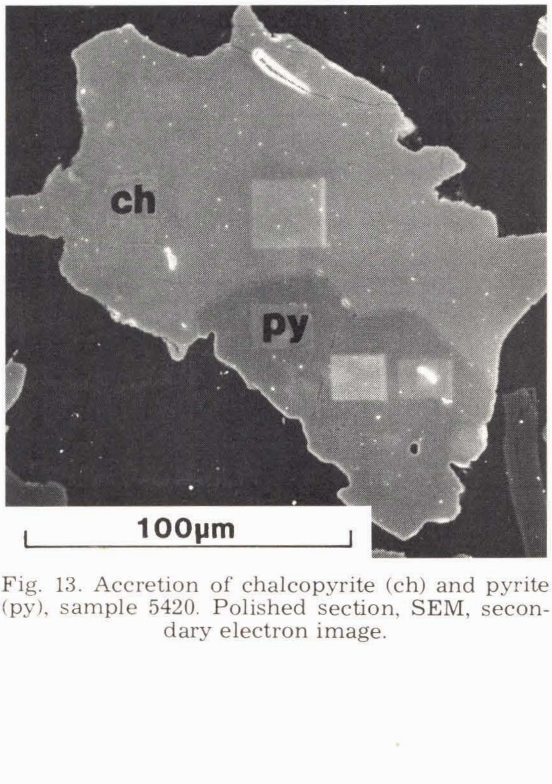


Fig. 13. Accretion of chalcopyrite (ch) and pyrite (py), sample 5420. Polished section, SEM, secondary electron image.

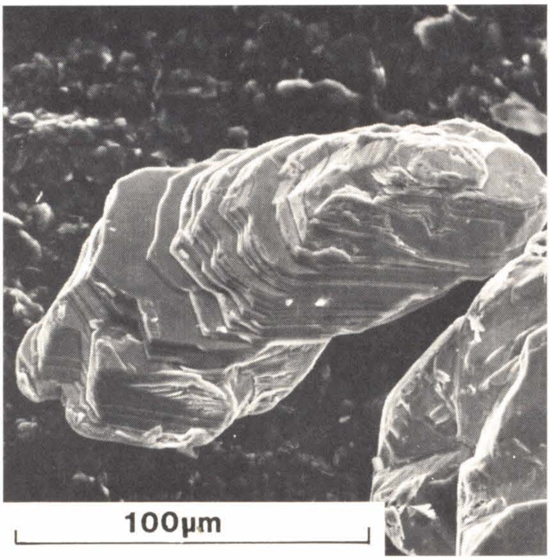


Fig. 14. Fresh molybdenite grain, sample 5420. SEM, secondary electron image.

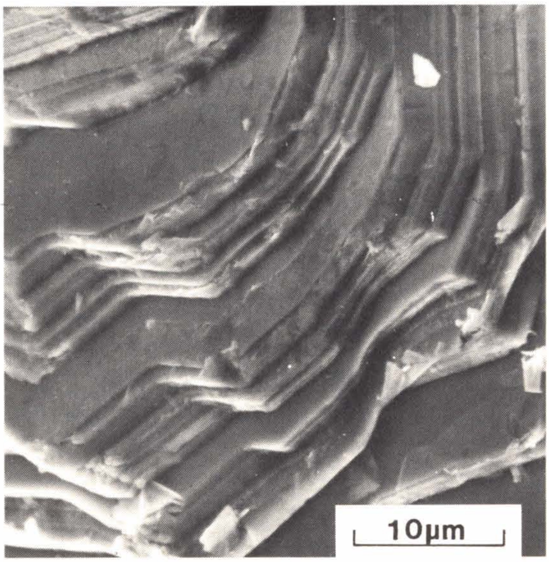


Fig. 15. Detail from Fig. 14. A pile of molybdenite flakes, SEM, secondary electron image.

should be mentioned that the identification of molybdenite from the polished section was very difficult because it polished so poorly.

A small amount of glacial milling might be an explanation of the fact that molybdenite occurs in this sample only in the coarser frac-

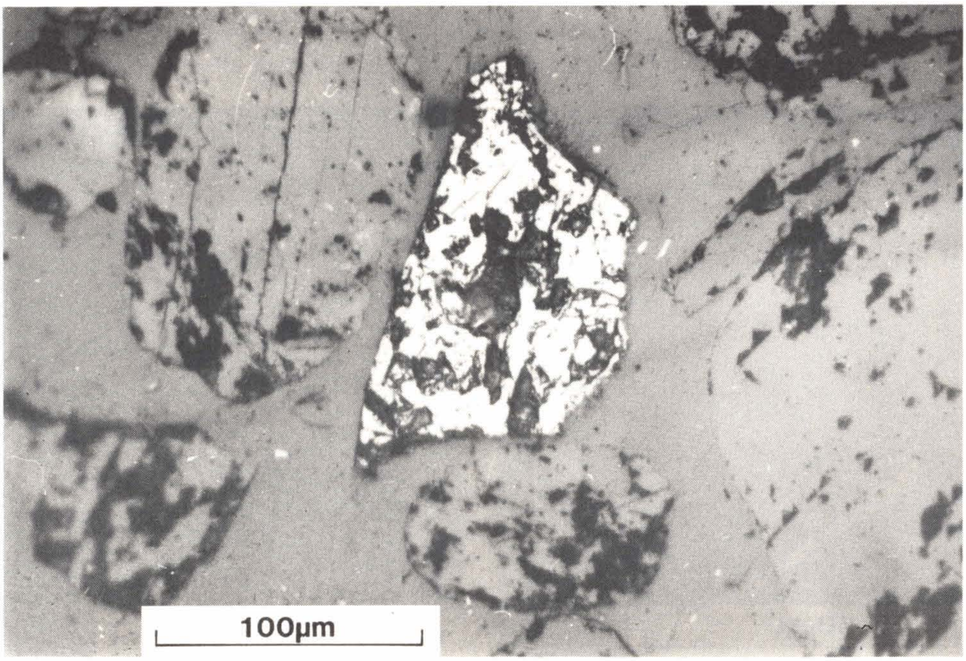


Fig. 16. Broken chalcopyrite grain, sample 7768. Polished section in reflected light, one nicol.

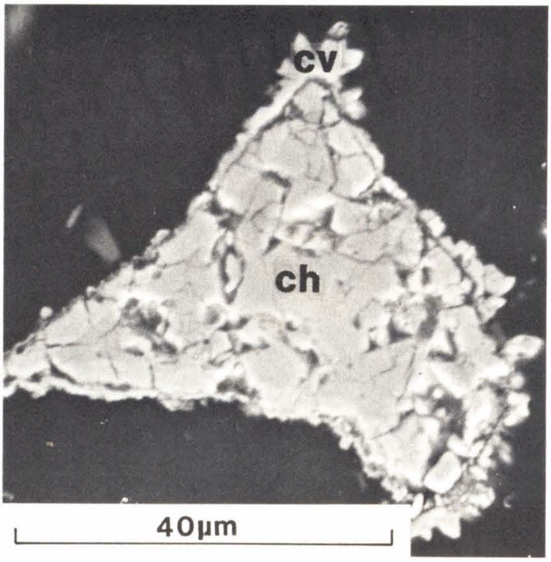


Fig. 17. Chalcopyrite (ch), which has been altered on its edges to covellite (cv), sample 7768. Polished section, SEM, secondary electron image.

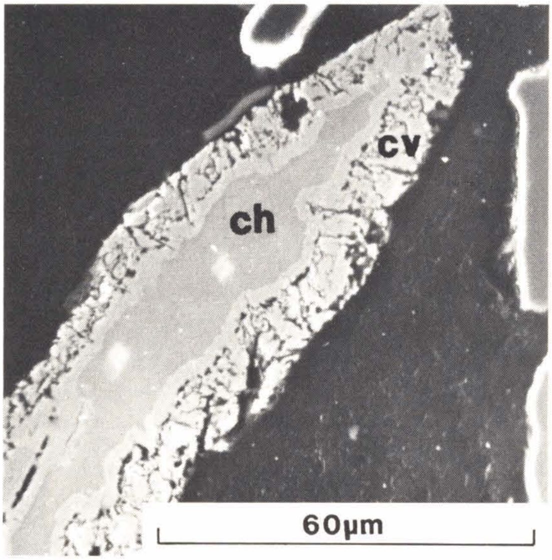


Fig. 18. Grain with dark core of chalcopyrite (ch) and light broken rim of covellite (cv), sample 5230. Polished section, SEM, secondary electron image.

tion. The rock chips of the sample are reddish granodiorite. On the whole, the geochemistry and mineralogy of the sample reflect the nearby porphyritic-type mineralization which is as yet undiscovered.

Sample 7768 (depth 3.0 m; 872 ppm Cu, 210 ppm Mo and 97 ppm Zn in the fine fraction), from the eastern shore of Lake Paavonlampi, contains only a few sulphide grains. Pyrite and chalcopyrite are rather worn and pitted (Fig. 16). Some grains of chalcopyrite have covellite rims (Fig. 17). Molybdenite

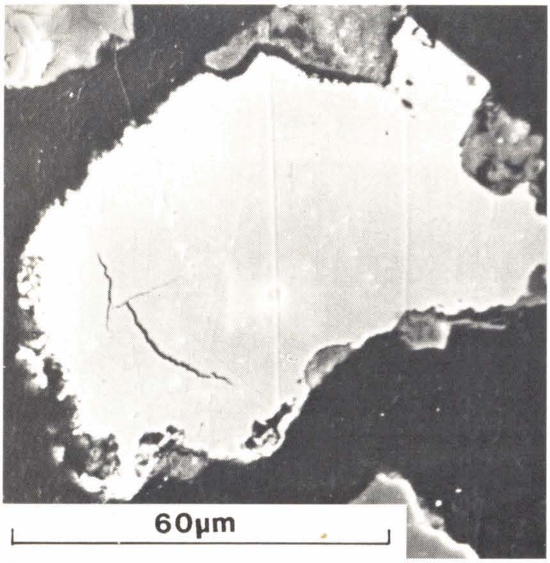


Fig. 19. A light covellite grain, sample 5230. Polished section, SEM, secondary electron image.

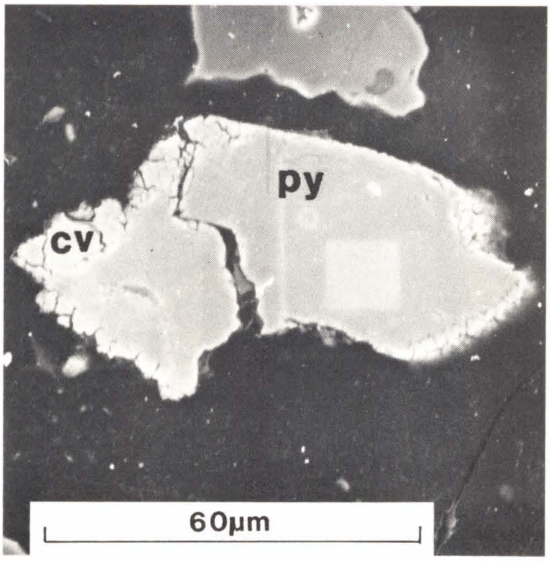


Fig. 20. Pyrite grain (py) with rim of covellite (cv), sample 5230. Polished section, SEM, secondary electron image.

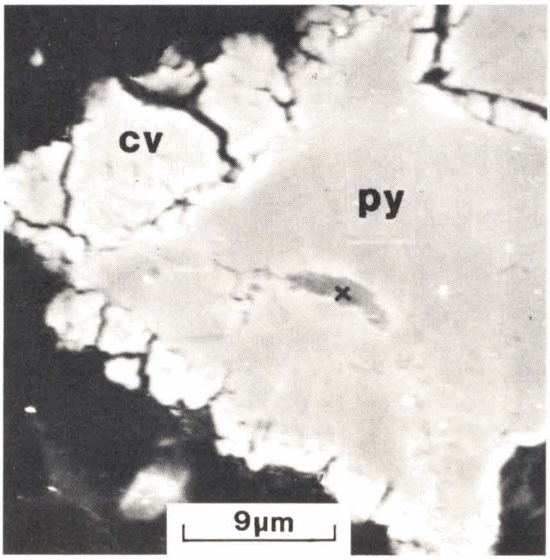


Fig. 21. Detail from Fig. 20. The raggedness of the covellite rim is clearly seen. X = ilmenite inclusion. Sample 5230. Polished section, SEM, secondary electron image.

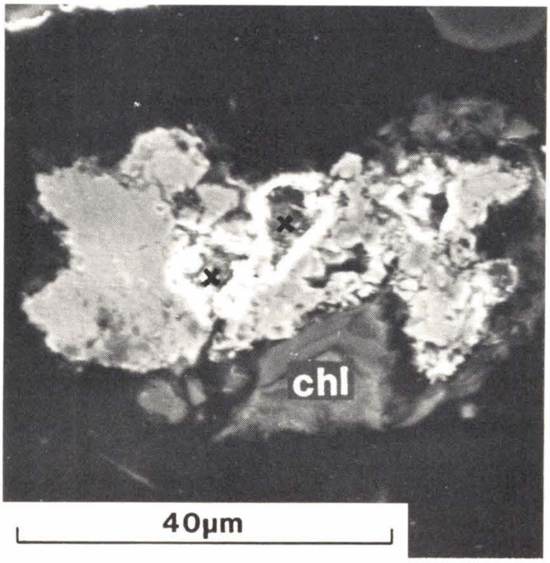


Fig. 22. A light grain of metallic copper. X = chalcopyrite, chl = chlorite. Sample 5230. Polished section, SEM, secondary electron image.

could not be found in this sample. The rock chips of this sample are granodiorite. One chip contains sphalerite dissemination.

Sample 5230 (depth 4.7 m; 960 ppm Cu, 18 ppm Mo and 182 ppm Zn in the fine fraction) is a part of the large copper-molybdenum

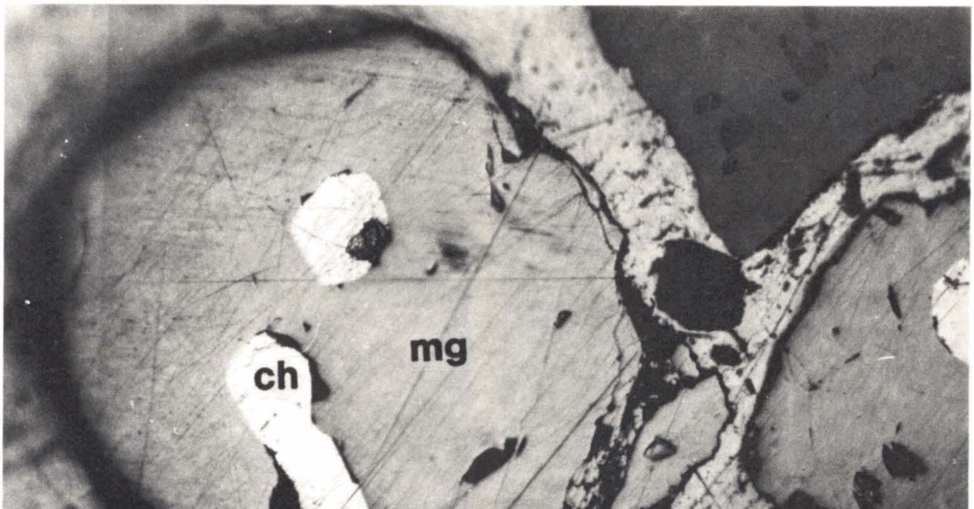


Fig. 23. Chalcopyrite inclusions (ch) in magnetite (mg), sample 8271. Polished section in reflected light, one nicol.

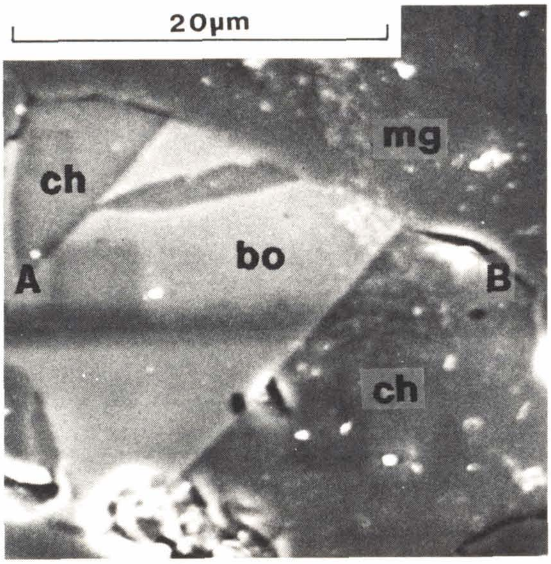


Fig. 24. Accretion of chalcopyrite (ch) and bornite (bo) in magnetite (mg). The line scan of copper along the line A–B is in Fig. 25. Sample 8271. Polished section, backscattered electron image.

anomaly on the southern side of Lake Paavonlampi. The mineralogy of the heavy fraction is very interesting. Chalcopyrite, pyrite and pyrrhotite are present fairly abundantly. Some of the sulphide grains are perfectly fresh. Most of the chalcopyrite grains are surrounded by covellite rims of varying thickness, however (Fig. 18). These rims are also broken. In some chalcopyrite grains, alteration to covellite has proceeded along cracks. Sometimes the whole grain has been altered to covellite (Fig. 19). Also, some pyrite grains are surrounded by covellite rims (Figs. 20–21). A few grains of metallic copper were also found (Fig. 22). When the heavy fraction was analyzed chemically, it was found to contain 3210 ppm Cu, 28 ppm Mo, 380 ppm Zn and and 200 ppm Pb. The rock chips of the sample are quartz-rich granodiorite.

In the southern part of the same large copper-molybdenum anomaly is located sample 8271 (depth 1.6 m), the fine fraction of which contains 1510 ppm Cu, 125 ppm Mo and 104 ppm Zn. In the heavy fraction there is abundant magnetite, which has chalcopyrite inclusions (Fig. 23). In one magnetite grain, a brownish mineral could be seen in connection with chalcopyrite, which on the basis of the line scan of copper (line A–B in Figs. 24–25) contains nearly twice as much copper as chalcopyrite and must therefore be bornite.

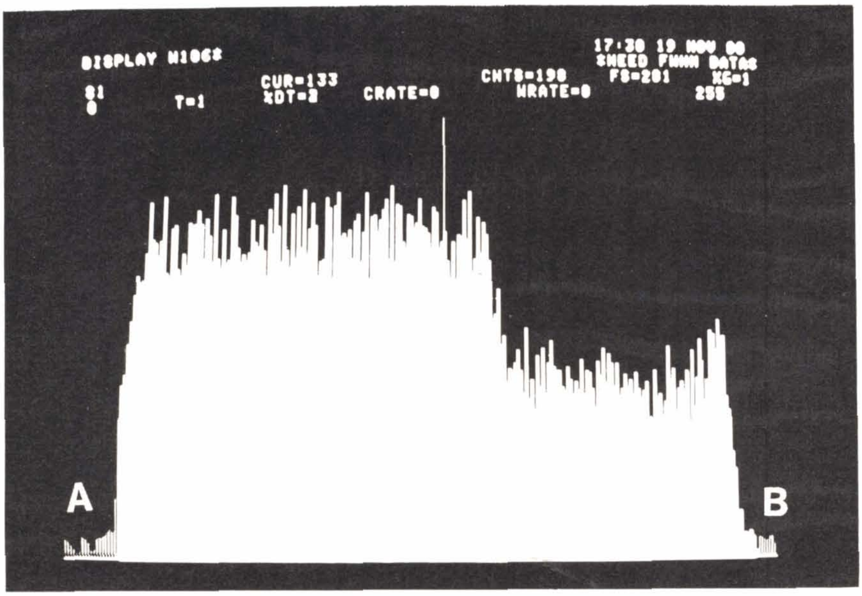


Fig. 25. The line scan of copper along line A–B in Fig. 24.

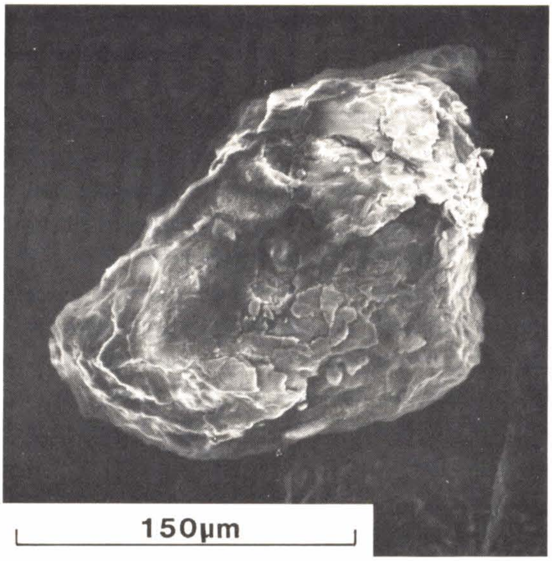


Fig. 26. Chalcopyrite grain, which has been altered to goethite in its surface part, sample 8271. SEM, secondary electron image.

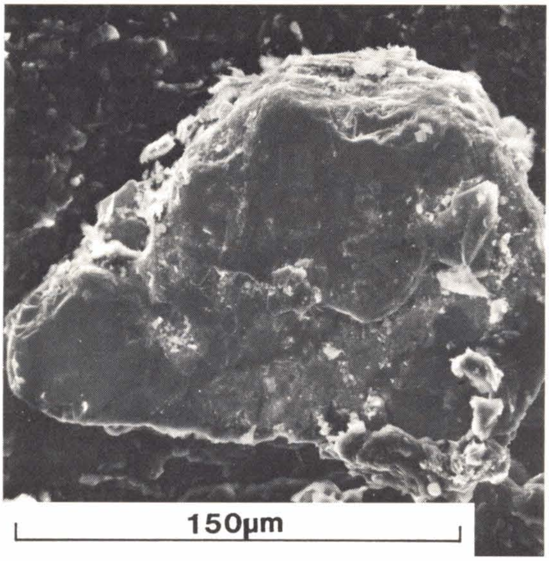


Fig. 27. Molybdenite grain, sample 8271. SEM, secondary electron image.

The sample includes some chalcopyrite grains which have been altered to goethite in their surficial parts (Fig. 26). Discrete fresh chalcopyrite grains could not be found. On the other hand, molybdenite could be identified (Fig. 27). Molybdenum probably also occurs adsorbed to goethite and possibly as ferrimolybdite. The rock chips of this sample are epidote-rich granodiorite.

Sample 7986 (depth 3.1 m) is directly above the small pyrite mineralization located on the southern side of Lake Kuokanlampi. Its fine fraction contains 374 ppm Cu, 5 ppm Mo and 91 ppm Zn. There is plenty of fresh pyrite in the heavy fraction. The few chalcopyrite grains present have no signs of weathering. The rock chips are almost all pyrite pieces.

Sample 5321 (depth 3.7 m) is a part of the copper-zinc-molybdenum anomaly located east of Lake Kuokanlampi. Its fine fraction contains 182 ppm Cu, 1040 ppm Zn and 15 ppm Mo. The heavy fraction includes pyrite, pyrrhotite, galena (Figs. 28–29), sphalerite (Fig. 30) and chalcopyrite. Some galena grains have inclusions of chalcopyrite (Fig. 28) and pentlandite (Fig. 29). All the sulphide grains have no signs of weathering. According to the chemical analysis the heavy fraction contains 1970 ppm Pb, 5750 ppm Zn, 490 ppm Cu and

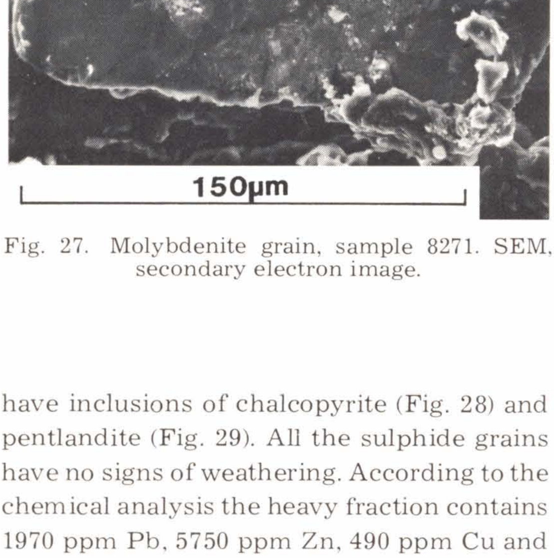


Fig. 28. A light galena grain (gl) with a dark chalcopyrite inclusion (ch), sample 5321. Polished section, SEM, secondary electron image.

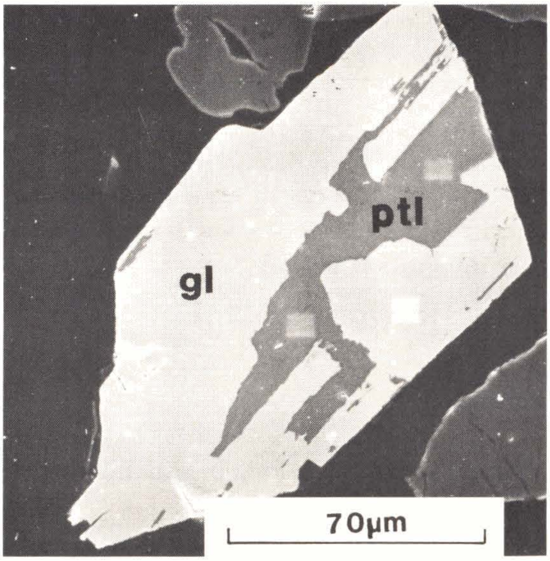


Fig. 29. A light galena grain (gl) with a dark pentlandite inclusion (ptl), sample 5321. Polished section, SEM, secondary electron image.

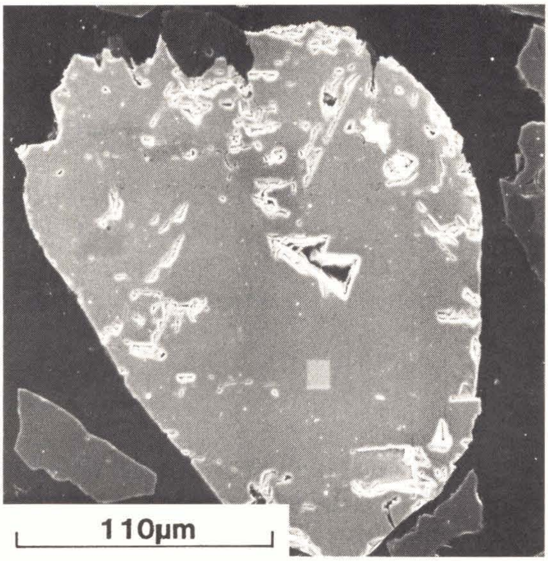


Fig. 30. Sphalerite grain, sample 5321. Polished section, SEM, secondary electron image.

31 ppm Mo. The rock chips are granodiorite, amphibolite and diabase.

Sample 8253 (depth 1.1 m) is a part of the copper-molybdenum anomaly at Lake Paavonlampi. It contains in its fine fraction 522 ppm Cu, 3 ppm Mo and 60 ppm Zn. The heavy fraction includes goethite and two iron sulphates: fibroferrite ($Fe(OH)SO_4 \cdot 5H_2O$) and carphosiderite ($Fe_3(SO_4)_2(OH)_5 \cdot 2H_2O$). No sulphide minerals were found.

Other heavy minerals in the till samples from the Rantavaara area are: amphibole, clinozoisite, hematite, ilmenite, sphene, apatite and chlorite. In addition, some samples contain almandine, zircon and augite.

The results of the mineralogical investigation show unquestionably the predominance of mechanical dispersion.

Those samples which contain unweathered sulphide minerals are from below the water table, generally from the mire area. The sulphide minerals have been weathered wholly or partly to goethite and iron sulphates in the surficial parts of the moraine hummocks. A part of the sulphide-bound metals has then been transported away with the groundwater and a part has been adsorbed on the secondary minerals.

Saksela (1952) has described two sulphate minerals from the weathering crust of the Otravaara pyrite mineralization about 20 km west of Rantavaara. According to him the sulphate minerals have formed during the postglacial.

Covellite and metallic copper may have formed postglacially, but most likely they are derived from the secondary enrichment zone of the weathering crust which covered the mineralization before glaciation (Garrels & Christ, 1965). The secondary copper minerals in the enrichment zone of the weathering crust are generally more copper-rich than the hypogene copper minerals (Park & MacDiarmid, 1975). If this kind of weathered material is abundant in till in some area, it is quite possible that the anomalies in till are too high in an ore prospecting sense.

SUSINEVA AREA

Location and topography

The survey area is situated in Central Ostrobothnia, in the commune of Kalajoki, 130 km southwest of Oulu (Fig. 1). The terrain is quite lowlying and flat, the absolute height being 75–80 m a.s.l. Extensive mire areas are characteristic of the area. The water table is often near the ground surface.

Bedrock and mineralizations

The area is a part of the Svecofennidic schist zone of Ostrobothnia (Salli, 1961). The bedrock map in Fig. 31 has been compiled from field mapping done by Rautaruukki Oy in the summer of 1974. The sedimentary rocks of the schist belt are turbidites and the volcanics are mainly intermediate pyroclastics (Gaal & Isohanni, 1979). The Rautio batholith intruded the sedimentary–volcanic sequence, which had been previously deformed and metamorphosed (*op.cit.*). The batholith is zoned so that the composition changes from basic to acidic when moving from the margin to the center. Granodiorite makes up the greatest part of the batholith. It is mostly even-grained, but in the central part it is clearly porphyritic. Aplite veins are the youngest igneous rock type.

The major constituents of the granodiorite are plagioclase, quartz, microcline, biotite and hornblende. Sphene, apatite and zircon occur as accessories. Plagioclase, microcline and quartz form phenocrysts.

The molybdenum mineralizations at Susineva occur in porphyritic granodiorite in the central part of the batholith. Molybdenite is the most important ore mineral. Chalcopyrite, pyrite and pyrrhotite are minor constituents. Sphalerite, valleriite and covellite have been seen in places. Chalcopyrite includes cubanite as lamellae (Marmo & Hyvärinen, 1953; Gaál & Isohanni, 1979). Molybdenite occurs in quartz and aplite veins, in biotite–chlorite–epidote-rich shear zones and as sparse disseminations in granodiorite. The molybdenite here is clearly more coarse grained than that in the mineralization at Rantavaara.

The molybdenum mineralizations of Susineva have been considered as possible Proterozoic porphyry coppers (Gaál & Isohanni, 1979).

Quaternary deposits

The area is located inside the former ice lobe whose marginal position is represented by the Second Salpausselkä. This ice lobe was named the Savo lobe by Brenner (1944) and later the Finnish Lake District lobe by Aario and Forsström (1978) and Punkari (1979).

When the bedrock map (Fig. 31) is compared to the map of the Quaternary deposits (Fig. 32), it can be observed that the border between the batholith and the schists is also a glaciogeological border. The topographical pattern of the schist area can be classified as a fluted moraine surface.

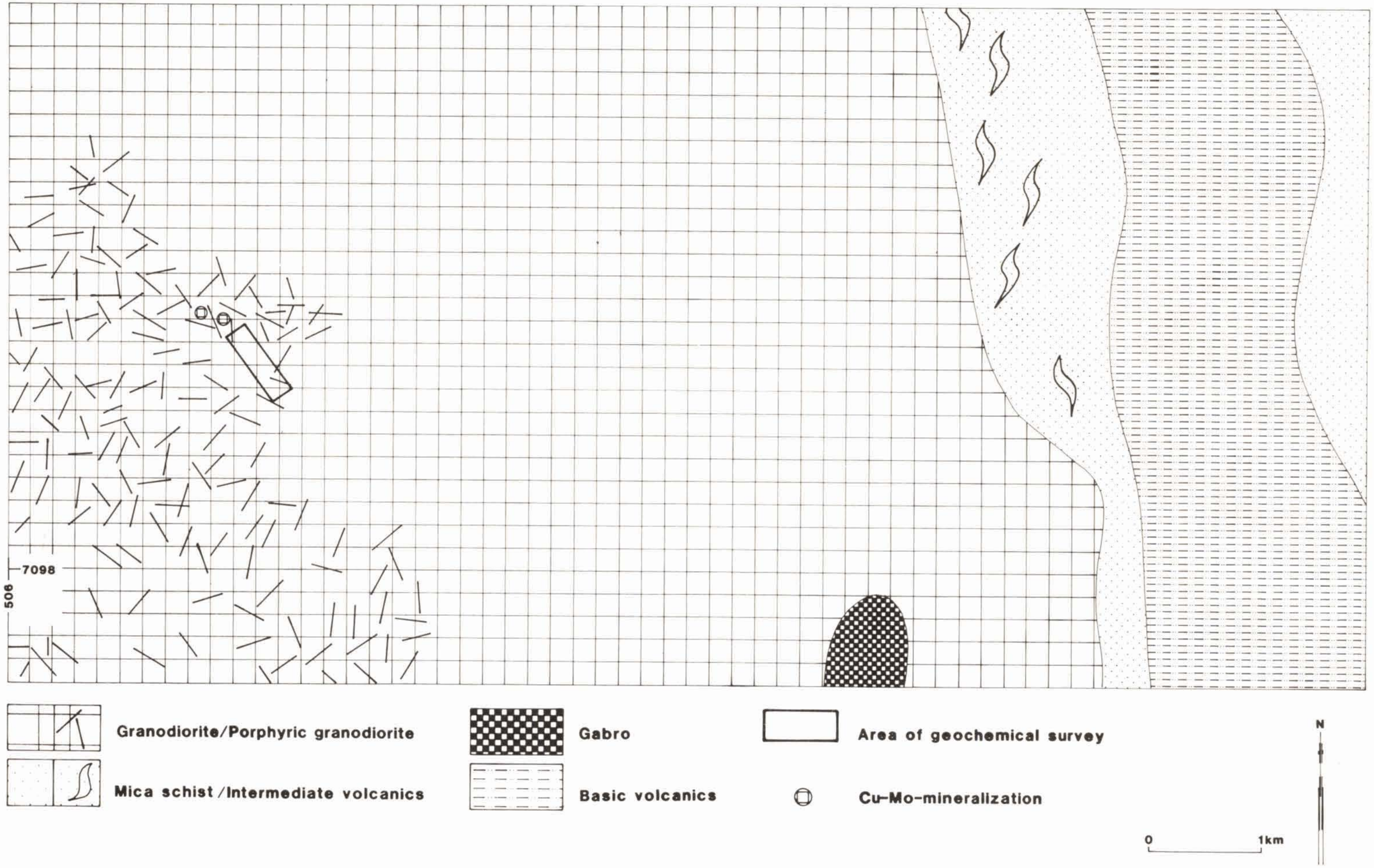


Fig. 31. Bedrock geology of the Susineva survey area.

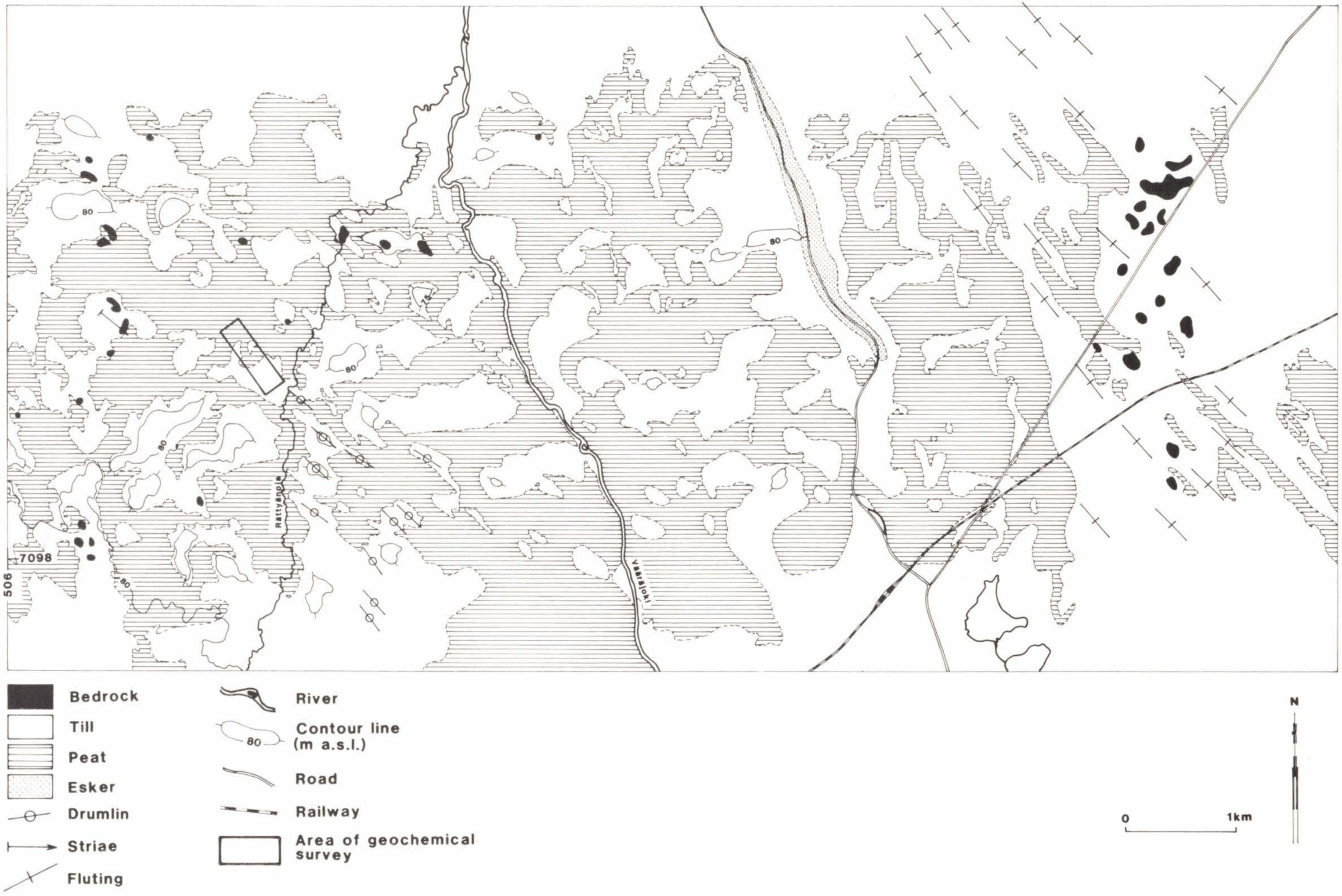


Fig. 32. Quaternary deposits of the Susineva survey area. The drumlins, fluting and striae indicate the general direction of ice movement.

The till in the batholith area has no preferred orientation. On the southeastern side of the geochemically surveyed area there is a small swarm of drumlins. The orientation of the drumlins is same as that of the fluted moraine surface in the schist area. Transverse orientations can also be discerned in the moraine hummocks in places, probably related to the development of Rogen moraine.

Bogs constitute a great part of the surface area. An esker oriented NW–SE crosses the eastern section of the area.

The till in the Susineva area is very compact and bouldery. Its colour is grey from the surface to the bottom. No separate till beds have been observed. The ground surface is in places covered by large boulders. According to Okko (1949) these block fields have been generated by coastal erosion of the Litorina Sea, frost wedging and frost action.

Quite a reliable picture can be inferred concerning the thickness of the overburden by inspection of data from diamond drilling and pneumatic drilling (Table 3). The thickness of the peat layer in mire areas is most often 1–2 m. There is in places sand between peat and till, even as thick as four metres.

The bedrock surface seems to be very even and so the till cover gives rise to the small topographical fluctuations. The area of Susineva can be classified as a ground moraine. This comes well within the definition of ground moraine (cf. Flint, 1971). Only one observation on striae has been carried out, and this, together with the fluted moraine surface and the drumlins, gives a clear and unambiguous picture of the direction of ice movement.

Table 3.

The thickness of the overburden on the basis of diamond and pneumatic drilling in the Susineva area. $\overline{X}$ = arithmetic mean, n = number of observations.

	minimum m	maximum m	$\overline{X}$ m	n
Diamond drilling	6.0	9.7	7.2	11
Pneumatic drilling	4.0	9.2	7.5	318

Ice movement has taken place from 310°–325° and thus it is correlative with the second youngest movement direction in Middle – Ostrobothnia described by Okko (1949). The youngest (285°–300°) and oldest (345°–360°) movements mentioned by him were not found in the Susineva area.

The boulder map in Fig. 33 gives a similar picture of the ice movement direction. The coherent part of the boulder train is about 400 m long and terminates in its northwestern side at the line K9200. Northwest of it is a mire area, which most likely causes the gap in the train. In reality, the length of the boulder train is about 800 m. If all the ore boulders were derived from the known mineralizations at Susineva, then the first ore boulders would appear at the ground surface 200 m from the distal contact of the mineralizations. In addition, the boulder train would extend to one kilometre from the distal contact. It is obvious, however, that boulders have been transported from several sources. The variable texture of the boulders and the strong variation in the proportions of the ore minerals they contain are evidence of multiple sources.

Some stone counts of the boulders in till have been done in exploration pits. The share of granodiorite varies between 80 and 95 % and the share of schists between 5 and 20 %. The distance from Susineva to the distal contact of the schists in the ice movement direction is 8 km. Perttunen (1977) has presented a similar picture of the dominance of local material in the coarse fraction of till in South Finland.

When the transport of ore boulders at Susineva is compared to that at Rantavaara, it can be concluded that the boulders have been transported a little longer from their source at Susineva than at Rantavaara. The difference is not very great, however.

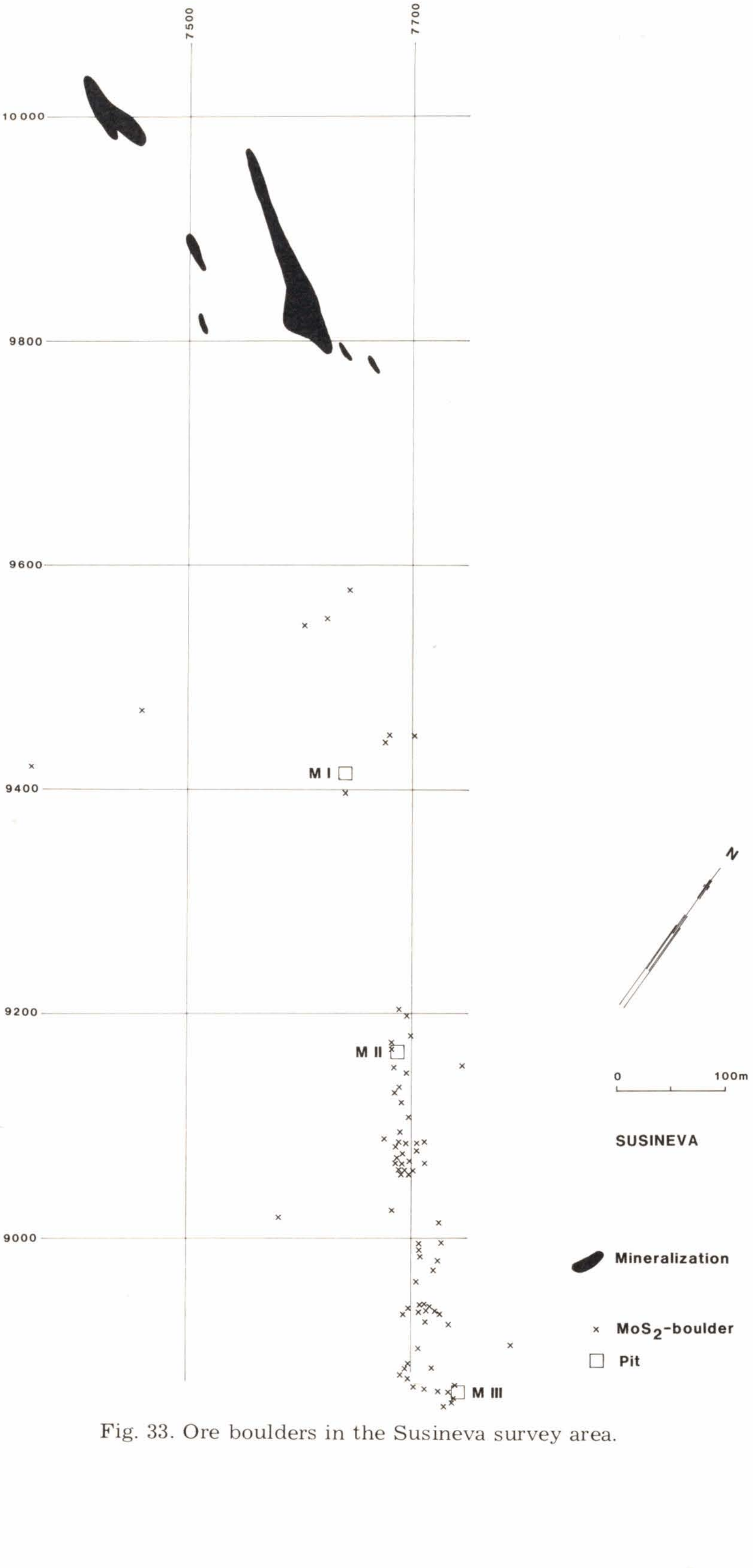


Fig. 33. Ore boulders in the Susineva survey area.

Lithogeochemistry

Only copper and molybdenum contents were determined for the bedrock samples. Because all the samples were of the same species of rock, the metal contents of all sampling points can be compared with each other without transformation calculations (cf. Salminen, 1980).

The distributions of copper and molybdenum can be estimated from Table 4 and the cumulative frequency curves (Fig. 34).

The average content of molybdenum is somewhat higher than the normal molybdenum content (1–2 ppm) of acid igneous rocks (Kuroda & Sandell, 1954; Levinson, 1974). The distribution of molybdenum is clearly skewed indicating anomalous values.

Table 4.

The statistical parameters of copper and molybdenum in bedrock at Susineva. $\overline{X}$ = arithmetic mean, M = median, s = standard deviation, c = coefficient of variation, n = number of samples.

	$\overline{X}$	M	s	c	n
Mo ppm	2.7	1.7	2.9	1.1	254
Cu ppm	43	30	32	0.7	254

The molybdenum contents are not high; the maximum absolute value is 21 ppm. No molybdenite flakes were found on the coarser rock chips of the samples.

The average copper content is also higher than the average (10–30 ppm) in acid igneous rocks (Levinson, 1974; Rose *et al.*, 1979). The distribution is not as skewed as that of molybdenum, but copper also has clearly anomalous values. The highest copper content is 660 ppm.

Sparse chalcopyrite and pyrite dissemination could be discerned in the rock chips of such samples, the copper content of which was some hundreds of ppm.

The anomaly threshold was set at the 80 percentile. The other limits of the anomaly classes are 90, 95 and 98 percentiles.

When the copper map (Fig. 35) and the molybdenum map (Fig. 36) are compared, it can be observed that mutual correlation of copper and molybdenum is poor; the anomalies of each metal are located in different places. The molybdenum anomalies are rather incoherent. Most of the anomalous points occur

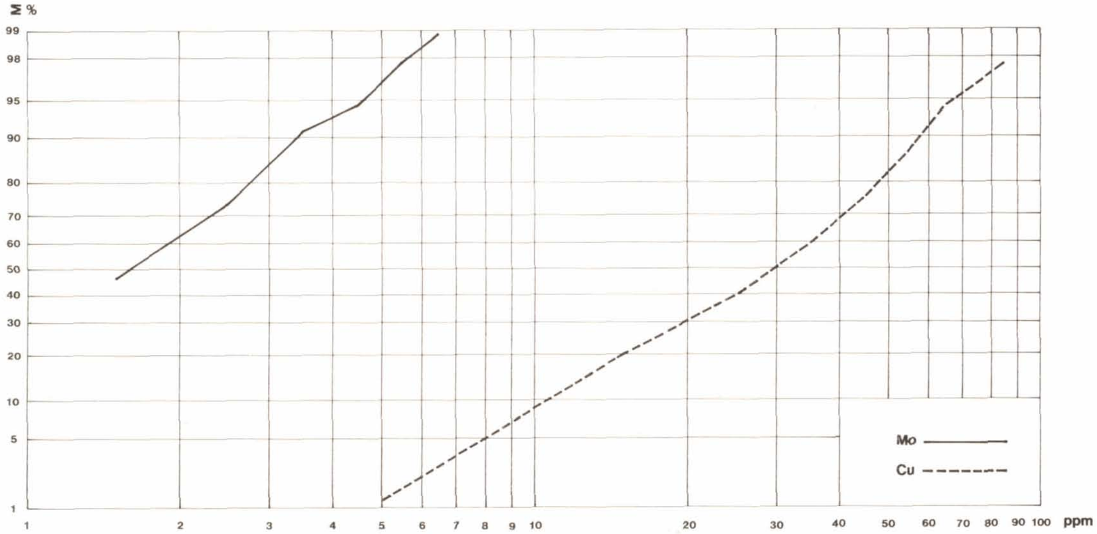


Fig. 34. Cumulative frequency distributions of molybdenum and copper in the bedrock samples at Susineva.

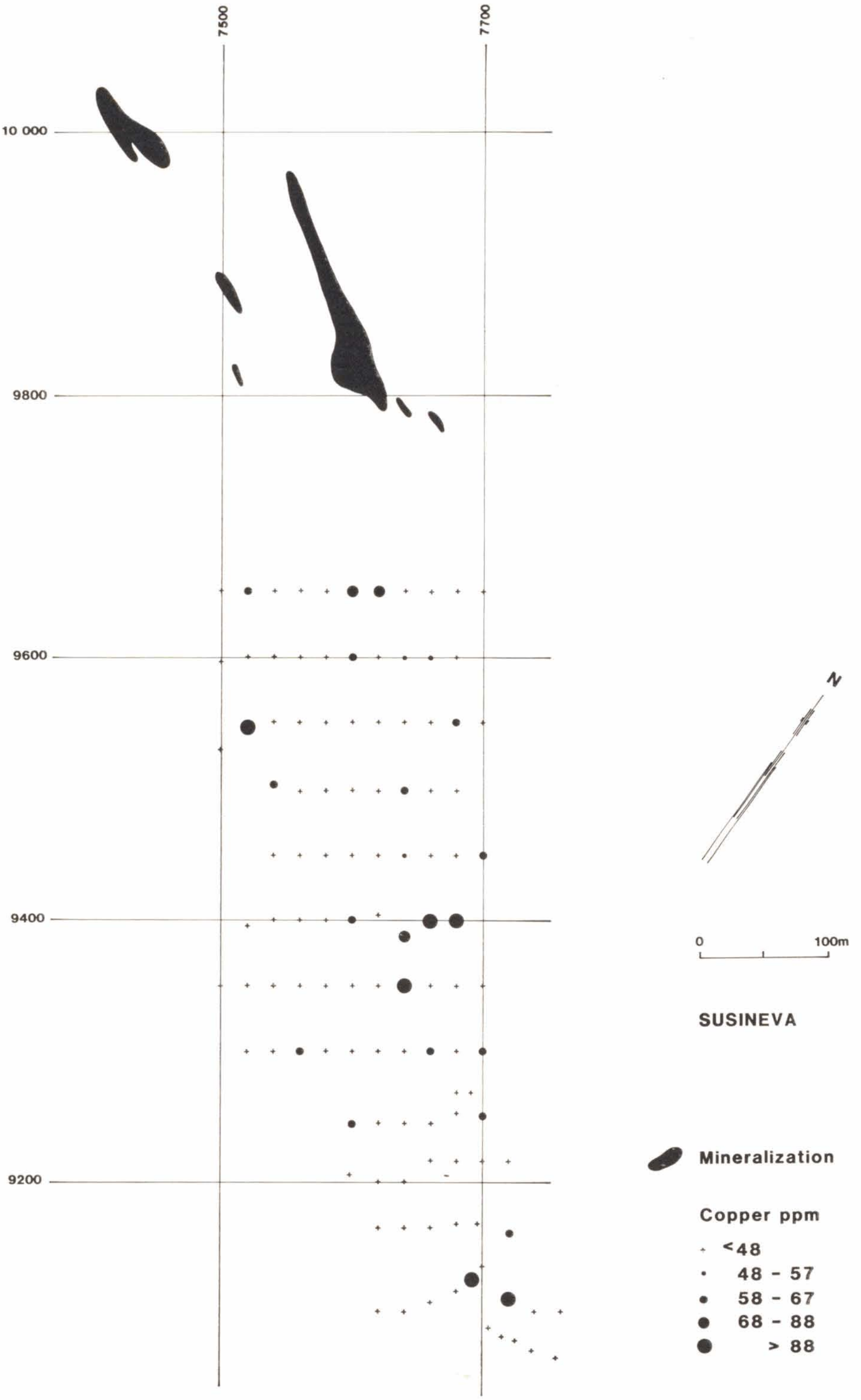


Fig. 35. Symbol map of the areal distribution of copper in the bedrock surface at Susineva.

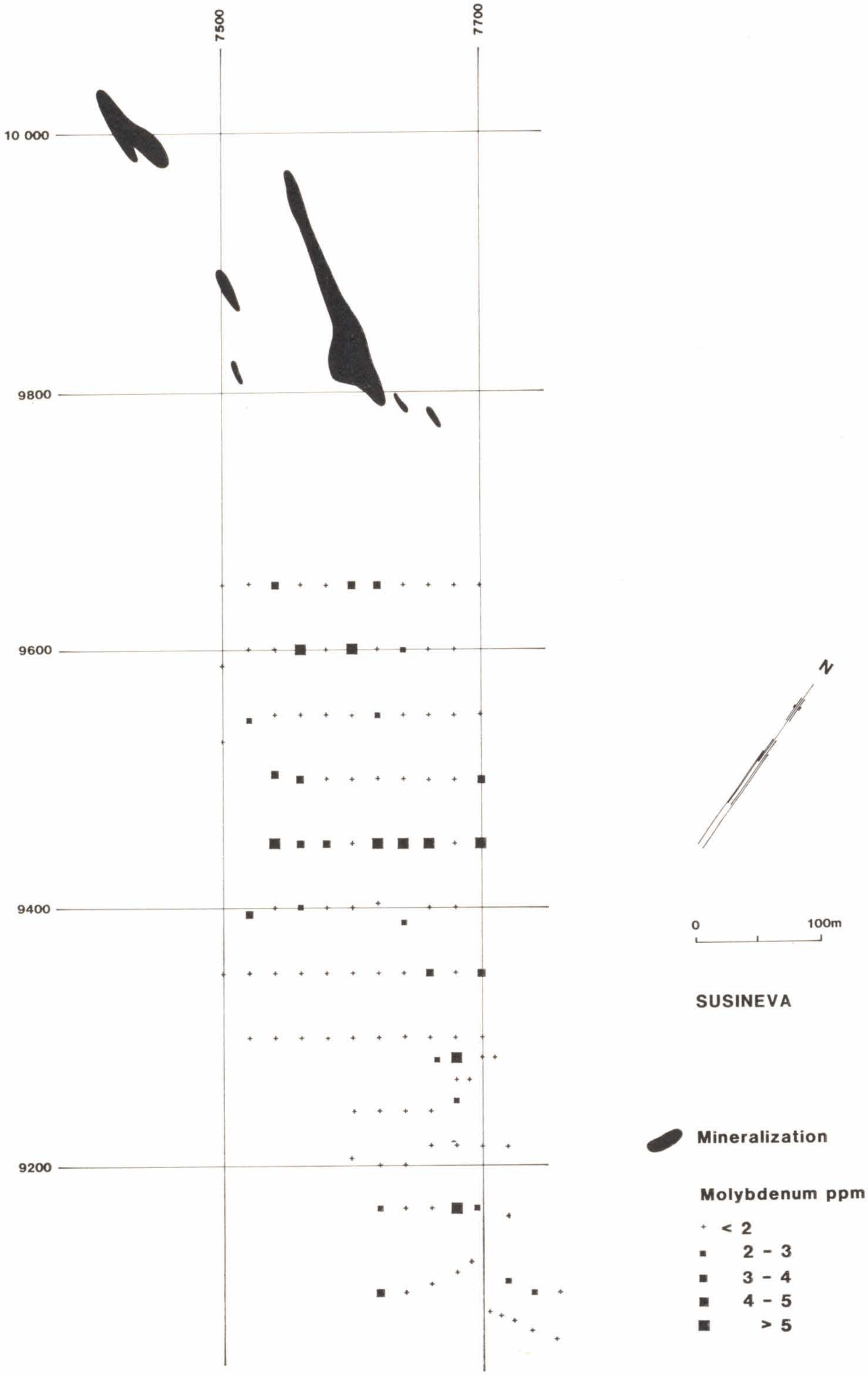


Fig. 36. Symbol map of the areal distribution of molybdenum in the bedrock surface at Susineva.

on line K9450. Sparse molybdenite dissemination was found in some of the drill cores from holes which were drilled later along this profile. The most coherent copper anomaly is between lines K9350 and 9400. The NW–SE directed features that can be observed on the copper map follow the same trend as the mineralizations in the northwest.

Geochemistry of till

Distributions of metals

The effect of grain size on metal contents was studied by sieving nine till samples into four fractions. The diameters of the sieve apertures were 2 mm, 0.297 mm, 0.149 mm and 0.074 mm. The results are presented in Table 5.

These samples were taken from pits M I–M III, which were dug in the boulder train. Pit M I is in the proximal part, pit M II is in the central part and pit M III is in the distal part of the boulder train (Fig. 33). The samples are from one, two and three metres depth. All the samples are from the surficial part of the till when compared to the total thickness of till.

The molybdenum and copper contents increase in almost all the samples as the grain size diminishes (cf. Kauranne, 1958). The only exception is in pit M II at one metre depth. There the highest molybdenum content of till is in the fraction 0.297–0.149 mm. Similarly, the molybdenum content in the fraction 0.149–0.074 mm is higher than in the finest fraction. Rather high molybdenum values occur in all the analyzed fractions in the other samples from the same pit. This was to a certain degree the reason that the upper limit of the analyzed fraction was placed rather high (0.5 mm) in the actual survey phase.

The essential statistical parameters of molybdenum and copper in till are presented in Table 6.

The average molybdenum content, 11 ppm, is noticeably above the normal background in rocks and soils (Kuroda & Sandell, 1954;

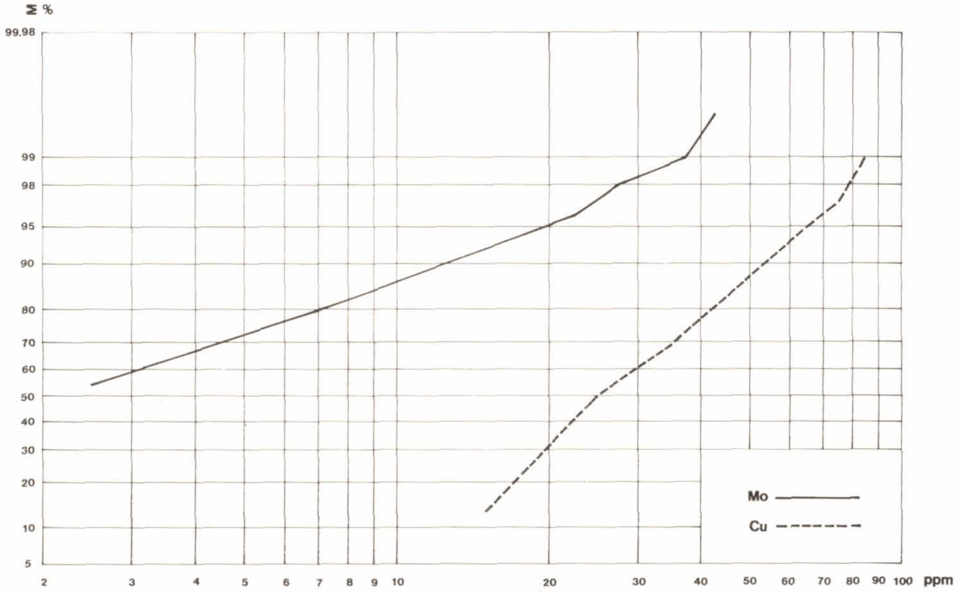


Fig. 37. Cumulative frequency distributions of molybdenum and copper in till at Susineva.

Table 5.

Copper and molybdenum contents in the various fractions of till at Susineva.

pit	M I						M II						M III					
depth m	1		2		3		1		2		3		1		2		3	
ppm	Mo	Cu	Mo	Cu	Mo	Cu	Mo	Cu	Mo	Cu	Mo	Cu	Mo	Cu	Mo	Cu	Mo	Cu
ø mm																		
2–0.297	4.0	21	3.0	23	4.0	22	53.0	24	16.0	32	18.0	26	2.0	18	1.5	24	1.5	26
0.297–0.149	9.5	24	5.0	18	13.0	42	123.0	31	41.0	40	72.0	30	4.5	19	2.5	26	2.5	26
0.149–0.074	11.0	27	6.5	18	13.5	40	115.0	33	50.0	42	93.0	35	5.0	20	3.5	29	4.5	30
< 0.074	27.0	48	20.5	42	42.5	80	87.0	52	135.0	92	105.0	71	11.5	31	6.0	58	6.0	61

Table 6.

The statistical parameters of copper and molybdenum in till at Susineva. $\overline{X}$ = arithmetic mean, M = median, s = standard deviation, c = coefficient of variation, n = number of samples.

	$\overline{X}$	M	s	c	n
Mo ppm	11.2	2.2	40	3.6	371
Cu ppm	38	25	33	0.9	371

Canney *et al.*, 1961; Davy, 1973). This is caused by the fact that the greatest part of the sampling area is anomalous as a result of its location near the known mineralizations. If the ten highest values of molybdenum were rejected, the average content would drop to 6.7 ppm.

The average copper content is also higher than the usual content in till in the granitic areas of Ostrobothnia (Kauranne, 1980).

The frequency distribution curves of molybdenum and copper are presented in Fig. 37. The exceptionally high molybdenum contents, over 50 ppm, were rejected when the frequency distribution was prepared. Because the area is enriched with copper and molybdenum by the known mineralizations, the anomaly threshold was raised to the 90 percentile (Mo 12.5 ppm, Cu 53 ppm), so that the geochemical response caused by possible new mineralizations would become better visible. The other limits of the anomaly classes are the 95 and 98 percentiles. In addition, the highest molybdenum contents were divided into two high anomaly classes, 50–100 ppm and over 100 ppm. The copper contents over 100 ppm were classified as high anomalies.

The symbol maps of copper (Fig. 38) and molybdenum (Fig. 39) have been prepared so that each sampling point is represented by its highest metal content irrespective of the sampling depth. Copper has two quite coherent anomalies. One is located in the northwestern corner of the survey area and it probably con-

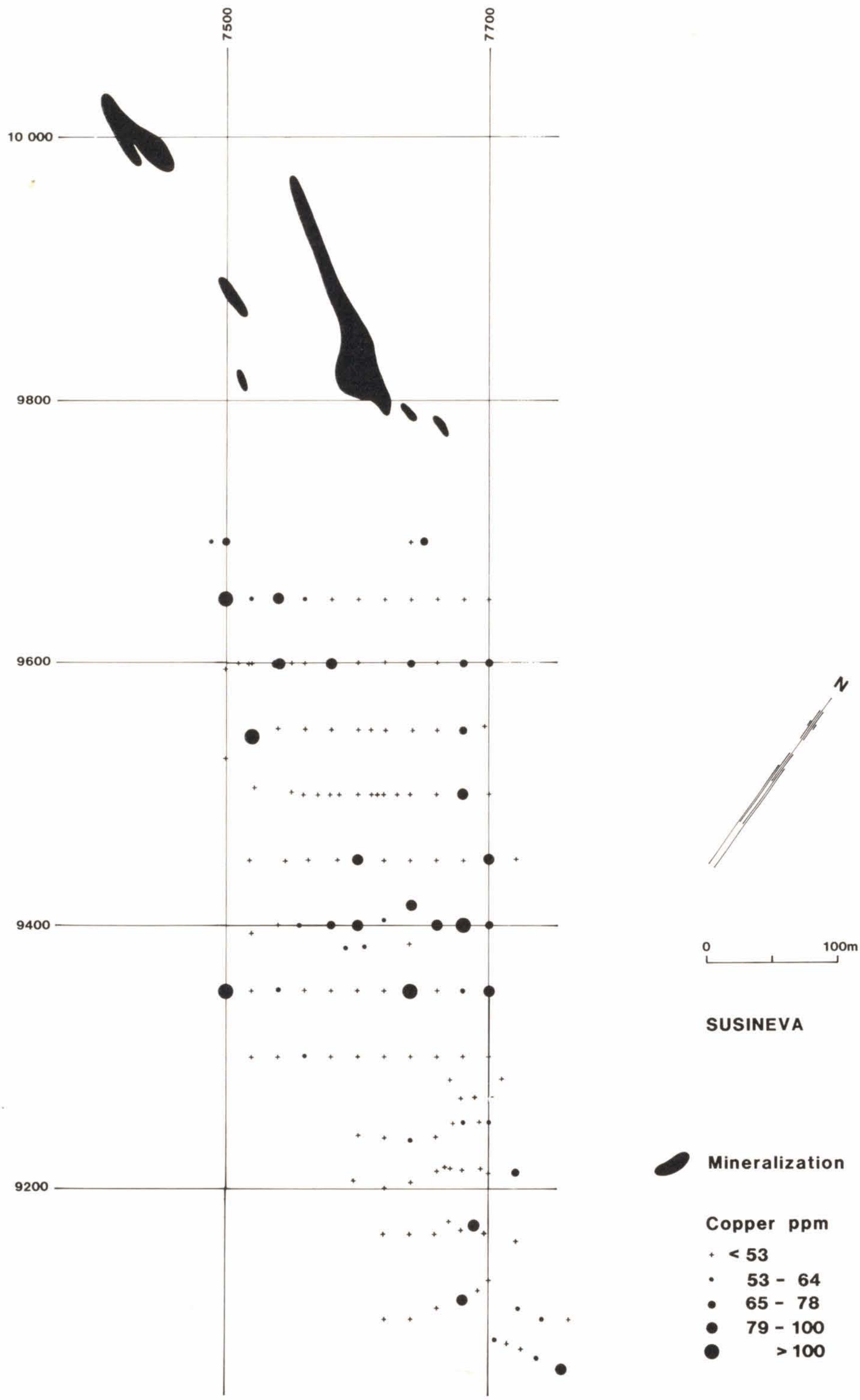


Fig. 38. Symbol map of the areal distribution of copper in till at Susineva. Every sampling point is represented by its highest copper content regardless of depth.

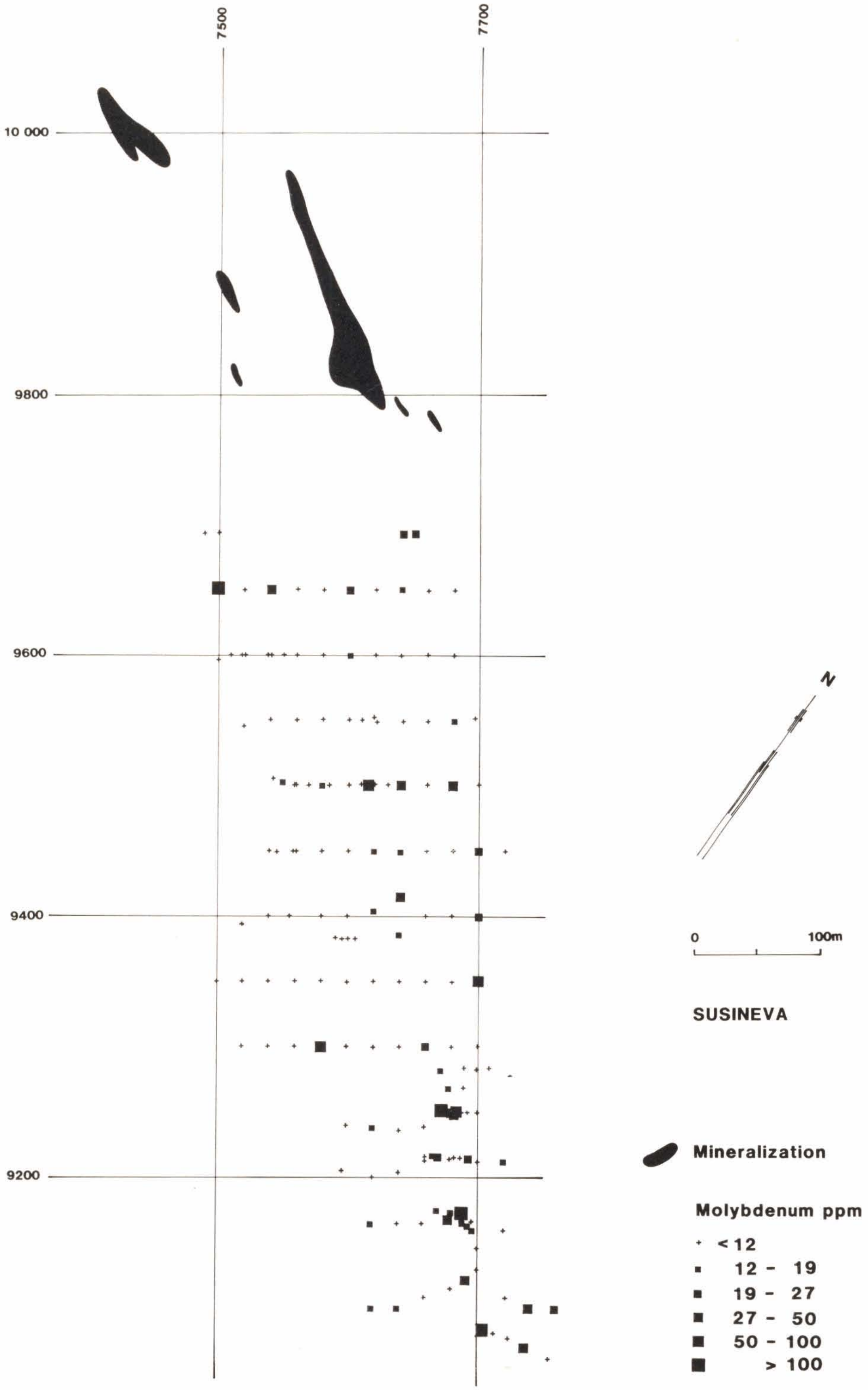


Fig. 39. Symbol map of the areal distribution of molybdenum in till at Susineva. Every sampling point is represented by its highest molybdenum content regardless of depth.

tinues to the northwest. The anomaly includes the highest copper (381 ppm) and molybdenum (665 ppm) contents of the whole area. Another wider copper anomaly is situated on lines K9350–9400 and narrows to the northwest. Molybdenum content is also high in some samples in this anomaly.

The most coherent molybdenum anomaly is located in the southeastern corner of the survey area. The anomaly overlaps partly with the boulder train. Several high values occur in it (274, 160 and 135 ppm). It is noteworthy that this anomaly is a pure molybdenum anomaly. Only in some samples is the copper content increased. Scattered molybdenum anomalies occur in the whole survey area.

If the molybdenum and copper anomalies were derived entirely from the known mineralizations, the length of dispersion train in the direction of ice movement would be 400 m for copper and 1000 m for molybdenum. This interpretation is ambiguous, however, because sparse molybdenite and chalcopyrite dissemination was found in several drill cores on profile K9450.

The copper and molybdenum contents for three different depth levels have been presented in Figs. 40–45. Copper and molybdenum differ clearly from each other in their behaviour as a function of depth. The copper contents increase downwards and the most coherent anomalies are just above the bedrock surface. The highest copper and molybdenum values (Cu 381 ppm, Mo 665 ppm) are in the 3–5 m depth range (Figs. 41 and 44). There are only scattered copper anomalies in till nearer the ground surface (Fig. 40). The geochemistry of copper in the deepest till samples (Fig. 45) correlates quite well with the lithogeochemistry of copper (Fig. 35). Thus, the copper content of till just above the bedrock surface reflects the copper content of the local bedrock.

The molybdenum anomalies are located for the greatest part at 3–5 m depth (Fig. 44). Quite high molybdenum contents (max 135 ppm) occur also in the uppermost till samples, particularly in the southeastern part of the area. In contrast to the copper data, there are only scattered molybdenum anomalies and no highly anomalous values in the deepest till samples (Fig. 45).

The geochemistry of molybdenum in the deepest till samples correlates very poorly with the lithogeochemistry of molybdenum. This may be reflected in the fact that no rock chips from the pneumatic drilling contained molybdenite and thus none of the deepest till samples are from just above the mineralization. Certainly, scanty molybdenite dissemination was found by diamond drilling, but the suboutcrops of the mineralizations may be of small area, because they were not intersected by the dense network of pneumatic drilling.

The source of the copper-molybdenum anomaly in the northwestern part of the survey area may be the old known mineralizations, in which case the length of dispersion would be 150–300 m.

The southeastern molybdenum anomaly may have been caused by mineralization that is presently undiscovered. That source would lie between the head of the anomaly and the known mineralizations. This idea would be favoured by the fact that the relatively pure molybdenum anomaly is involved, whereas the known mineralizations contain copper in a noticeable degree in addition to molybdenum.

Mode of occurrence of metals

Mineralogical studies

Molybdenite flakes were observed in the till at Susineva even during the field stage of the surveys. All till samples were studied mineralogically. The share of the heavy fraction (>3.31 g/cm^3) in the samples was 0.001–

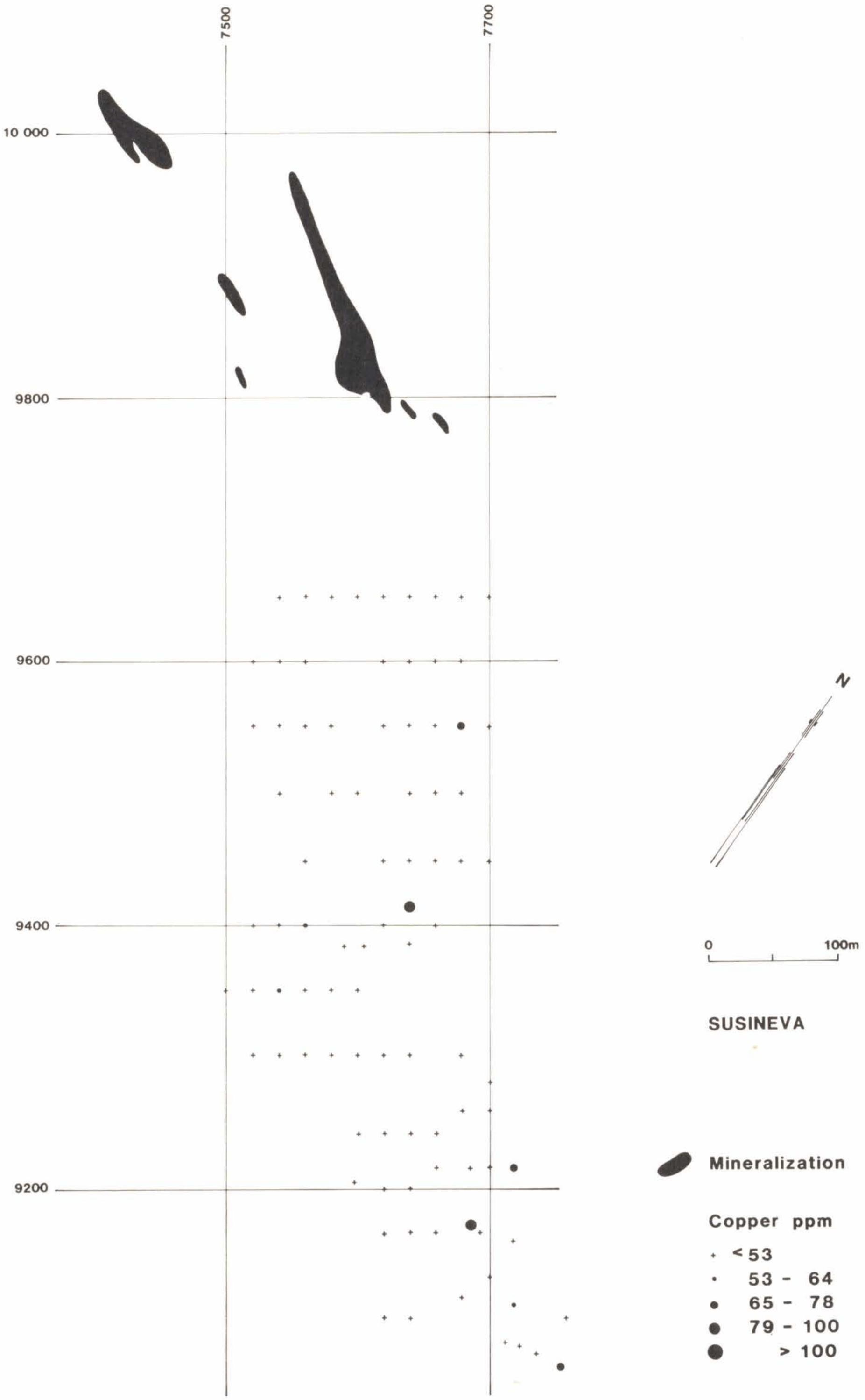


Fig. 40. Symbol map of the distribution of copper in till at 2–3 metres depth at Susineva.

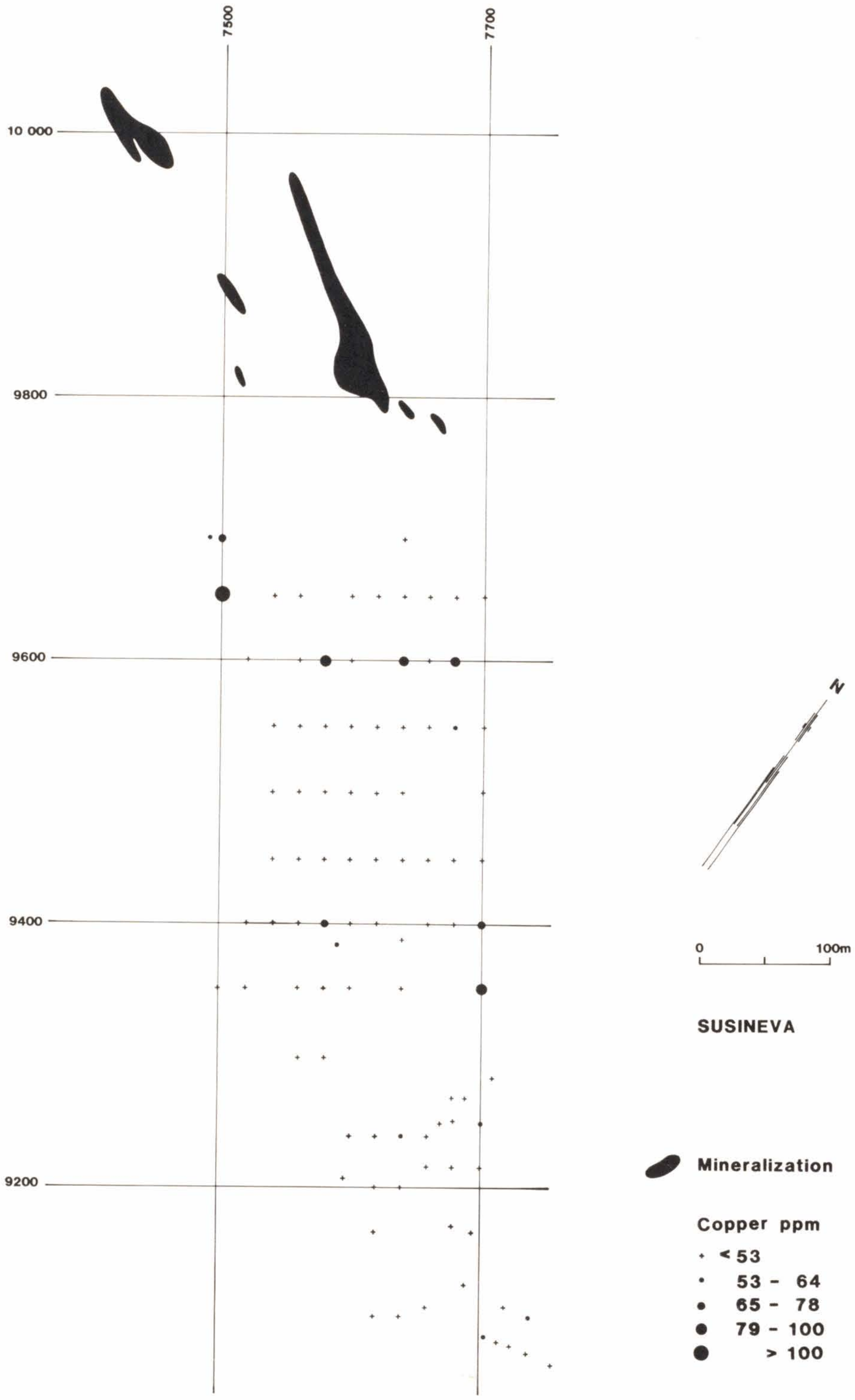


Fig. 41. Symbol map of the distribution of copper in till at 3–5 metres depth at Susineva.

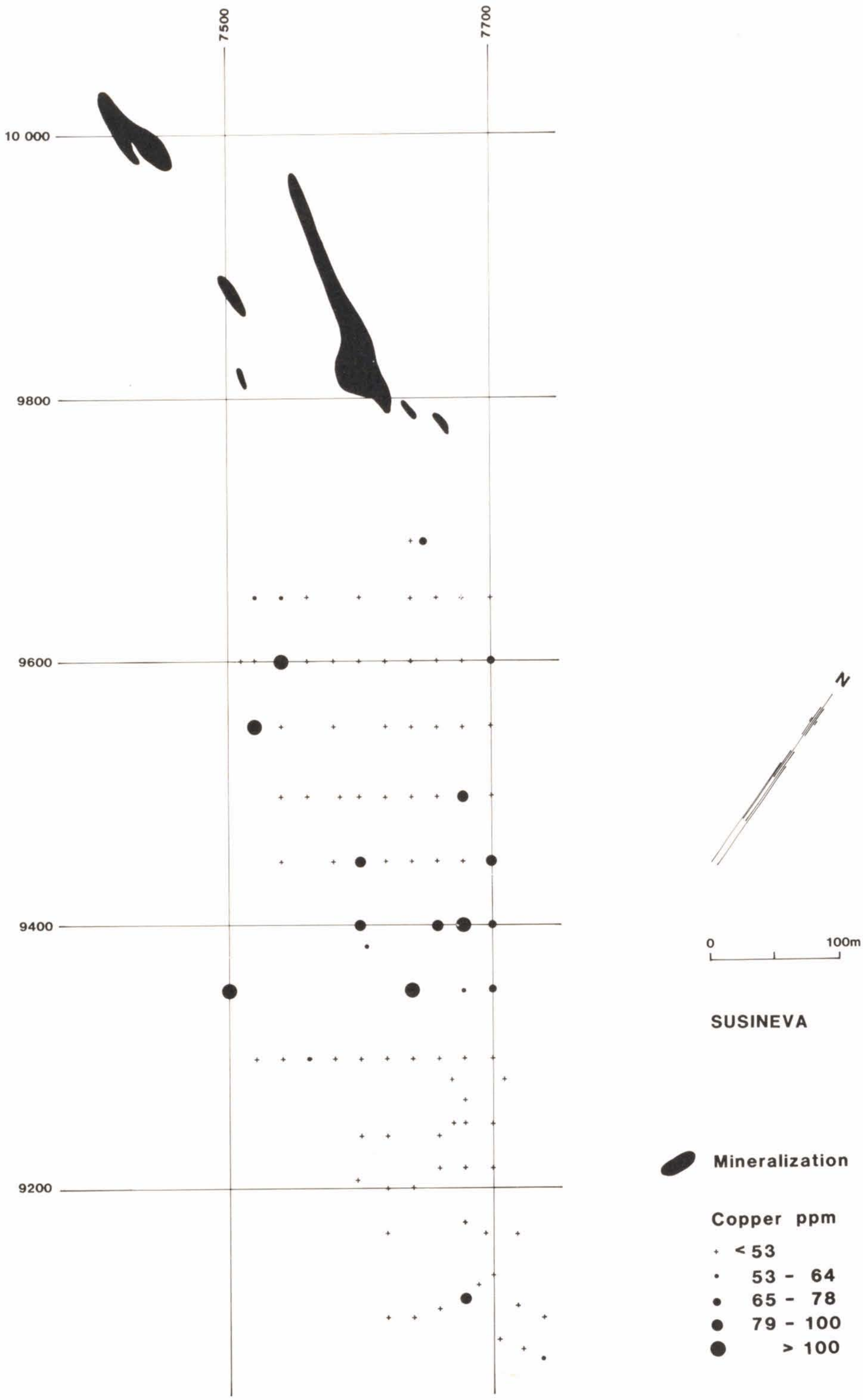


Fig. 42. Symbol map of the distribution of copper in till just above the bedrock surface at Susineva.

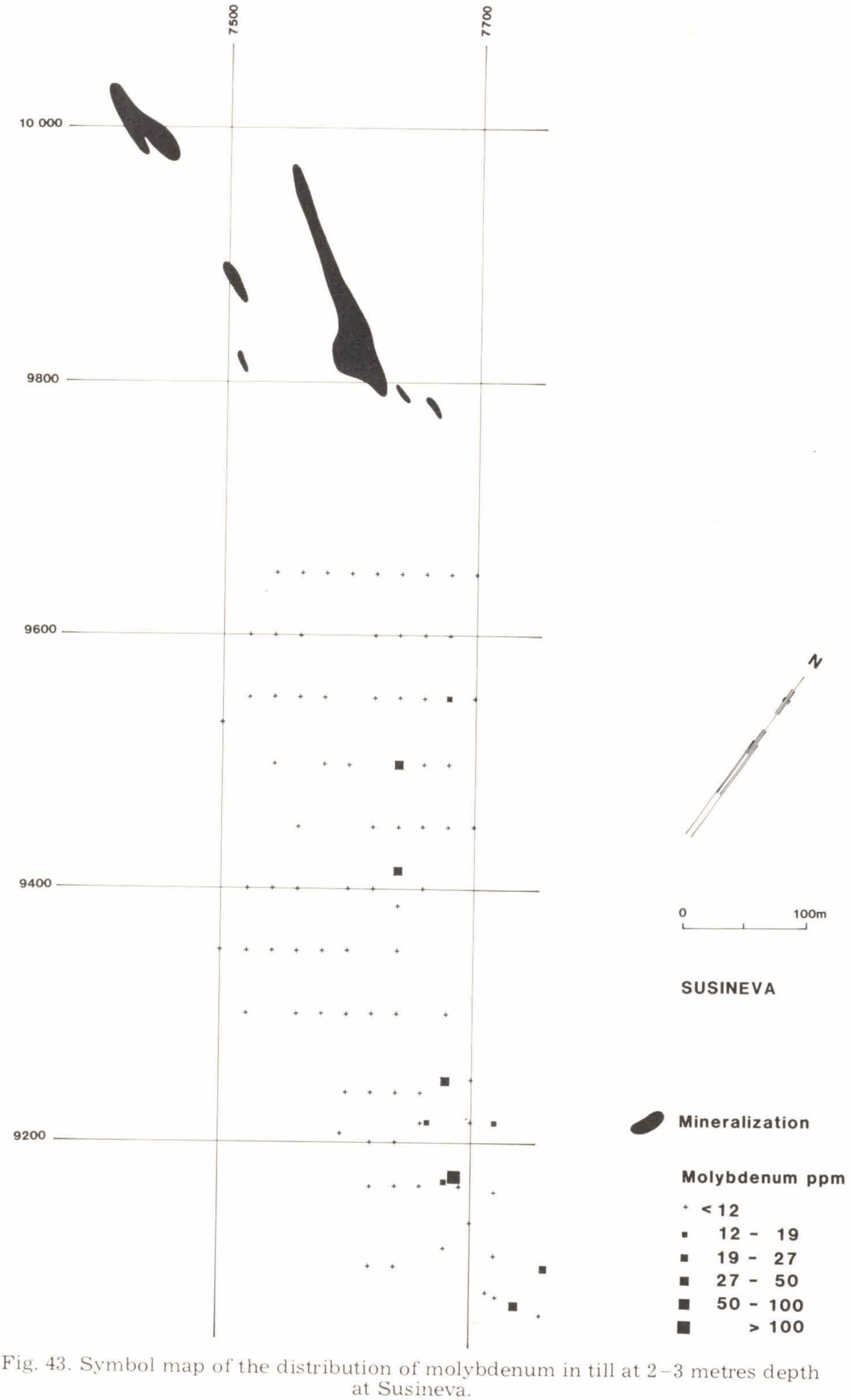


Fig. 43. Symbol map of the distribution of molybdenum in till at 2–3 metres depth at Susineva.

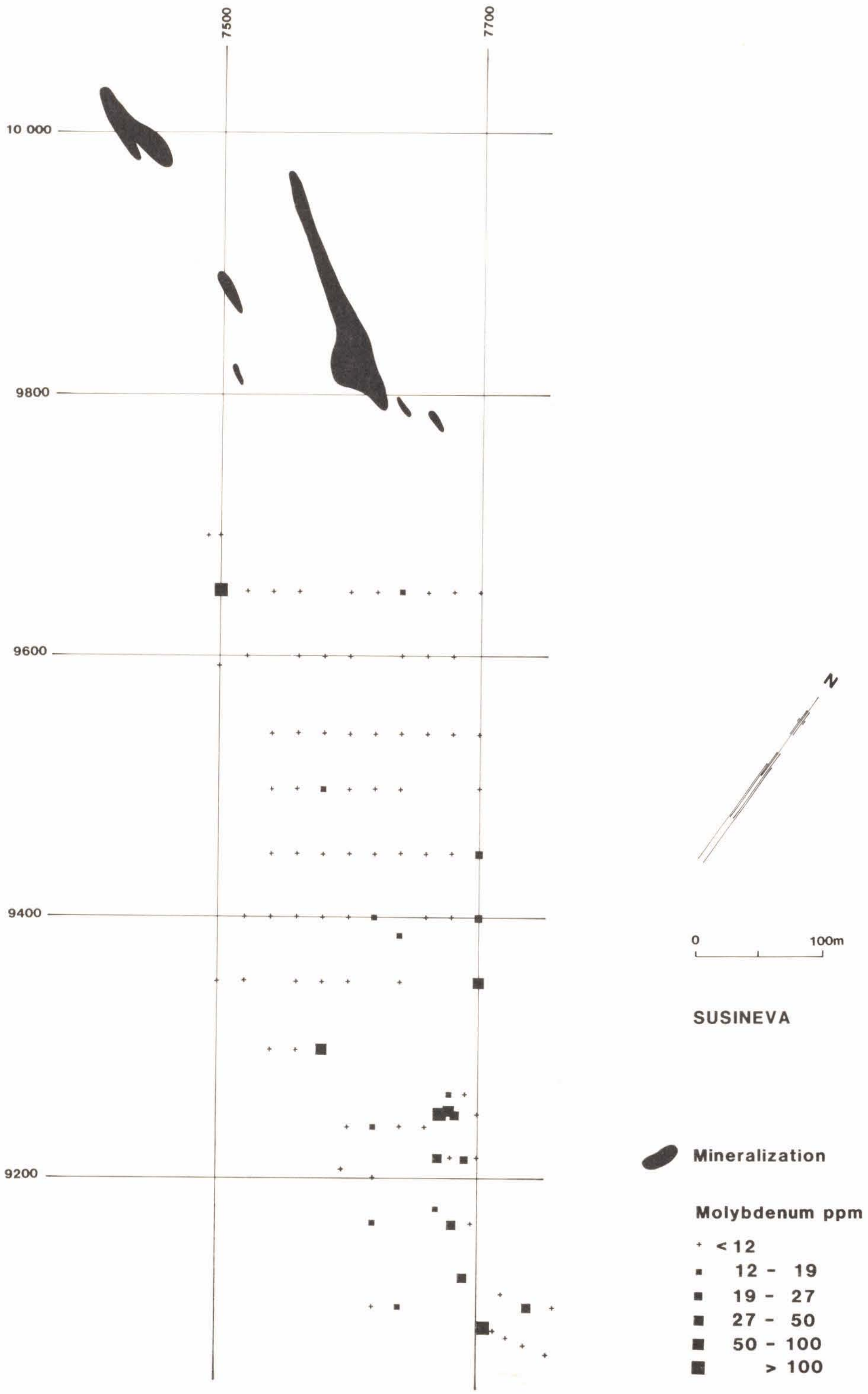


Fig. 44. Symbol map of the distribution of molybdenum in till at 3–5 metres depth at Susineva.

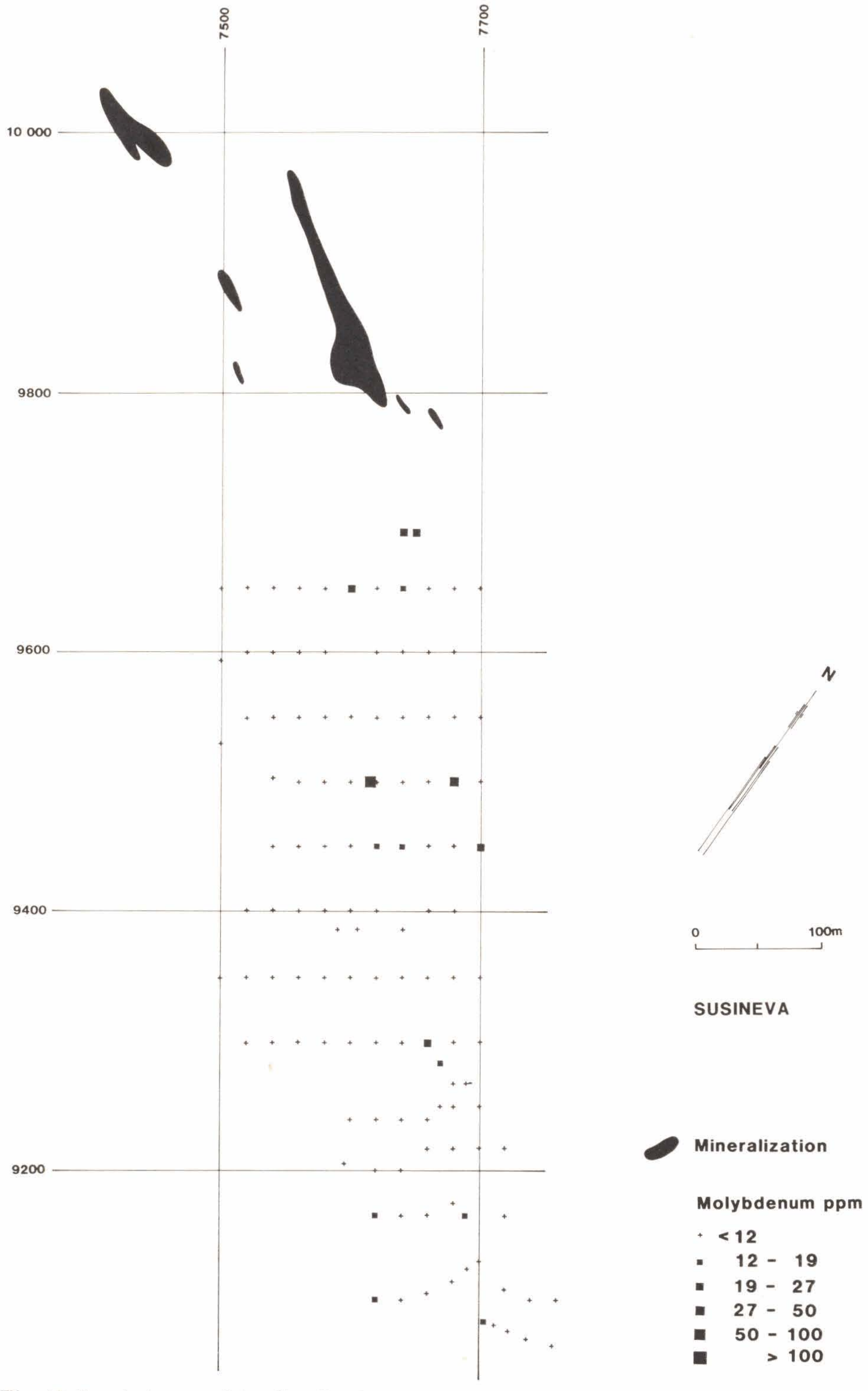


Fig. 45. Symbol map of the distribution of molybdenum in till just above the bedrock surface at Susineva.

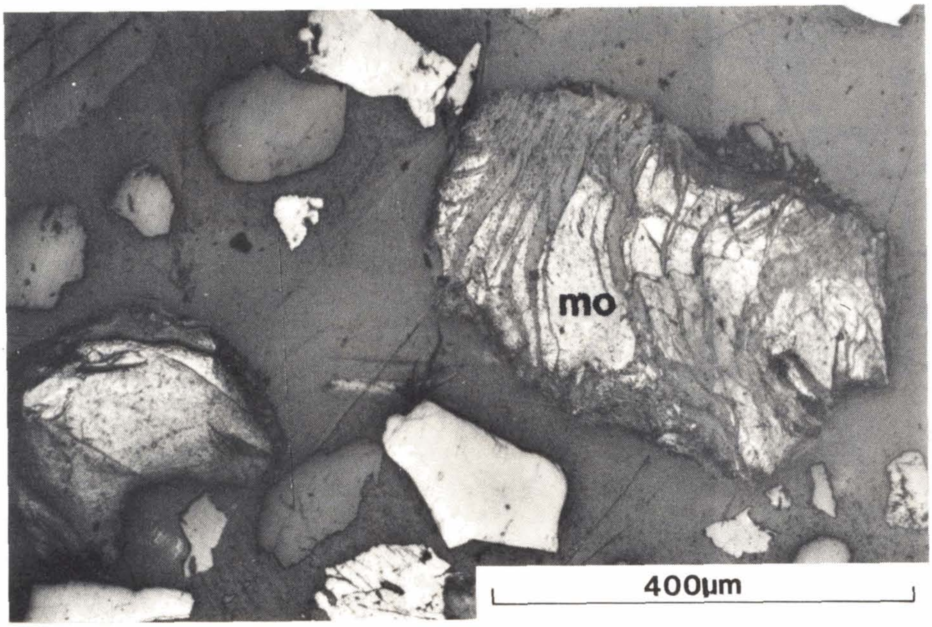


Fig. 46. Fresh molybdenite (mo), sample 5414. Polished section in reflected light, one nicol.

1 %. Most of the samples studied contain molybdenite, chalcopyrite and pyrite. Molybdenite occurs as bright flakes and piles of flakes which have no signs of weathering (Fig. 46). Molybdenite can be found also in the heavy fractions of such samples, whose fine fractions contain no anomalous contents of molybdenum.

Chalcopyrite and pyrite also occur as bright, unweathered grains (Figs. 47–48). Sphalerite occurs as inclusions in some chalcopyrite and pyrite grains (Figs. 47–48), but no separate sphalerite grains have been found in the till samples. Unweathered pyrrhotite and magnetite are present in some samples. Covellite or valleriite have not been seen in the heavy fraction. This is quite understandable, because they are rare in the bedrock of the area (Marmo & Hyvärinen, 1953).

There are few silicate minerals in the heavy fraction, because the specific gravity of most of the silicates is lower than that of methylene iodide. Micas, amphiboles, epidote and garnet are present in some samples.

The sample that has the highest copper and molybdenum contents included the greatest number of sulphides in its heavy fraction: 1100 molybdenite flakes, 1032 chalcopyrite grains, 92 pyrite grains and 16 pyrrhotite grains. The sample from the southeastern molybdenum anomaly contains only molybdenite in its heavy fraction (1000 flakes).

Thus, the geochemical difference evident in the fine fraction of till between the northwestern and southeastern parts of the area is seen also in the heavy fraction. The sulphide minerals may be preserved unweathered, even in the surface parts of till in any area like Susineva, where the groundwater level is near the surface and the conditions are reducing.

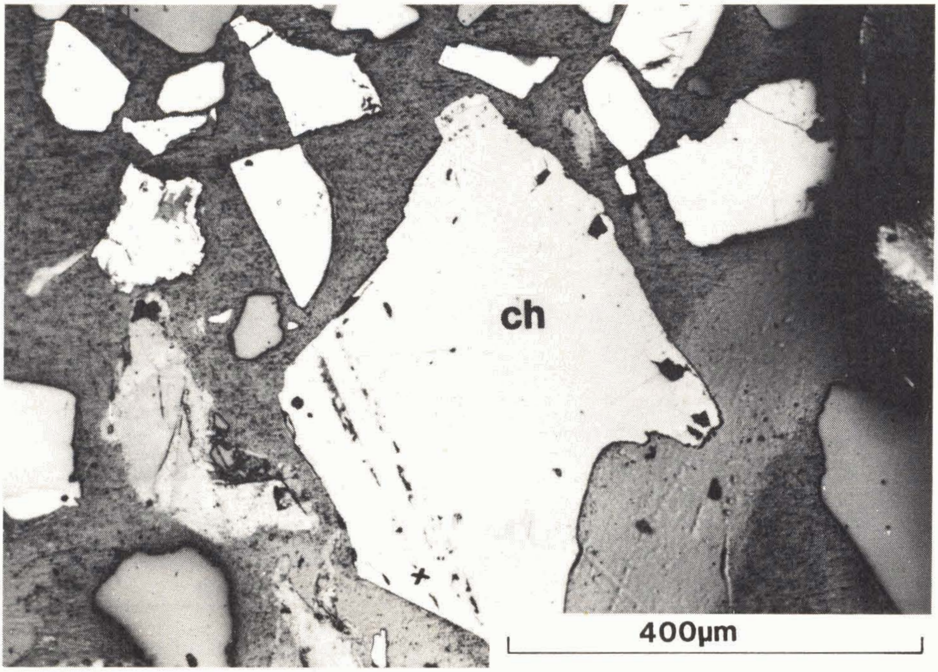


Fig. 47. Chalcopyrite grain (ch) with sphalerite (X) as inclusion rows, sample 5414. Polished section in reflected light, one nicol.

Fig. 48. Pyrite grain (py) with sphalerite (X) as inclusion rows, sample 5414. Polished section in reflected light, one nicol.

KANGERJÄRVI AREA

Location and topography

The survey area is situated in the commune of Kuusamo, 20 km northwest of Kuusamo village, in northeastern Finland (Fig. 1). The local relief is quite great, the 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.

Bedrock and mineralizations

The bedrock of the area belongs to the Karelidic schist belt (Hackman & Wilkman, 1929; Piispanen, 1972; Silvennoinen, 1972). The bedrock map seen in Fig. 49 has been compiled from outcrop mapping done by Rautaruukki Oy in the summer of 1976. The

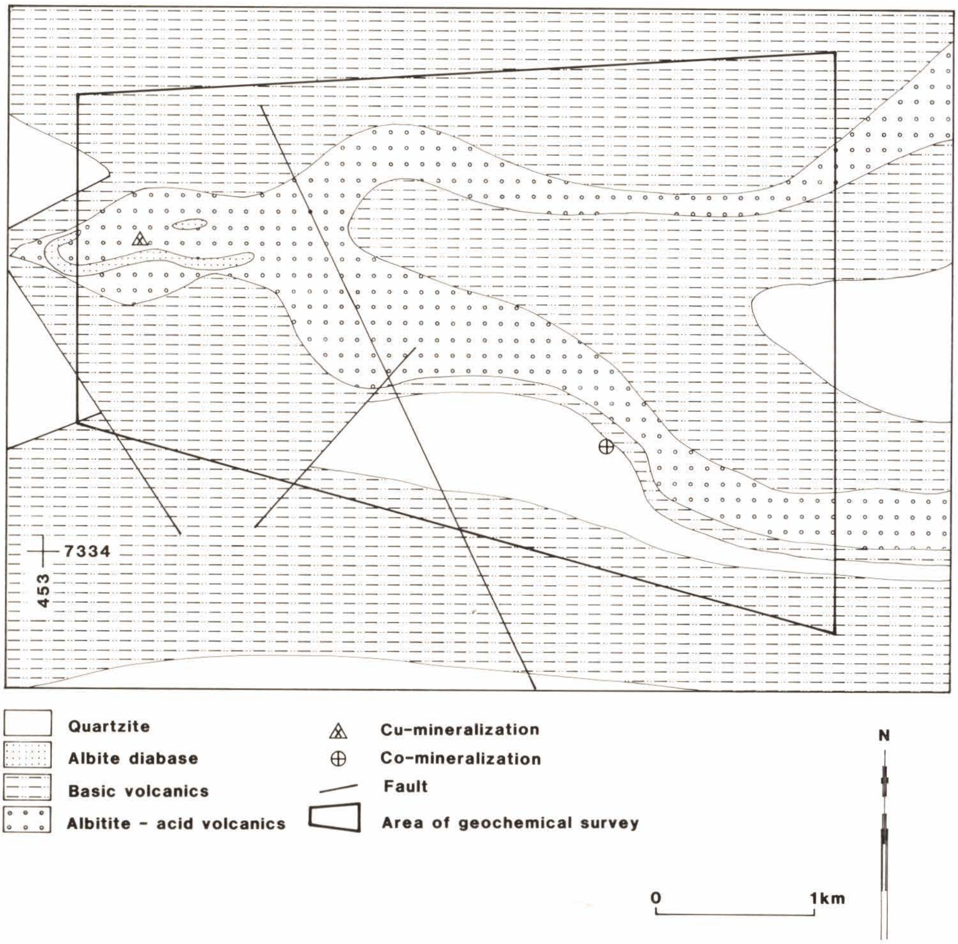


Fig. 49. Bedrock geology of the Kangerjärvi survey area.

metasedimentary rocks are sericitic quartzite, phyllite and mica schist. All the metasedimentary rocks are presented on the map under the name quartzite. Basic volcanics constitute a significant part of the area. Albite diabase and albitite are hypabyssal dykes, which are associated with carbonate–albite rocks.

Pyrite and chalcopyrite are common accessory minerals in the albitites and carbonate–albite rocks of the area (Piispanen, 1972). Cobalt-bearing pyrite was found in one albitite rock chip taken during pneumatic drilling by Rautaruukki Oy. Outokumpu Oy has investigated a small copper mineralization which is located in the western part of the area. It is also associated with albitite. Pyrite, chalcopyrite and pyrrhotite occur in this mineralization. The pyrite contains cobalt, but not to a degree worth mentioning. Hematite occurs as minute veins in albitite of the area.

Quaternary deposits

Two deglacial ice flow phases have been recognized in the area, the older Tuoppajärvi flow phase and the younger Kuusamo flow phase (Aario & Forsström, 1978, 1979). On the map of the Quaternary deposits of the area (Fig. 50) are seen the long, narrow drumlins that are peculiar to the area north and east of Lake Kangerjärvi. They originated during the last deglaciation phases of the Kuusamo lobe (*op. cit.*).

The drumlins are composed of grey or brownish grey sandy till. There is an area of hummocky moraine south of Lake Kangerjärvi where the hummocks are composed of till similar to that in the drumlins. The form of the hummocks is roundish and they have no preferred orientation. Drumlins and hummocks together belong to the active ice assemblage, which is typical of the whole area of northeastern Finland (Aario, 1977). There are few rock outcrops in the survey area. Weathered bedrock was found at 27 sampling points. The statistical parameters of the drilling depths of percussion and pneumatic drilling are presented in Table 7.

Table 7.

The thickness of the overburden on the basis of pneumatic and percussion drilling in the Kangerjärvi area. $\bar{X}$ = arithmetic mean, n = number of observations.

	minimum m	maximum m	$\bar{X}$ m	n
Pneumatic drilling	1.0	13.0	6.6	65
Percussion drilling	0.3	10.2	2.7	650

When the figures in Table 7 are evaluated, it must be remembered that pneumatic drilling was done only on three short lines in the hummocky moraine area south of Lake Kangerjärvi. The true average thickness of the overburden in the whole survey area may be between the averages of the percussion and pneumatic drilling depths. The thickness of the overburden in the drumlin and hummocky moraine area at Kangerjärvi seems to be smaller than that of the ground moraine area at Susineva, but greater than that of the cover moraine area at Rantavaara. The till samples taken by percussion drilling are probably not from near the bedrock surface at every point. They are basal till by their facies, however.

The orientation of the drumlins is 290° and two striae observations, both 280°, have been made in the area. Hence, ice movement took place from the west-northwest during the Kuusamo flow phase. The ice flowed from about the same direction in the earlier Tuoppajärvi flow phase (Aario & Forsström, 1979). Possible deposits of the Tuoppajärvi lobe could not be observed, because there are no deep sections in the area.

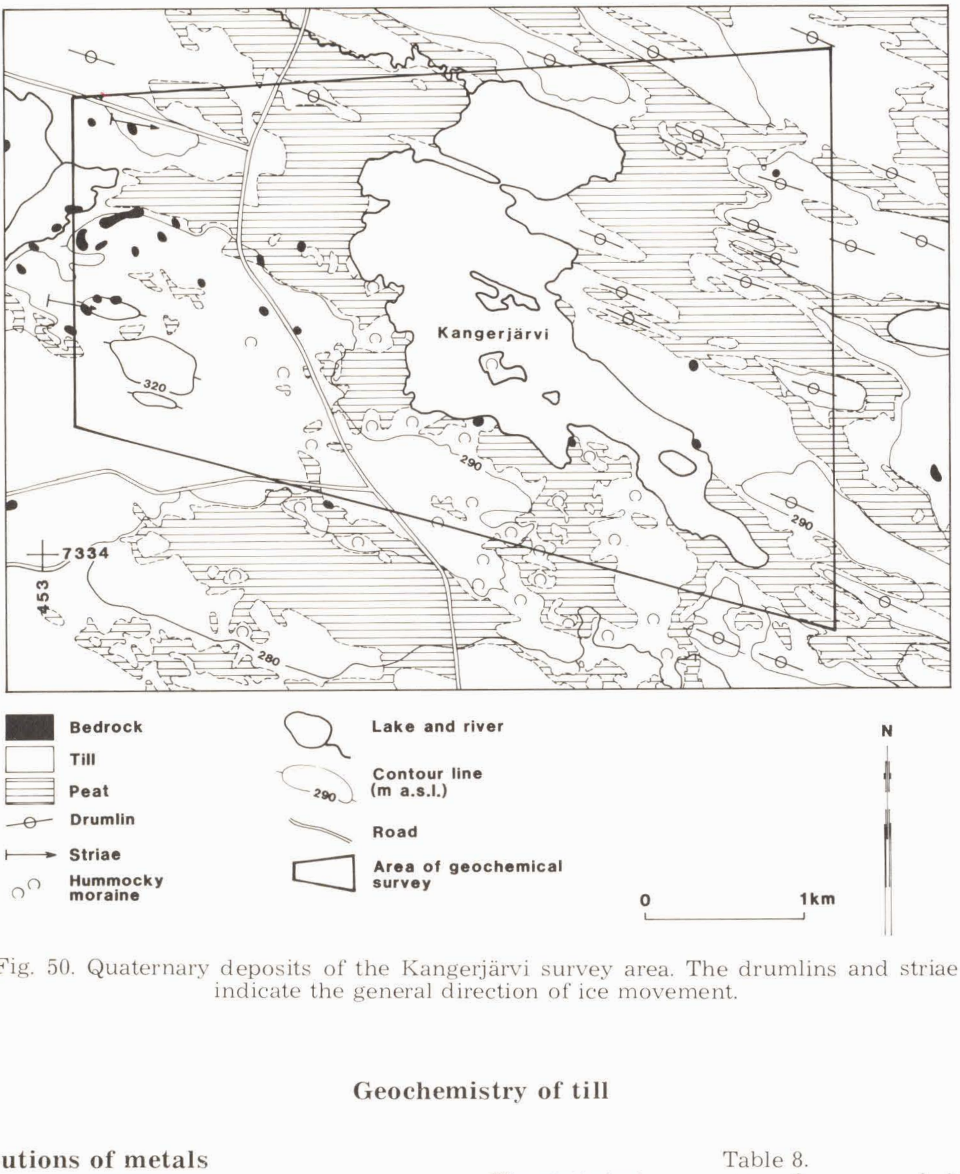


Fig. 50. Quaternary deposits of the Kangerjärvi survey area. The drumlins and striae indicate the general direction of ice movement.

Geochemistry of till

Distributions of metals

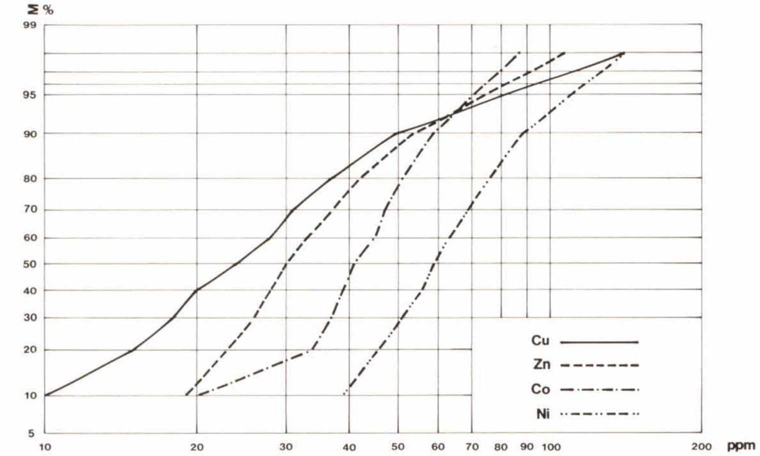
The essential statistical parameters of copper, cobalt, nickel and zinc are presented in Table 8. The quite high average content of cobalt is noteworthy. The mean content of copper is quite low. It is lower than for example in the survey areas at Rantavaara and Susineva. Also, the mean content of zinc is clearly lower than in the Rantavaara area.

Table 8.
The statistical parameters of copper, cobalt, nickel and zinc in till at Kangerjärvi. $\bar{X}$ = arithmetic mean, M = median, s = standard deviation, c = coefficient of variation, n = number of samples.

	$\bar{X}$	M	s	c	n
Cu ppm	33	24	50	1.5	650
Co ppm	42	41	17	0.4	650
Ni ppm	64	59	27	0.4	650
Zn ppm	36	30	32	0.9	650

The differences in copper contents might be explained by the different mineralization types in the areas. In Rantavaara and Susineva are involved extensive disseminations and

Fig. 51. Cumulative frequency distributions of copper, nickel, cobalt and zinc in till at Kangerjärvi.



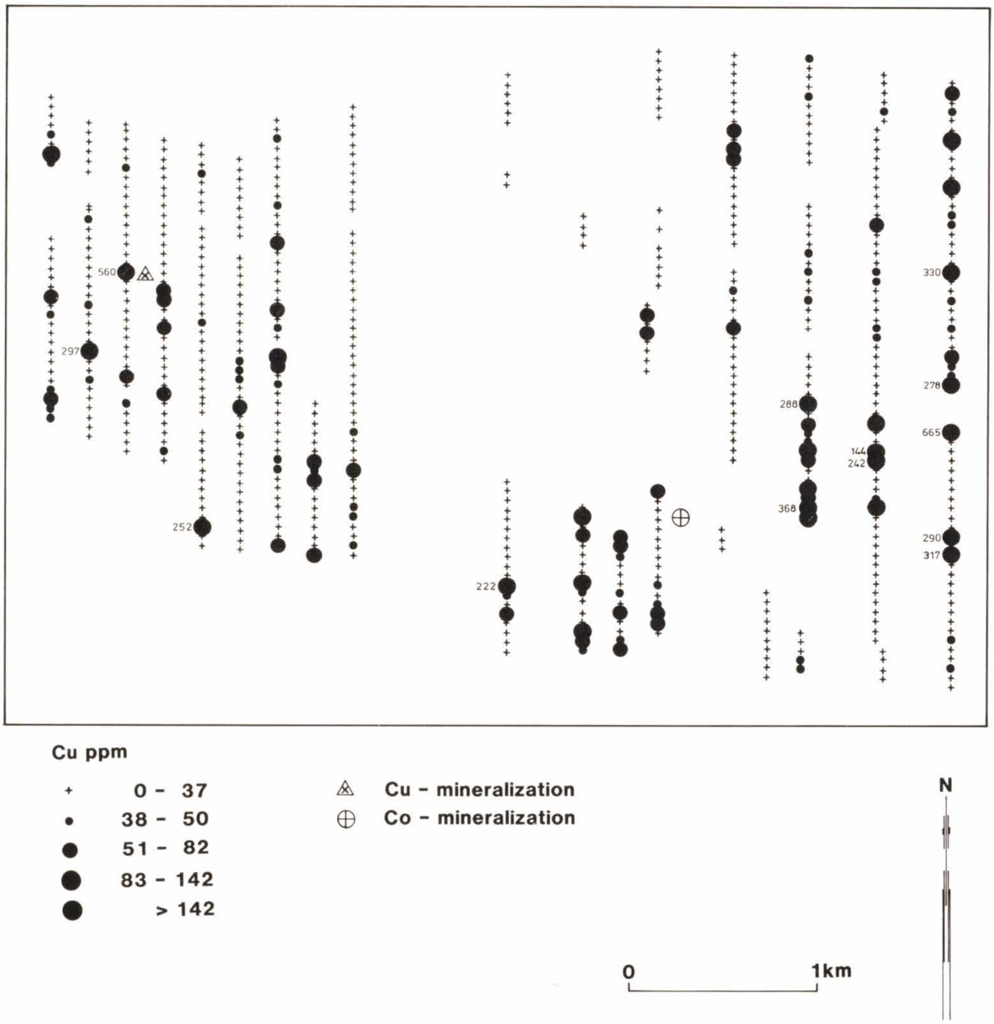


Fig. 52. Symbol map of the areal distribution of copper in till at Kangerjärvi.

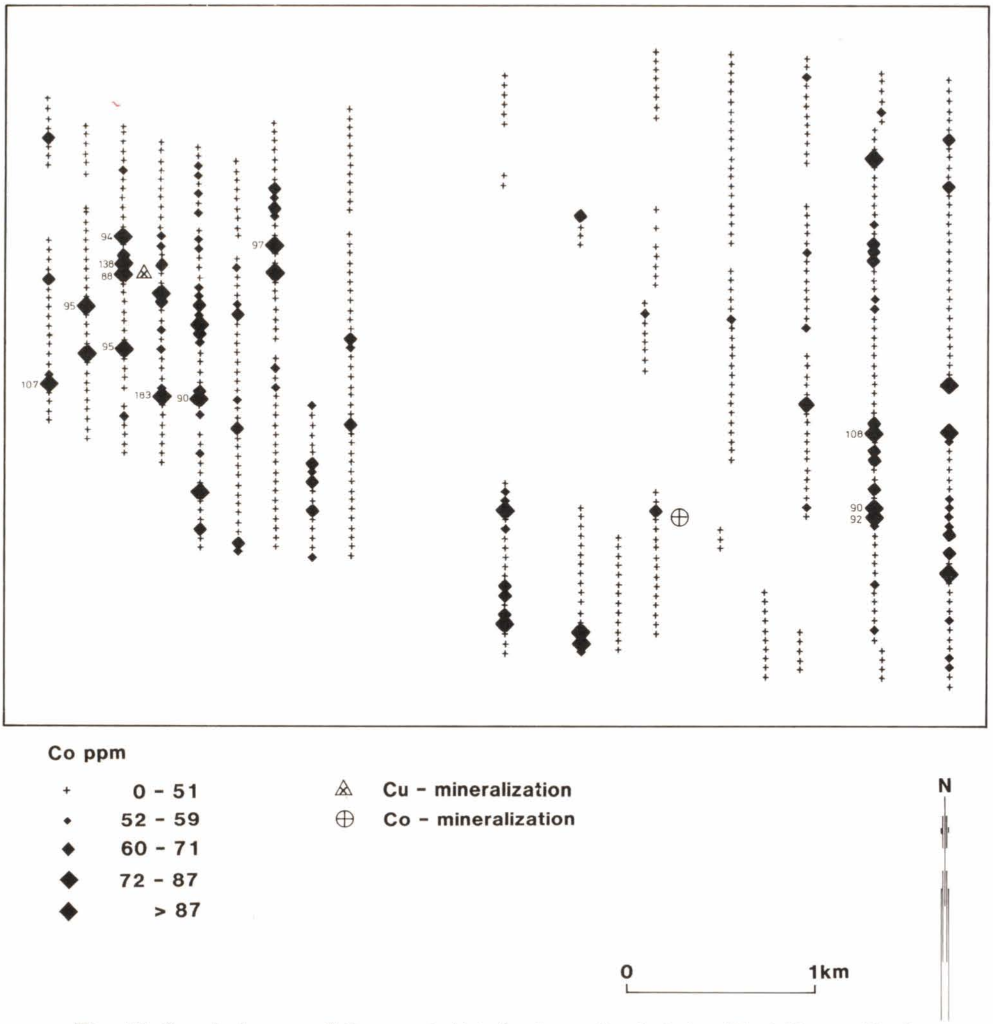


Fig. 53. Symbol map of the areal distribution of cobalt in till at Kangerjärvi.

in Kangerjärvi are involved vein type mineralizations. Naturally, the disseminated mineralizations enrich till with metals over a broader area than the areally small vein type mineralizations. The mean content of nickel is at the same level as in till in the mica schist and volcanite areas of North Karelia (Kauranne, 1980).

The cumulative frequency curves of the metal contents are presented in Fig. 51. Copper has the most skewed distribution. The distributions of the other metals are nearly normal; however, the highest contents of cobalt, nickel and zinc can be regarded as anomalous. The limits of the anomaly classes are the 80, 90, 95 and 98 percentiles. The symbol maps of the metals are seen in Figs. 52–55.

With regard to copper, the relationship of the anomalies to the underlying bedrock can be estimated in the area of the copper mineralization that was investigated by Outokumpu Oy.

A quite high copper content (560 ppm) was found in the till sample which was taken from 1.1 m depth, just above the mineralization. The same sample also had anomalous cobalt

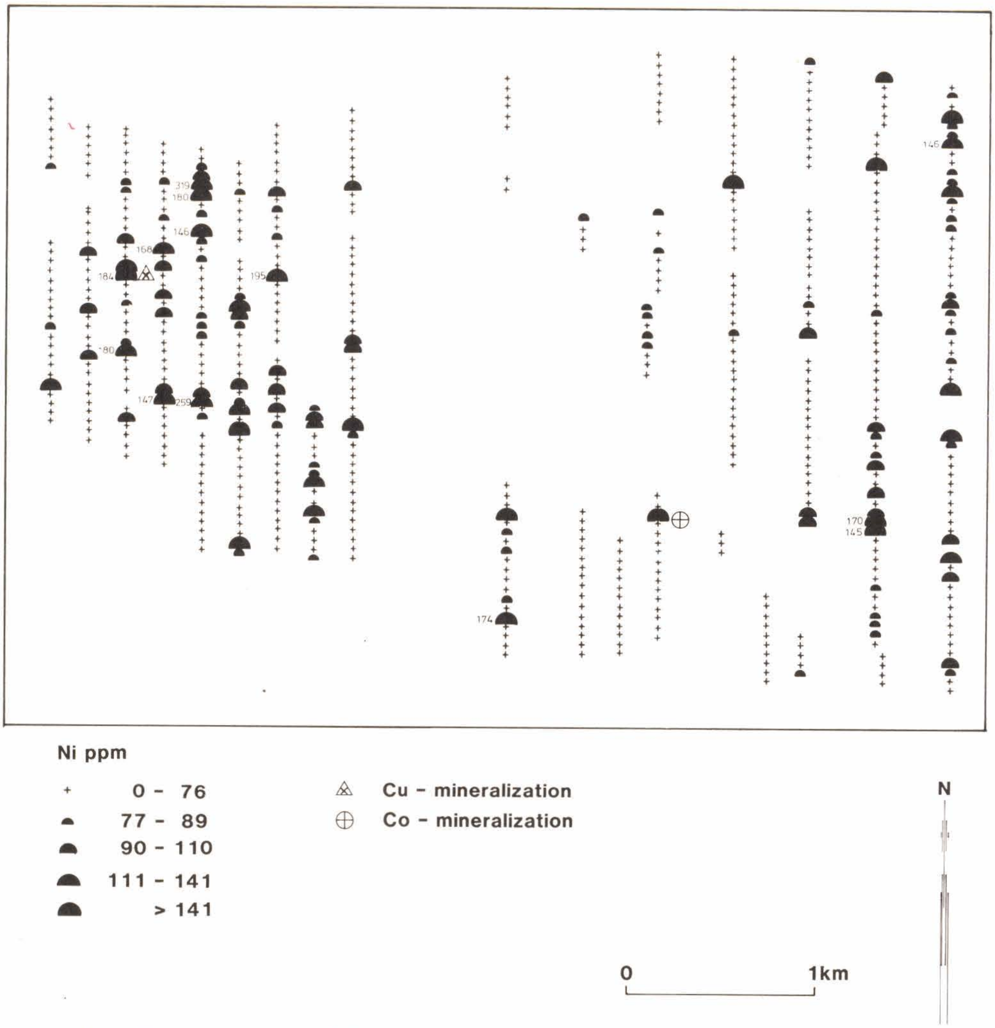


Fig. 54. Symbol map of the areal distribution of nickel in till at Kangerjärvi.

(88 ppm) and nickel (184 ppm). The copper anomaly extends to about 400 m east-southeast of the mineralization. The cobalt anomaly follows the copper one, although the highest cobalt content (138 ppm) is located 50 metres north of the mineralization. The cobalt anomaly continues to the east-southeast for 600–700 metres. Although the known mineralization does not contain high cobalt content, it is possible that the adjacent bedrock includes cobalt-bearing mineralization. The source of the nickel anomalies here and in the whole survey area might be in the albite diabases and volcanics.

No percussion drilling profile goes over the cobalt-bearing pyrite mineralization. One till sample has been taken by pneumatic drilling from near the suboutcrop of the mineralization. It has an anomalously high cobalt content, 140 ppm. In this case the dilution of the trace element content is ninefold, when the cobalt content of the till is compared to that of the bedrock.

Many copper anomalies occur in the survey

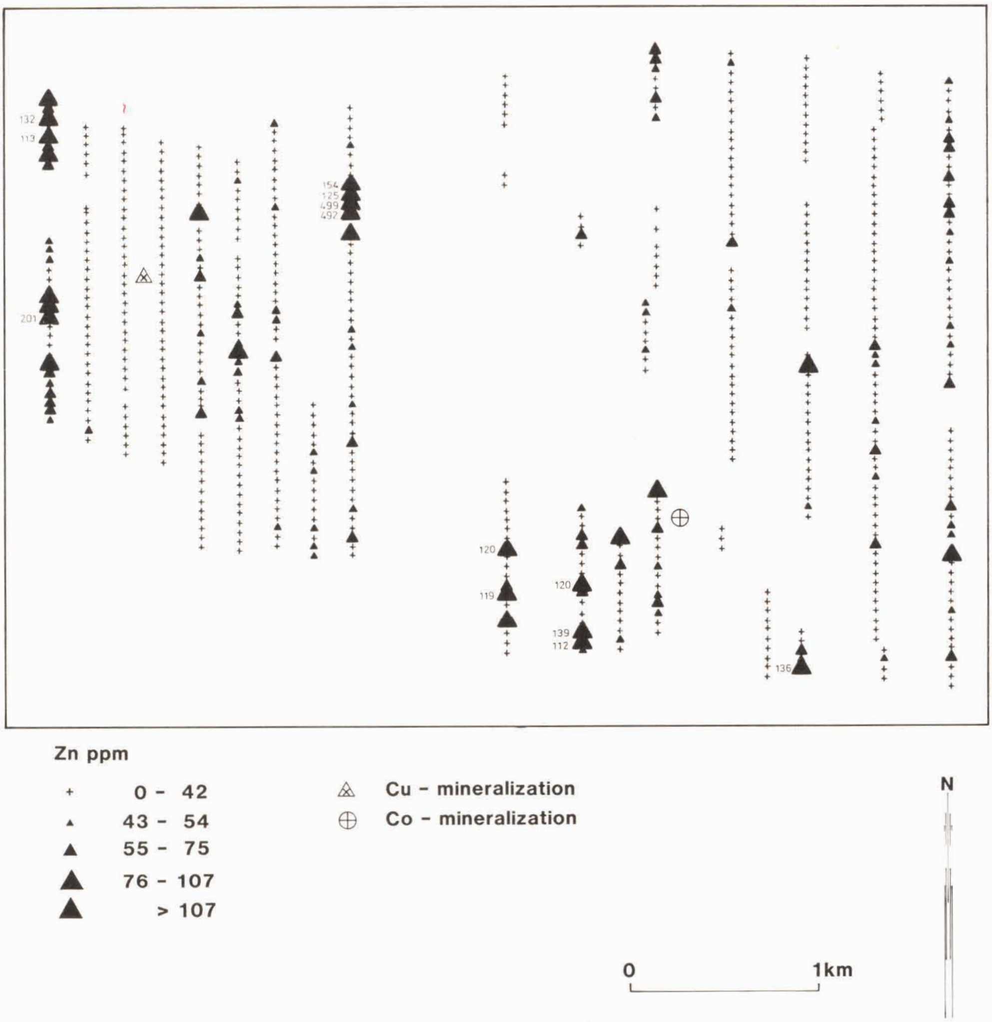


Fig. 55. Symbol map of the areal distribution of zinc in till at Kangerjärvi.

area. The most interesting anomaly, located east of Lake Kangerjärvi, includes the highest copper content, 665 ppm, in the whole area. Increased cobalt and nickel values are in part associated with this anomaly. No attempts have been made to identify the source of the anomaly for the present. The highest cobalt content (183 ppm) in the area is situated 650 m south of the known copper mineralization (Fig. 53). Nickel and copper values are also increased in this anomaly, but the source of the anomaly is unknown.

The dispersion pattern of zinc is quite different from that of the other metals. The most significant zinc anomaly (499 and 492 ppm) is located on the western shore of Lake Kangerjärvi. Its source is also unknown.

Mode of occurrence of metals

Chemical studies

Thirty samples were extracted with citric acid. The results have been presented as

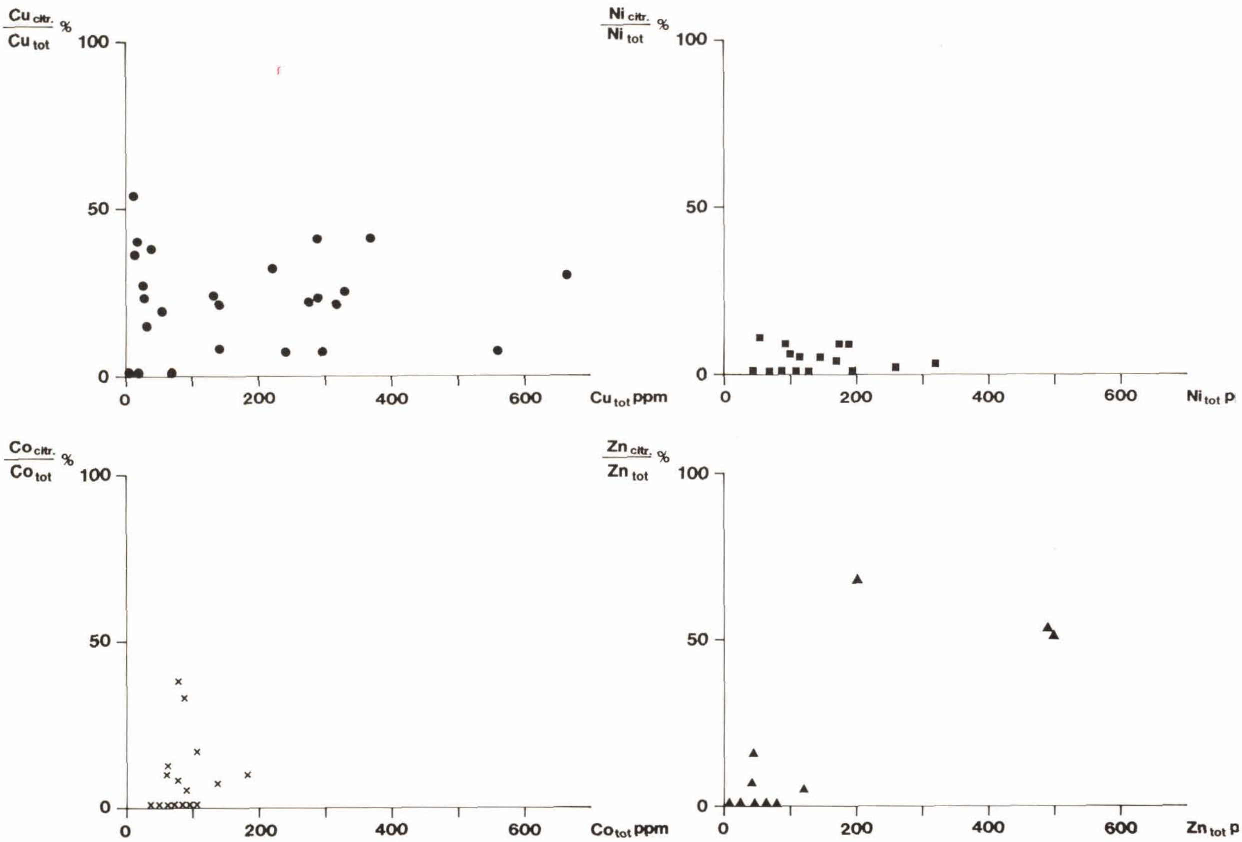


Fig. 56. Citric acid soluble metals in till at Kangerjärvi.

diagrams in Fig. 56. Copper has the largest cold-extractable component, on the average 19 % of the total content. This is clearly more than in the Rantavaara area. Cobalt has 5 % cold-extractable component, nickel 3 % and zinc 7 %, on the average. Therefore, mechanical dispersion is involved in this area also. On the other hand, the cold-extractable component of zinc is over 50 % of the total content in the highly anomalous samples. Thus, it seems that the zinc anomalies have been generated by hydromorphic dispersion.

Mineralogical studies

Only those samples which contained anomalous contents of copper, cobalt, nickel or zinc in their fine fraction were studied mineralogically. The heavy fraction comprises 1–20 % of the samples.

No zinc minerals were found in samples 4096 (499 ppm Zn) and 4097 (492 ppm Zn). This confirms the result of the cold leach i.e., the zinc anomaly is generated by hydromorphic dispersion. No nickel minerals were found either in the samples investigated. This, along with the low amount of cold-extractable nickel, shows that even the highest nickel contents are bound in the silicate lattices.

Sample 5878 (depth 1.1 m; 560 ppm Cu in the fine fraction), which was taken from above the known copper mineralization, contains in its heavy fraction abundant

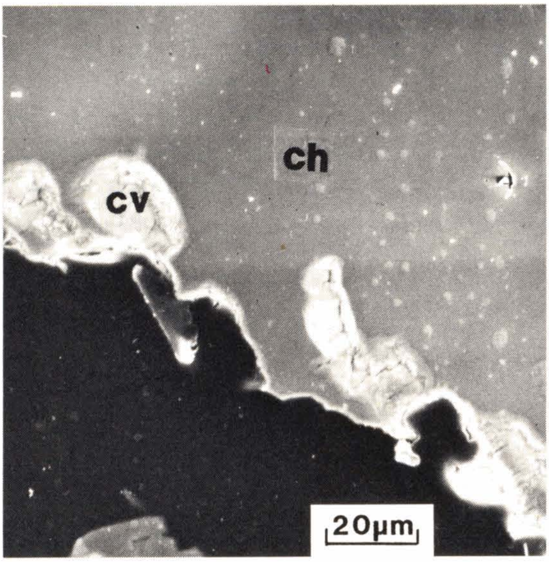


Fig. 57. Spotted alteration of the rim part of chalcopyrite (ch) to covellite (cv), sample 4375. Polished section, SEM, secondary electron image.

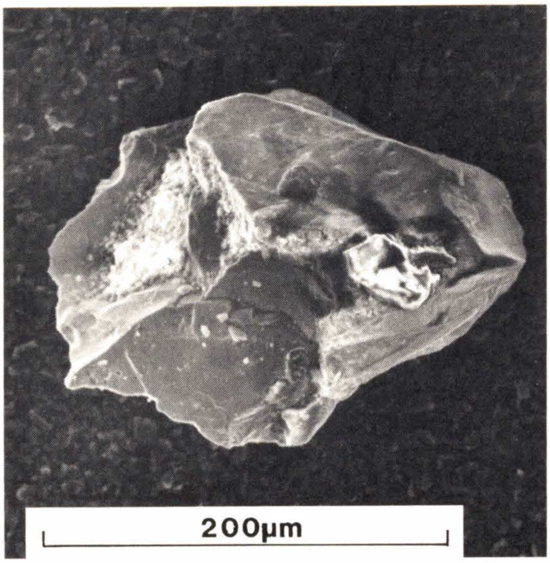


Fig. 58. Fresh pyrite grain, sample 4401. SEM, secondary electron image.

pyrite, chalcopyrite and pyrrhotite. Some of the sulphide grains have altered to goethite in their marginal parts, but part of the sulphides is quite unweathered. The heavy fraction of sample 4388 (depth 4.3 m; 665 ppm Cu in the fine fraction) also contains chalcopyrite and pyrite which show no signs of weathering. Sample 4375 (depth 2.1 m; 317 ppm Cu in the fine fraction) includes some chalcopyrite grains, the marginal parts of which have altered in spots to covellite (Fig. 57).

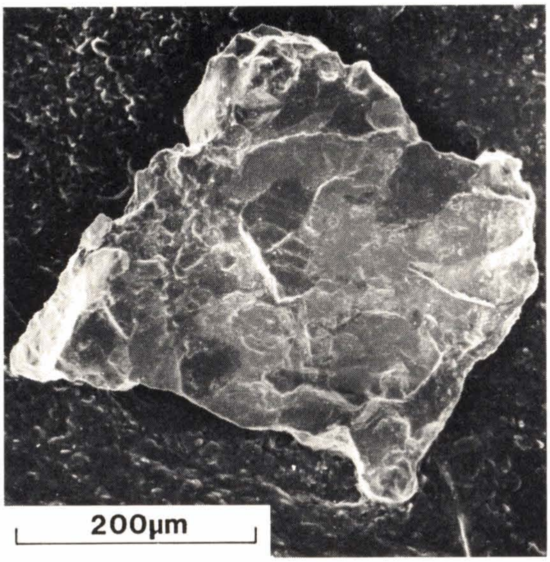


Fig. 59. Hematite grain, sample 5904. SEM, secondary electron image.

Although the fine fraction of sample 4401 (depth 1.2 m) contains 330 ppm Cu, only unweathered pyrite can be found in its heavy fraction (Fig. 58). Sample 5904 (depth 1.0 m), which has the highest cobalt content (183 ppm) in the fine fraction, contains pyrite fairly abundantly. Quite fresh hematite grains are present in many samples (Fig. 59).

Other heavy minerals occurring in the samples are: amphibole, magnetite, ilmenite, rutile, chlorite, apatite, augite and zircon.

The results of the mineralogical study show clearly that the dispersion of copper and cobalt has been mechanical. On the contrary, the only significant zinc anomaly is the result of hydromorphic dispersion. The level of the groundwater surface has an important influence on the weathering of sulphide minerals. In the samples which have been taken from below the groundwater surface, the sulphide minerals are mainly unweathered. Above the groundwater surface, the sulphide grains are weathered and altered to goethite, particularly on their surficial parts.

An important observation from the prospecting point of view is that the sulphide minerals have been preserved in part even in till near the ground surface. The alteration of chalcopyrite to covellite seen in one sample is probably the result of the secondary enrichment process in the preglacial weathering crust similar to that interpreted in the Rantavaara area.

PETÄJÄSKOSKI AREA

Location and topography

The survey area is situated in the Kemijoki river valley, 30 km southwest of Rovaniemi (Fig. 1). The absolute height varies between 70 and 105 m a.s.l. In the surroundings there are several high so-called calotte hills (*kalottivaarat* in Finnish). On their upper slopes between contour lines at 180 and 220 m a.s.l. is seen the uppermost shoreline of the Yoldia Sea as a bare stone belt.

Bedrock and mineralizations

The bedrock of the survey area is a part of the Peräpohja schist area (Hackman, 1918; Mikkola, 1949). The bedrock map in Fig. 60 has been compiled from outcrop mapping done by Rautaruukki Oy in the summer of 1976.

The bedrock is composed of quartzite and albite diabase. The narrow greenstone horizons have been interpreted to be higher-level parts of albite diabases. A small Fe-Cu mineralization occurs at the lower contact of one albite diabase dyke (Figs. 60 and 63). The ore minerals in the mineralization are magnetite, chalcopyrite and pyrite. Albite diabases contain magnetite disseminations in the whole area. Pyrite and chalcopyrite have been seen also in places as disseminations in albite diabases and at one site in quartzite.

Quaternary deposits

The overburden in the survey area consists of long Rogen moraine ridges and intervening bog depressions (Fig. 61). The orientation of the Rogen ridges is north-northwesterly or northerly. There is a drumlinoid landscape north of the sampling area in which the orientation of the drumlins is northeasterly. An older ice movement took place from the northwest and a younger one from the west in the whole area of the Kemijoki valley (Korpela, 1969). It seems that the younger movement shifted to take place from the southwest in the survey area.

The Rogen ridges are composed of grey,

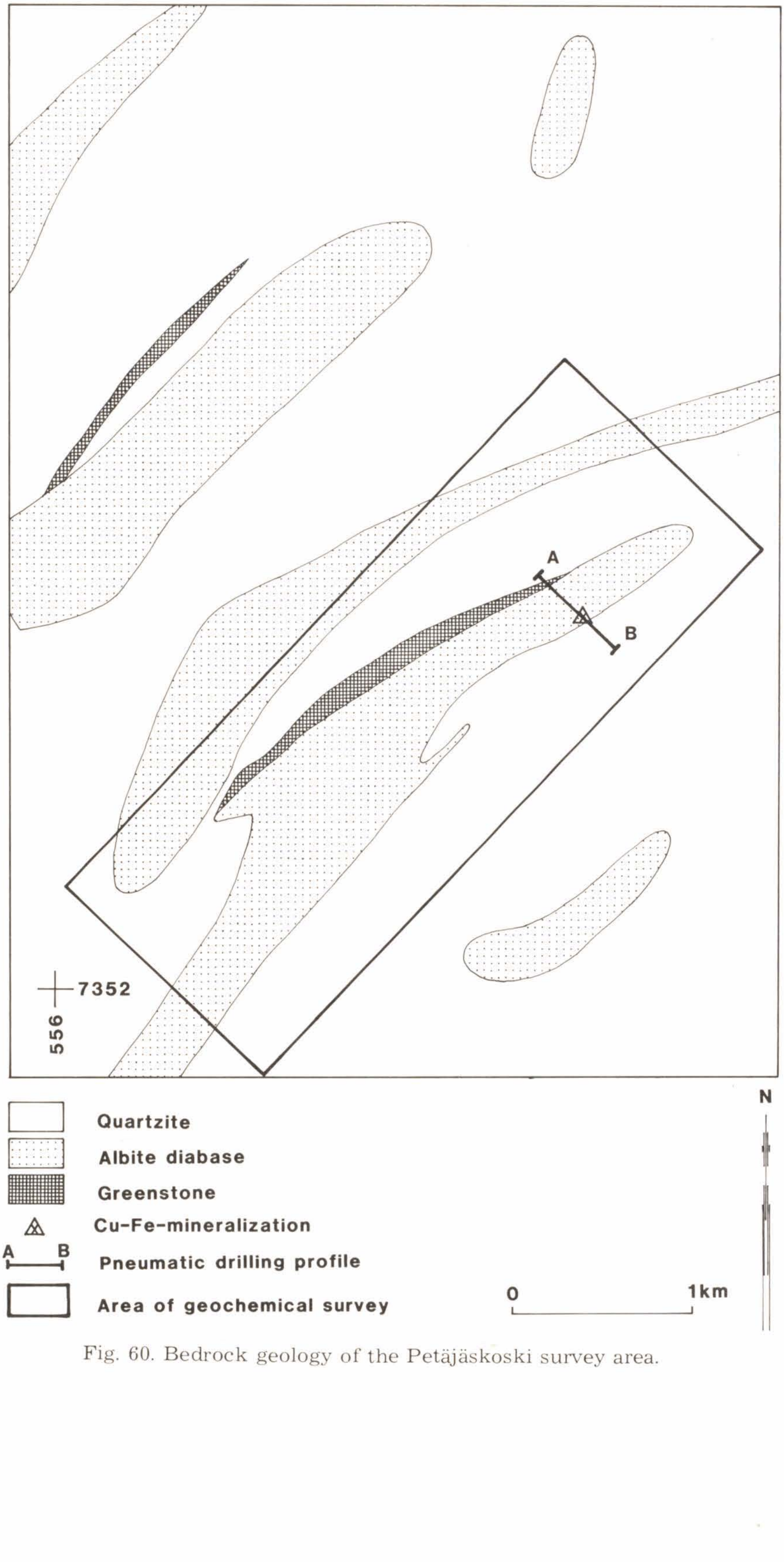


Fig. 60. Bedrock geology of the Petäjäskoski survey area.

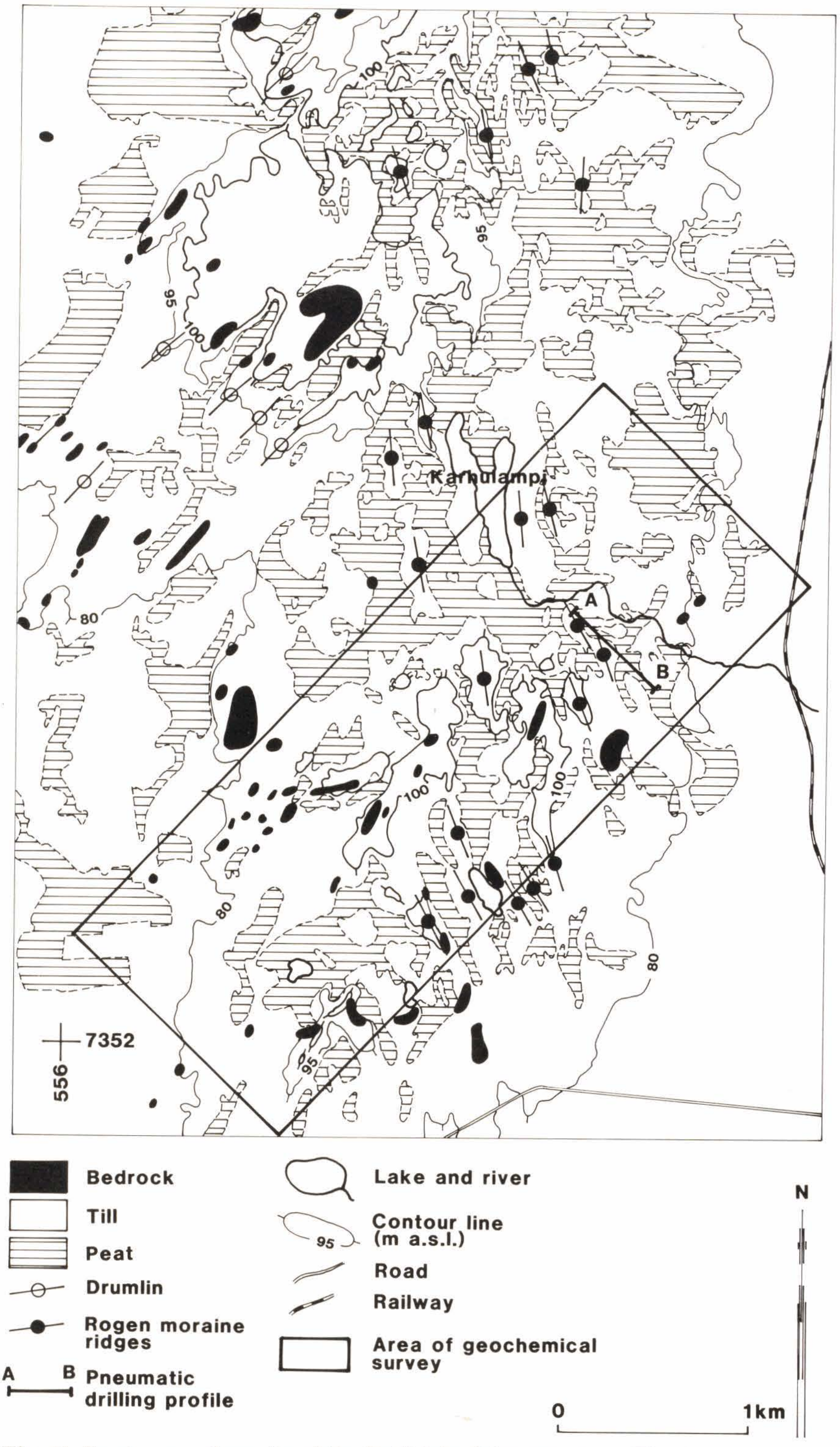


Fig. 61. Quaternary deposits of the Petäjäskoski survey area. The drumlins indicate the local direction of ice movement.

compact sandy till. The surface is in places very boulder-rich and difficult to drill through. As to the depositional facies, the material of the Rogen ridges is usually classified as basal till (cf. Lundqvist, 1969, Aario, 1977). The sampling depths of the pneumatic and percussion drilling are presented in Table 9. Two diamond drill holes have been made in which the thickness of the overburden is 5.0 and 8.5 m.

Clearly, the percussion drilling has not reached the bedrock surface at every sampling point. This is especially true in the Rogen ridges, where the boring stopped near the surface.

Table 9.

The thickness of the overburden on the basis of pneumatic and percussion drilling in the Petäjäskoski area. $\overline{X}$ = arithmetic mean, n = number of observations.

	minimum m	maximum m	$\overline{X}$ m	n
Pneumatic drilling	1.2	11.5	4.7	78
Percussion drilling	0.2	9.5	1.5	651

Geochemistry of till

Distributions of metals

The statistical parameters of copper, cobalt, zinc and lead are presented in Table 10. The mean copper content is higher than that in the three other survey areas excluding the first and second sampling stage at Rantavaara. The cobalt content is at the same level as at Kangerjärvi. The zinc value is lower than at Rantavaara, but higher than at Kangerjärvi. The copper and zinc contents are lower and the cobalt content is higher than usual in tills of Lappland (Kauranne, 1980). Lead is at the same level as in Lappland *(op cit.)*.

The cumulative frequency curves of the metals are presented in Fig. 62. The distribution of copper is strongly skewed, but cobalt, zinc and lead are nearly normally distributed.

A pneumatic drilling profile over the known Fe-Cu mineralization is seen in Fig. 63. The location of the profile has been marked on both the bedrock map and the map of the Quaternary deposits (Figs. 60 and 61). The profile is perpendicular to the strike of the bedrock and the direction of ice movement. The till samples are taken from just above the bedrock surface. The topography of the ground surface has not been drawn in Fig. 63 because the profile has not been levelled, but the ground surface generally declines from left to right.

Table 10.

The statistical parameters of copper, cobalt, zinc and lead in till at Petäjäskoski. $\overline{X}$ = arithmetic mean, M = median, s = standard deviation, c = coefficient of variation, n = number of samples.

	$\overline{X}$	M	s	c	n
Cu ppm	63	37	85	1.3	651
Co ppm	48	45	18	0.4	651
Zn ppm	52	47	26	0.5	651
Pb ppm	28	28	9	0.3	651

The overburden is thickest at the northwestern end of the profile, where it is 12 m, and it is thinnest in the central part of the profile, two metres. Over the mineralization, the overburden is three metres thick, consisting of one metre of peat and two metres of till.

The copper and iron contents of the till are presented as broken lines in Fig. 63. The mineralization is expressed in the till as a strong and sharply contrasted copper anomaly. The maximum copper content in the till is 4510 ppm, just above the mineralization. The breadth of the anomaly is 40 metres, about five times the breadth of the suboutcrop. The iron anomaly is at the same place (maximum Fe = 14 %), but the anomaly contrast for

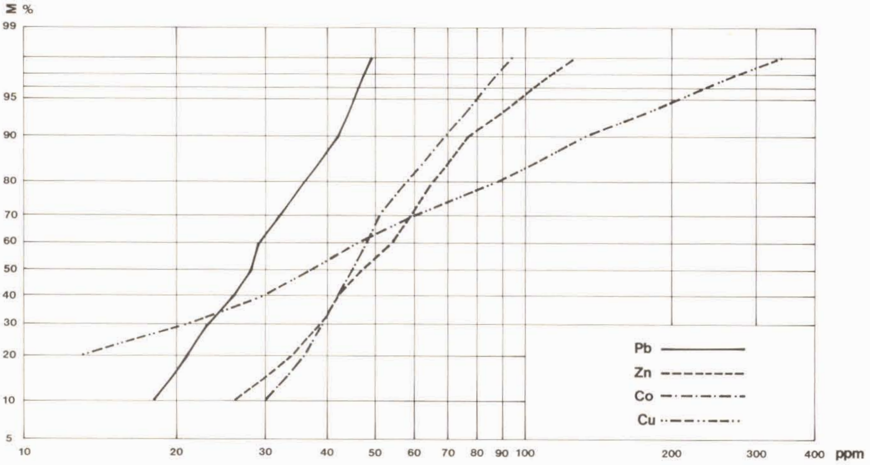


Fig. 62. Cumulative frequency distributions of copper, cobalt, zinc and lead in till at Petäjäskoski.

iron is considerably lower than that for copper.

The minor anomaly peak (Cu 290 ppm, Fe 10 %) in the northwestern part of the profile is caused by the magnetite-pyrite-chalcopyrite dissemination in albite diabase at the same site as the peak. Copper and iron are generally at a somewhat higher level in the till above albite diabase than above quartzite. A low iron peak (8 %) at the southeastern end of the profile is caused by an albite diabase dyke which contains disseminated magnetite.

The limits of the anomaly classes were set

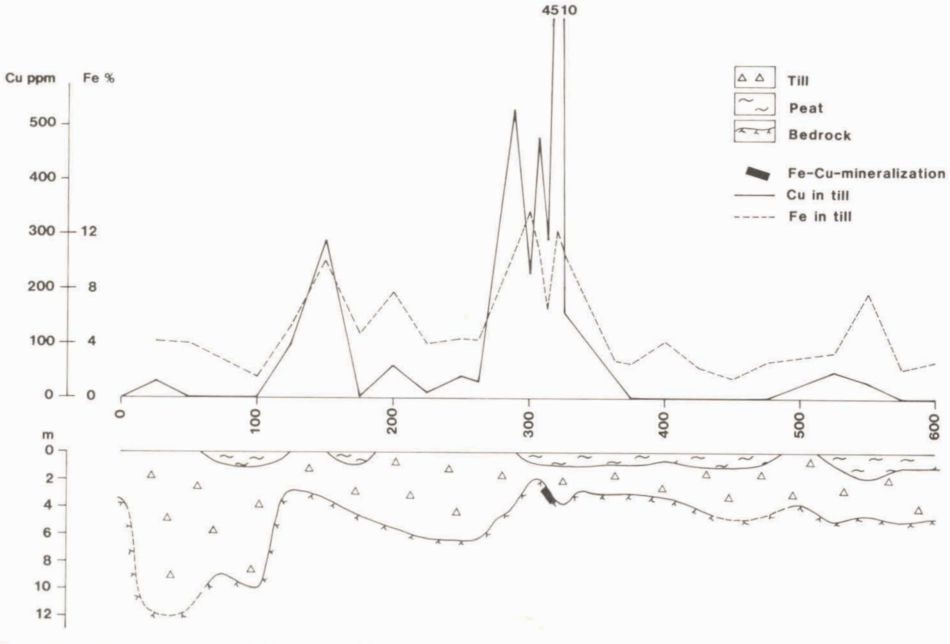


Fig. 63. Pneumatic drilling profile A–B over the known Fe-Cu mineralization at Petäjäskoski.

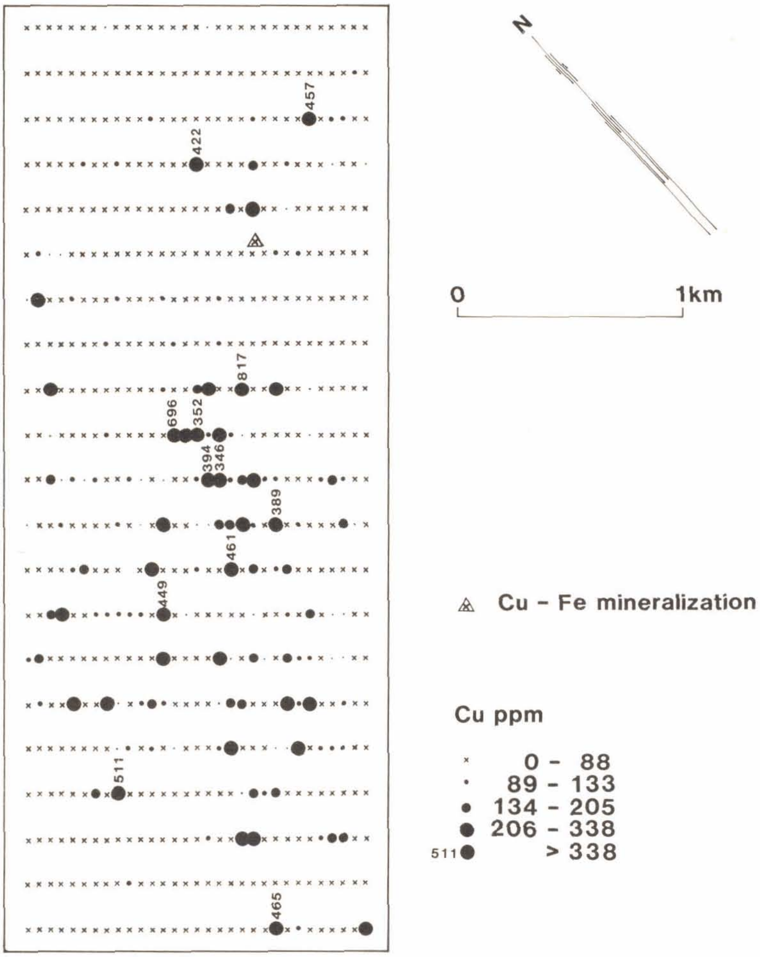


Fig. 64. Symbol map of the areal distribution of copper in till at Petäjäskoski.

at the 80, 90, 95 and 98 percentiles of the cumulative distribution when the symbol maps of copper and cobalt were compiled (Figs. 64–65). The general orientation of the copper anomalies is southwest–northeast, the same as the strike of the bedrock and the latest direction of ice movement. There are several samples that have anomalous copper contents northeast of the known Fe-Cu mineralization which may represent a glaciogenic dispersion train. If so, the anomalous dispersion of copper would extend 600 m from the mineralization.

The most interesting copper anomaly is located in the central part of the area. It is quite coherent, 800 m long and 250–300 m broad. There are several high values of copper in the anomaly (maximum 817 ppm). Sample depths in the anomaly are quite small; on the Rogen ridges, samples were taken only from 0.5 metres depth. Some samples are from the B horizon of the soil and some are from the unaltered till (C horizon). The sample depth is somewhat greater in bog depressions.

The pebble fraction of the samples in the large copper anomaly is composed of albite diabase (80–95 %) and quartzite (5–20 %). The

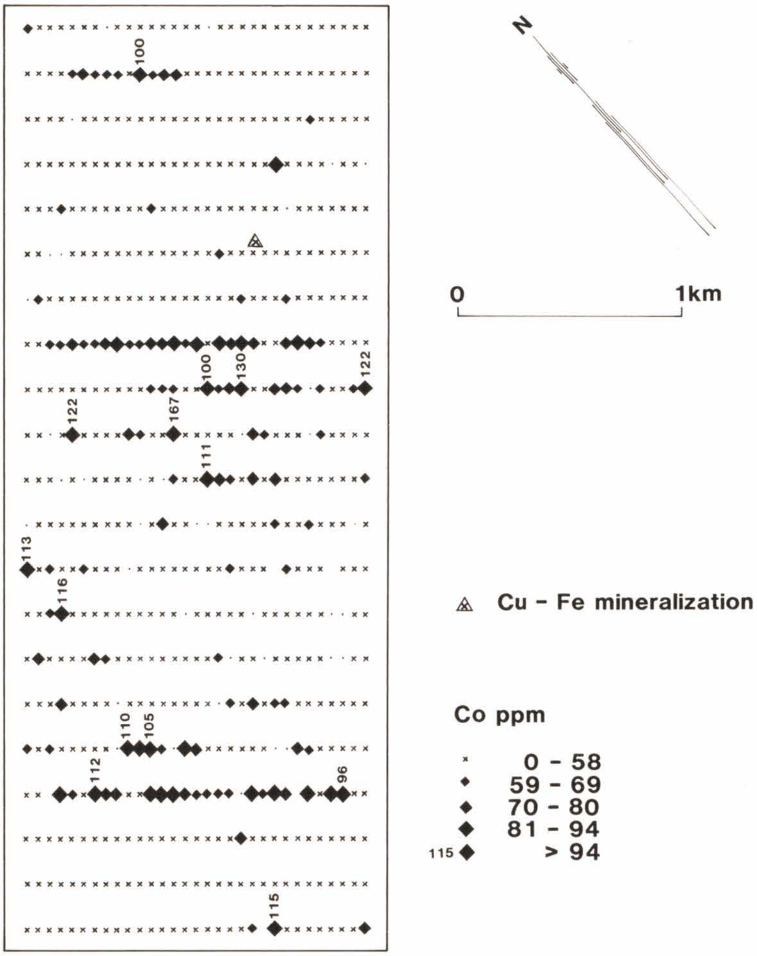


Fig. 65. Symbol map of the areal distribution of cobalt in till at Petäjäskoski.

anomaly is situated over albite diabase (Fig. 60), but the source of the anomaly has not yet been found.

The other copper anomalies of the area also are located mainly over albite diabase and its contacts. All this suggests that the Rogen ridges are composed primarily of a quite local basal till. It can be concluded that till samples should not always be from near the bedrock surface, especially in a regional prospecting program when new ore prospects are sought.

The cobalt anomalies occur along the sampling lines (Fig. 65). Because cobalt has a normal distribution, this suggests that the anomalies are only statistical. However, the highest cobalt contents coincide with copper anomalies, e.g. one sample contains 167 ppm cobalt and 696 ppm copper.

Mode of occurrence of metals

Chemical studies

To determine the share of the cold-extractable component, 17 samples with anomalous copper content were extracted with citric acid.

The results for copper, cobalt and zinc are

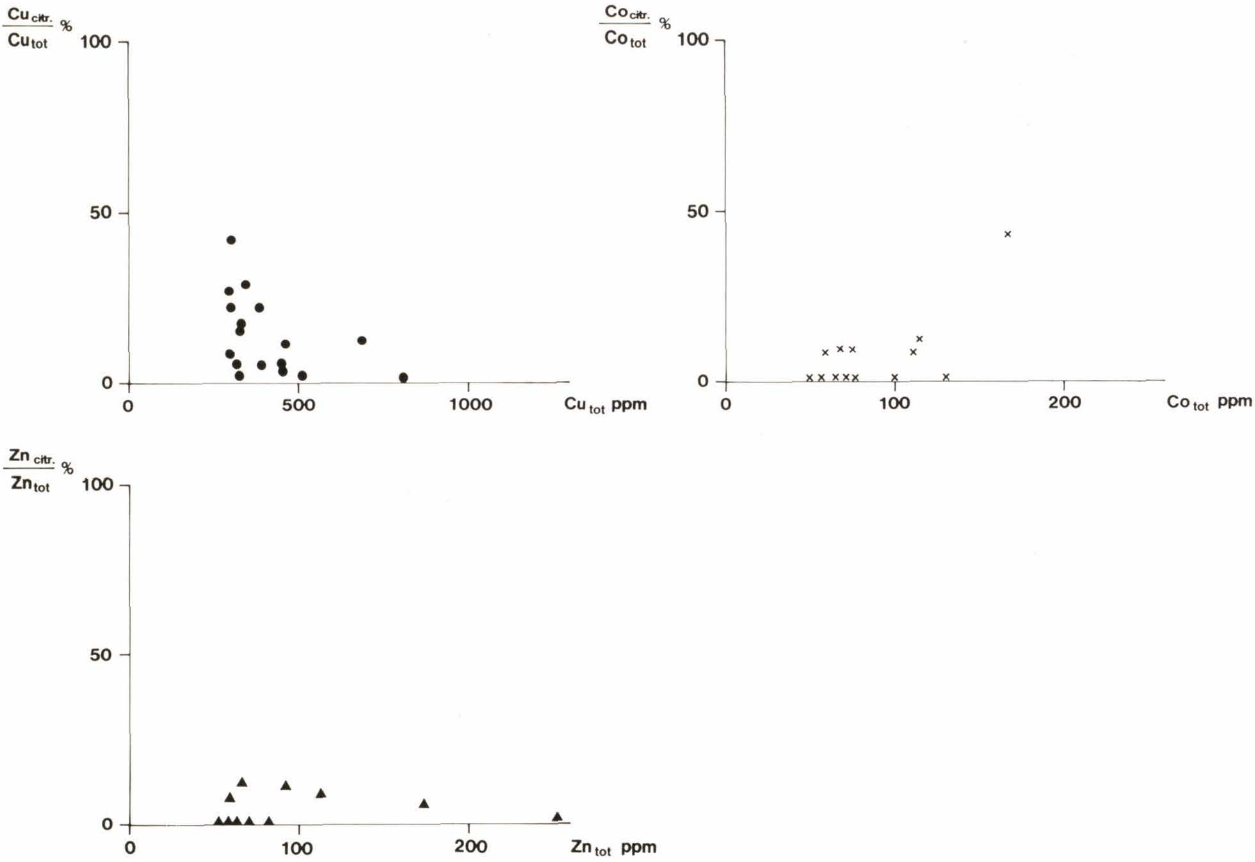


Fig. 66. Citric acid soluble metals in till at Petäjäskoski.

presented in Fig. 66. The share of the cold-extractable component is fairly insignificant, on the average 13 % for copper, 5 % for cobalt and 3 % for zinc; therefore the dispersion of the metals in the area has been mainly mechanical. Only one sample has a significant cold-extractable copper content (42 % of the total). That sample is from 2.6 metres depth in a bog depression, which is located 150 m southeast of the large copper anomaly in the central part of the area. At this site, hydromorphic dispersion has taken place.

Mineralogical studies

Only those samples were studied mineralogically which contained over 300 ppm copper. The share of the heavy fraction in the samples varied between 1.5 and 41.5 %. Chalcopyrite, pyrite and pyrrhotite are weathered to goethite either wholly or in part (Fig. 67) in samples 260 (depth 0.5 m; 817 ppm Cu in the fine fraction) and 297 (depth 0.5 m; 696 ppm Cu in the fine fraction). The sulphide minerals are weathered to goethite in their surface parts in sample 68 (depth 0.2 m; 457 ppm Cu in the fine fraction), which was taken from the B horizon of soil. The surfaces of the sulphide grains are also broken (Fig. 68).

In contrast, chalcopyrite and pyrite are unweathered (Fig. 69) in sample 321 (depth 6.7 m; 338 ppm Cu in the fine fraction), which also contains abundant framboidal pyrite (Fig. 70). Sample 385 (depth 0.5 m; 461 ppm Cu in

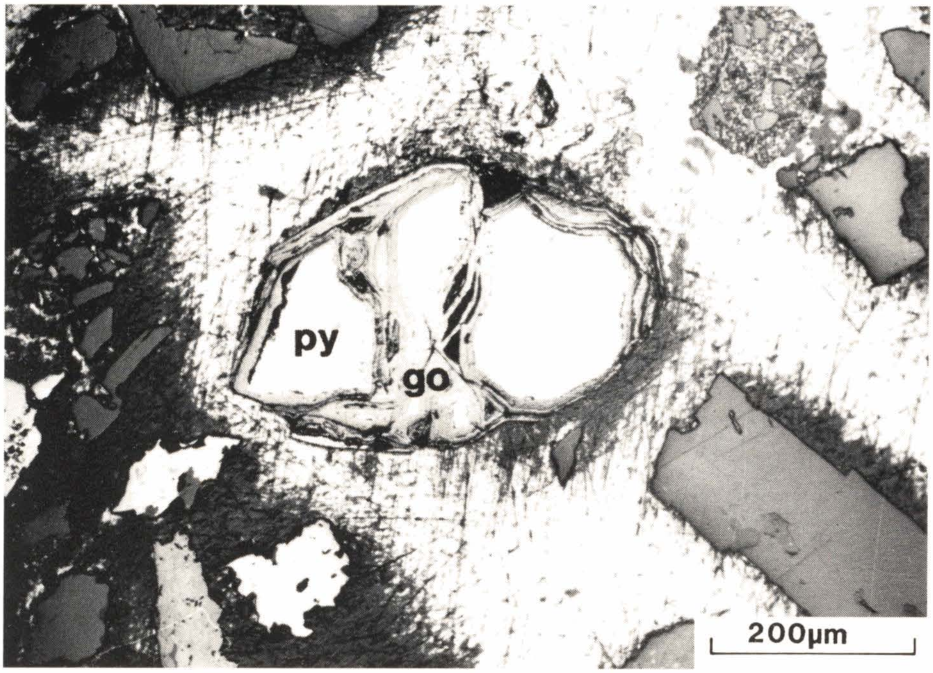


Fig. 67. Pyrite grain (py), which has in part altered to goethite (go), sample 297. Polished section in reflected light, one nicol.

the fine fraction) contains some unweathered chalcopyrite in its heavy fraction, although most of the chalcopyrite and pyrite have been altered to goethite. Chalcopyrite also occurs

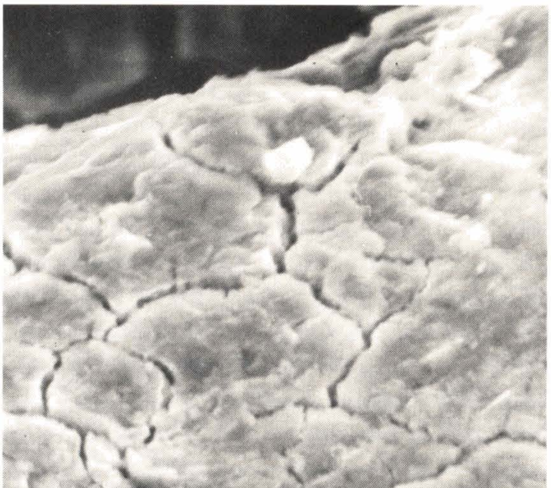


Fig. 68. The broken surface of an altered chalcopyrite grain, sample 68. SEM, secondary electron image.

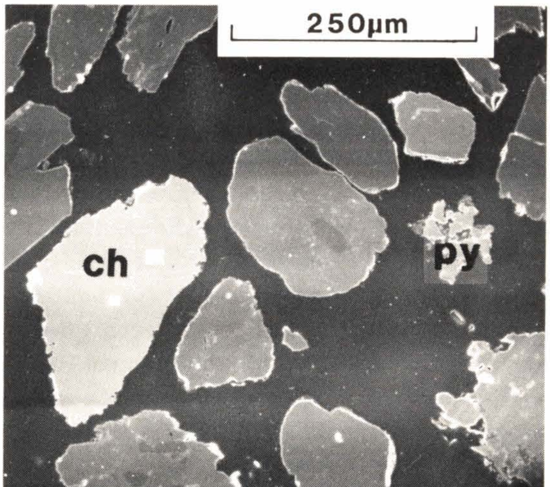


Fig. 69. Fresh chalcopyrite (ch) and pyrite (py), sample 321. Polished section, SEM, secondary electron image.

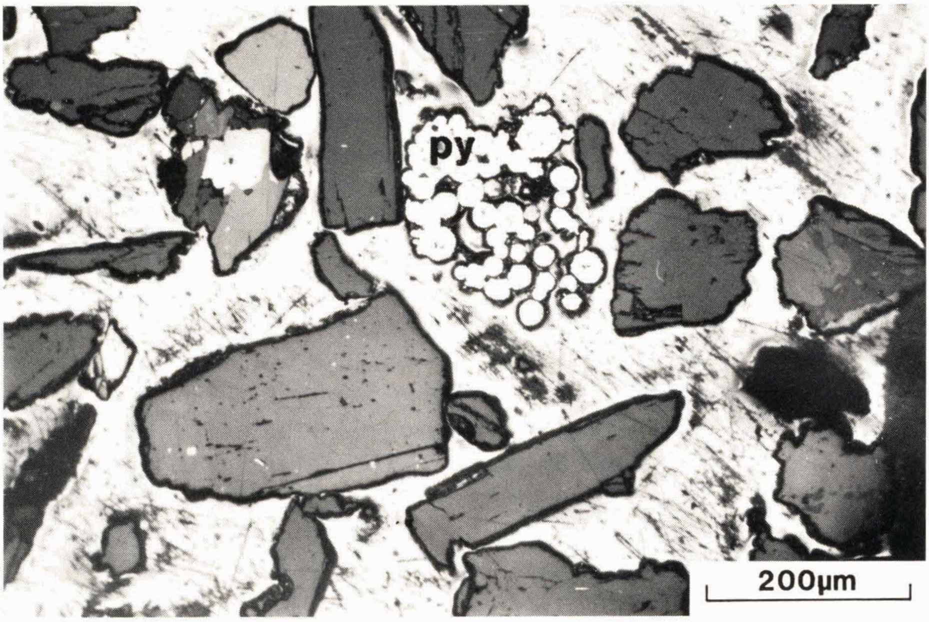


Fig. 70. Framboidal pyrite (py), sample 321. Polished section in reflected light, one nicol.

as inclusions in hornblende in the same sample (Fig. 71).

Other heavy minerals in the till samples from Petäjäskoski are: amphibole, ilmenite, sphene, hematite, apatite, chlorite and magnetite. Rutile, anatase and siderite are present in some samples. Magnetite is the most abundant heavy mineral.

The sulphide minerals are preserved intact in till that is below the groundwater level. On the other hand, the sulphide minerals have been altered to goethite in the superficial parts of the Rogen ridges. The sulphides have not been destroyed completely even in the soil horizons, where weathering processes are strongest. The results of this mineralogical investigation confirm the predominance of mechanical dispersion.

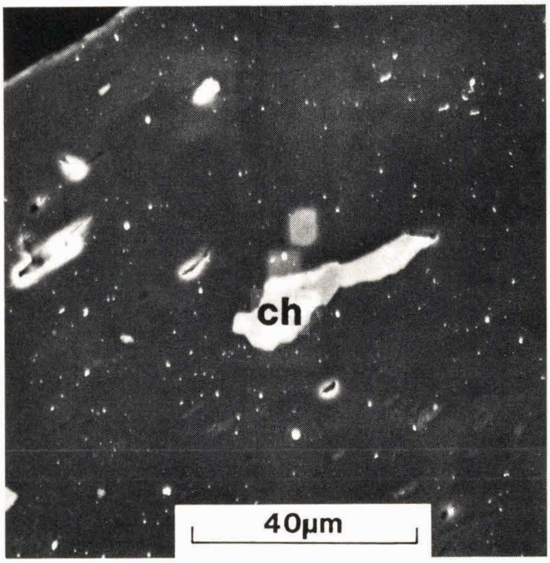


Fig. 71. Chalcopyrite inclusions (ch) in hornblende, sample 385. Polished section, SEM, secondary electron image.

CONCLUSIONS

The areas of this survey represent four different types of morainic landforms: cover moraine, ground moraine, drumlins and Rogen moraine. As to the depositional facies, all these types are composed primarily of basal till. The overburden is thinnest and the effect of the bedrock on the topography greatest in the cover moraine area. The effect of the bedrock on the topography is minor in the areas of the other morainic landforms. Till sampling with a light-weight percussion drill succeeds best in the cover moraine area. The percussion drill often stops in the superficial parts of the till in the other areas where the overburden is thicker. In boulder-rich till, as at Susineva, heavy sampling equipment is needed.

The effect of the number of samples on the statistical distributions of metals was studied with the material from Rantavaara. Even a relatively small number of samples gives a rather reliable picture of the distributions. The mean contents of metals can be disproportionately high, however, if a large number of the samples are from a mineralized area.

There is contradictory information about the metal contents as a function of depth. The highest copper contents occur in the deepest till samples just above the bedrock surface at Susineva. On the other hand, the highest molybdenum contents there are some metres above the bedrock surface.

In the other survey areas, there are anomalous metal values both in the shallow and deep till samples. This is greatly influenced by the type of moraine and the mechanism of dispersion in it.

The effect of grain size on the metal contents was studied with the material from Susineva. The metal contents generally increase as the grain size dimishes. Such is not always the case, however, as the molybdenum contents of till in pit M II at Susineva indicate. It must be borne in mind that sample 5420 at Rantavaara, whose fine fraction contained only 1 ppm molybdenum, contained abundant molybdenite in its sand fraction. Thus, molybdenum has a tendency to concentrate in the coarser fractions. This is caused at least in the examples described above by the occurrence of molybdenite as ductile flakes, which can resist even strong glacial milling. The original grain size of the ore minerals in bedrock has an important significance when we are thinking about the interdependence of the metal values and the grain size in till.

Several fractions from some till samples should be analyzed in every survey area, although the analysis of several fractions from all samples is economically not realistic.

Chemical cold-extractability studies and mineralogical investigations were used to interpret the anomaly types. The leach with citric acid gives a reliable picture of the content of the weakly bonded metals. The mixture of ascorbic acid-hydrogen peroxide is useful when the metals are in the form of sulphides. It must be remembered, however, that the sulphide minerals are not wholly dissolved by this mixture.

The anomalies in till proved to be predominantly clastic and glaciogenic in all four survey areas. Sulphide minerals were found in till in all the survey areas. The observed sulphides have been presented in Table 11. They are unweathered at Susineva. This is understandable, because the circumstances are reducing in most of the Susineva area. Sulphide minerals have been preserved, unweathered, in till saturated with groundwater in the Rantavaara, Kangerjärvi and Petäjäskoski areas. Such is the case particularly in flat mire areas, where the movement of groundwater is sluggish. The sulphides have been weathered to variable extents above the

Table 11.
The sulphide minerals found in till in the survey areas.

Rantavaara	Susineva	Kangerjärvi	Petäjäskoski
chalcopyrite	chalcopyrite	chalcopyrite	chalcopyrite
covellite	molybdenite	covellite	pyrite
bornite	pyrite	pyrite	pyrrhotite
metallic copper	pyrrhotite	pyrrhotite	
pyrite	sphalerite		
pyrrhotite			
sphalerite			
galena			
pentlandite			
molybdenite			

groundwater level in the superficial parts of the till deposits. A small portion of the sulphide grains has been preserved in the fresh state, even in the superficial parts. During weathering, the sulphides have been altered most commonly to goethite. The alteration started from the edges of the grains and proceeded along cracks. The surfaces of the grains quickly became scaly and broken.

Two iron sulphates, fibroferrite and carphosiderite were found in till at Rantavaara. These mineral species are also weathering products of the sulphides. Goethite, fibroferrite and carphosiderite all have been generated probably in postglacial times. In contrast, covellite and metallic copper were derived in all probability from the secondary enrichment zone of the preglacial weathering crust.

Weathering of the sulphides releases metals, which can immediately be bound to the secondary minerals and to the surfaces of the silicate minerals. Then the metals are more weakly bound than in the lattices of the primary sulphide minerals. Thus, a large amount of metals can be dissolved from the sample with the weak extractant, although the real hydromorphic dispersion would not be involved.

Hydromorphic dispersion caused by groundwater could be verified with certainty at Rantavaara in sample 5420, in which chalcopyrite was quite fresh, but the share of cold-extractable copper is nevertheless 47 % of the total content. Another apparent case of hydromorphic dispersion occurs at Petäjäskoski in sample 257, in which 42 % of the total content was readily extractable. Also, the zinc anomaly at Kangerjärvi (492–499 ppm Zn) was caused by hydromorphic dispersion.

The transport distance of till has been estimated with the aid of ore boulders and geochemical anomalies. Generally the ore boulders reach somewhat farther from the mineralization than the geochemical anomalies in the fine fraction of till. It seems that the ore boulders and the geochemical anomalies are more local in the cover moraine area and more far-travelled in the ground moraine area. The difference between the four moraine types is not very great, however. The geochemical anomalies can be traced up to 400–600 m from the mineralization in the direction of ice movement. The occurrence of high metal contents in till fines at a distance of over one kilometre from the mineralization is quite accidental.

Till geochemistry is very applicable in all four moraine types when we are searching for indications of the mineralizations and locating them. The samples need not necessarily be from near the bedrock surface in the regional prospecting phase when a sparse sampling grid is used.

It is important to determine the glacigene landforms of the survey area in the planning stage of the geochemical studies. This can be done well with aerial photo interpretation.

The mode of occurrence of metals in the samples ought to be investigated in every till-geochemical survey. Both chemical cold-extractability studies and mineralogical studies should be used. Besides the possible ore minerals, the silicate minerals also are useful in interpretation of the anomalies so that it is possible to get more detailed information about the mineralization type to be sought.

Mineralogical studies are particularly important in areas where there is a thick preglacial weathering crust. There is a possibility that in such areas, the geochemical anomalies in till are too high because the till can contain large amounts of recycled secondarily enriched material.

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