SVERIGES GEOLOGISKA UNDERSÖKNING

SER C NR 698 AVHANDLINGAR OCH UPPSATSER ÅRSBOK 68 NR 5

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ABSTRACT

Water, vegetation and glacial till have been investigated above a well-defined complex sulphide ore-body in the Skellefte district of northern Sweden in an attempt to correlate the trace element distribution in the different materials.

Ground-water yielded anomalies (Zn, Cu, Pb) in two drainage channels downslope of the ore, whilst surface-water gave only occasional high Zn values. Of the vegetation investigated, birch-bark gave pronounced anomalies of Zn and Pb which were closely correlated with ground-water anomalies.

The glacial till was composed of at least two layers, an upper till dominated by far transported rock-types and a lower till dominated by local types. The former had significantly lower background values than the latter. Sampling at the level near the contact of the two tills (1.5—3.0 m) gave misleading results due to the higher background contents in the lower till. Sampling at the 0.5 m level gave distinct, although weak, anomalous patterns of Zn and Pb which correlated closely with those of the ground-water and the birch-bark. This is interpreted as an effect of biogenic and hydromorphic processes.

INTRODUCTION

During the last seventeen years geochemical soil surveys have been used in Sweden as an integrated part of the prospecting for ores. In contrast to the success in many other parts of the country, the method has often failed to reflect even the well-known ore-bodies in the most important sulphidebearing area of Sweden, the Skellefte district (Brotzen in Kvalheim, 1967). The investigation described here has been made to attack this problem and some preliminary results have been given by Brotzen et al (in Cameron, 1966). The Norra Norrliden ore-body, chosen for the study, is situated in the Malånäs area in the central part of the Skellefte district (Fig. 1). The general geology and the ores of that area have been described by Gavelin (1939), but the Norra Norrliden ore which was discovered in the 1950's by geophysical methods has only recently been described (Pettersson, 1974). The ore-body is a complex Zn, Cu, Pb-mineralization, sub-outcropping below the till as a 200 m long WNW-trending unit. The ore immediately below the till shows the highest concentrations of the three dominant elements towards the ends of the sub-outcrop, the central part being both narrower and less concentrated. Till, plant and water sampling was

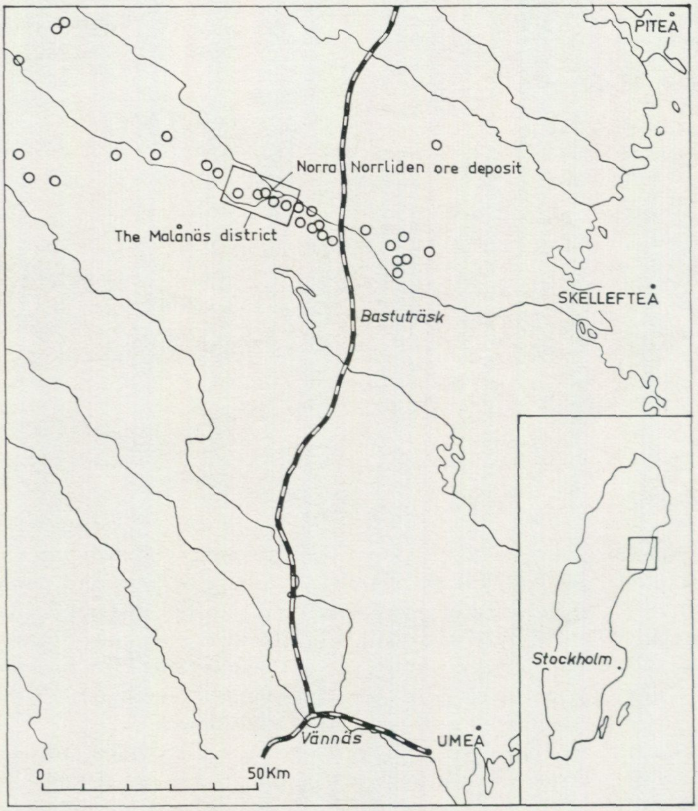


Fig. 1. Location of the Malånäs district showing the situation of the Norra Norrliden ore-deposit. From Gavelin (1939).

carried out in the area above the ore-body (Fig. 2). The present paper describes the variation patterns of Zn, Cu and Pb in these samples and discusses the intercorrelations between them with respect to the different factors involved, such as lithology of the till, drainage and biogenic processes.

DESCRIPTION OF THE AREA

Topography

The investigated area is situated on the northern slope of a WNW-trending valley, a feature reflecting the general structural trend within the region. The altitude is c. 225 m a. s. l., i. e. above the highest level of the post-glacial sea, which in this vicinity reached 217 m. Thus no wave-washing of the surface soil took place on the hill slopes, although the bottom of the valley was reached by the sea and filled with post-glacial sediments and peat. The whole area is characterized by small hills and the depressions between them are occupied by lakes and peat-bogs.

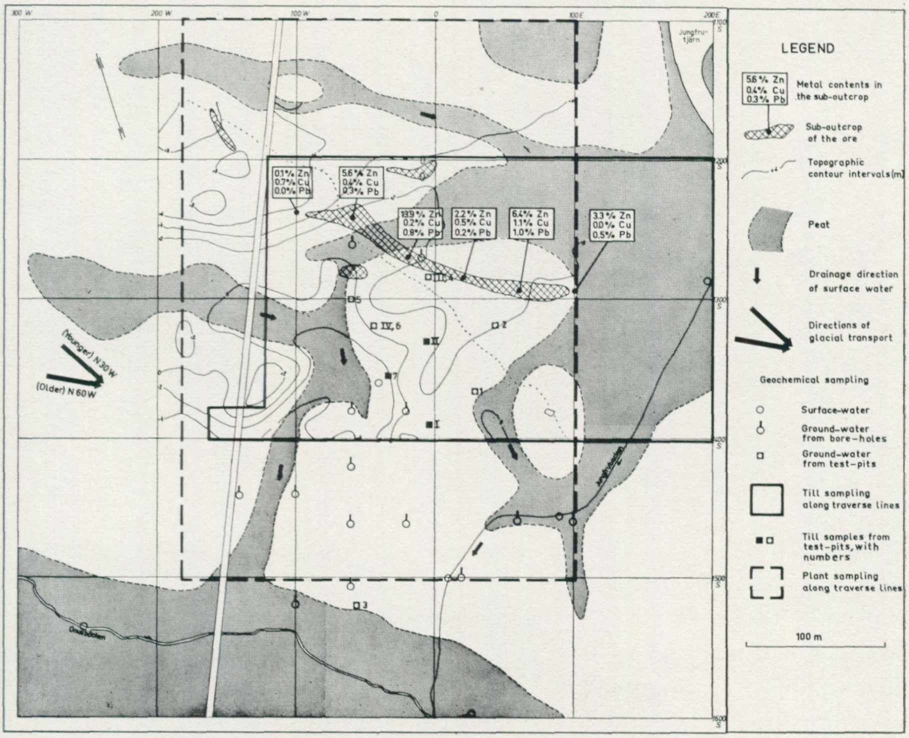


Fig. 2. Key-map showing location of the ore-body and the sampling areas at Norra Norrliden.

Drainage

The regional drainage direction is from WNW to ESE following the structural trend and is reflected by the stream Önusbäcken that drains the valley to the south of the sampled area (Fig. 3). The shape of some peat-bogs within the sampled area reflects this structural direction. However, the drainage within the area is of course controlled by the local topographical conditions, resulting in a drainage down the slope to the SSW.

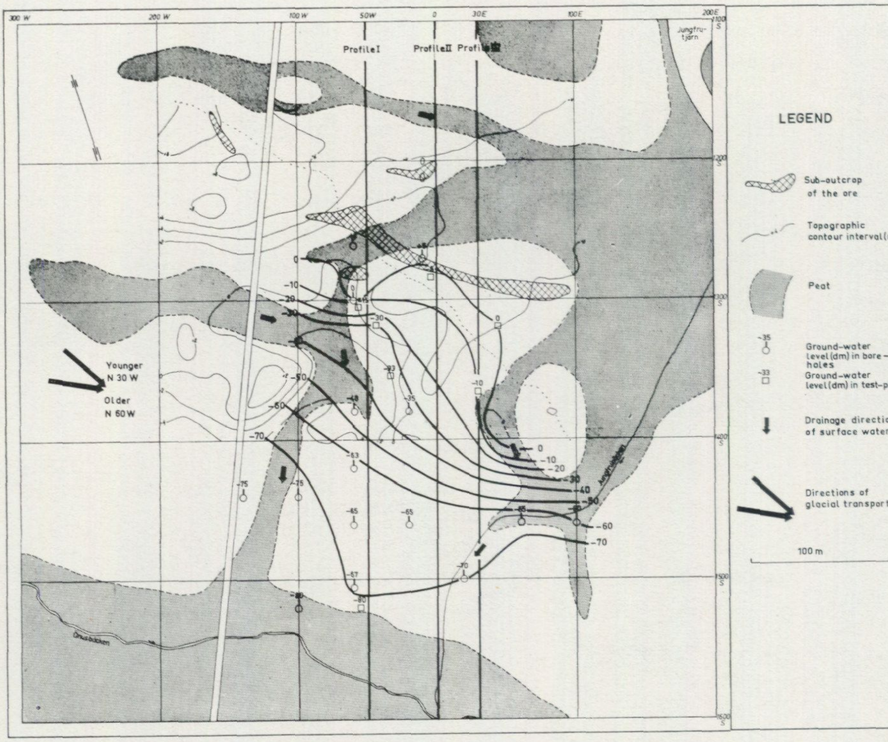


Fig. 3. Map showing the ground-water level at Norra Norrliden. Iso-lines for each 10 dm.

Two main features can be distinguished. One is the peat-bog passing over the western end of the ore-body and continuing southwards to the bottom of the valley. The other one is associated with the small streamlet Jungfrubäcken in the eastern part of the sampled area. The area between the two drainage channels is dry and characterized by weakly undulating ablation till (Fig. 15 and 16). Iso-lines of the water-table downslope from the ore-body were constructed from measurements of the ground-water level in bore-holes, test-pits and peat-bogs (Fig. 3). They indicate a rapid flow of ground-water along the eastern drainage channel, a minimum of flow in the central part of the area and again a more rapid flow along the western drainage.

Quarternary deposits

The glacial deposits of the region have been described by Granlund (1943). The investigated area at Norra Norrliden is completely covered by glacial till. Its thickness and the sub-surface configuration of the bedrock are well known from drill-holes (Fig. 14—16). In the upper (northern) part of the slope the thickness is about 6 m increasing to about 18 m in the lower (southern) part.

The surface layer has the characteristics of a superglacial till, having a very loose consistency with silt and sand as dominant size fractions, very low contents of the finest fractions, and moderate contents of coarse material. In addition to this material there was found, in the deepest part of one of the test-pits, a more dense and clayey type of till with a clearly pressed texture.

It is known from glacial striae investigations that there have been two marked glacial transport directions in the region. The ice-movement during the major stage of the last glaciation was from the WNW. In the final stage the ice-movement changed into a direction from the NNW.

Observations of different beds of till with clear-cut contacts have been made repeatedly as recorded by Högbom (1937), Granlund (1943) and Lundqvist (1943), mainly in connection with excavations for mining operations.

Vegetation

The vegetation in the region is forest of pine, spruce and birch on typical podsolic soil with the C-horizon starting at about 0.5 m. Peat areas are numerous, and they have in general a WNW-trending elongation. Within the sampling site the S-trending downslope drainage-structures are also covered with peat.

INVESTIGATION OF THE TILL

GEOCHEMICAL INVESTIGATION OF GRID-SAMPLES

METHODS OF SAMPLING AND ANALYSIS

After obtaining two Zn-anomalous stream sediment samples at the discharge points of the two drainage channels into Önusbäcken, a geochemical soil survey was carried out in the area over the ore-body. Samples were collected at 20 m intervals along lines 40 m apart. The traverse lines were laid out perpendicular to the ore-body. At each sampling point two samples were taken from the till, using a steel auger, one sample from 0.5—0.7 m depth and one from about 1.5 m depth.

Since the podsol profile was found to be about 0.5 m thick, which is normal for this part of Sweden, a number of samples taken at the upper level are likely to originate from the B-horizon, whilst those from the lower level (1.5 m) all originate from the unweathered till (i. e. from the C-horizon). However, the thickness of the peat-layers, mainly in the eastern part of the area prevented sampling from the 0.5—0.7 m level at some sampling points.

The samples were dried at 100° C and sieved through a nylon sieve, and the < 0.1 mm fraction was analysed using a direct reading spectrometer provided with a tape machine. This is a standard method at the Swedish Geological Survey having the advantages of being rapid, because it requires no enrichment of elements and comprehensive in that it enables determination of many minor and major elements in a single procedure. The special advantages of the tape method as regards accuracy have been discussed elsewhere (Brotzen & Danielsson, 1963).

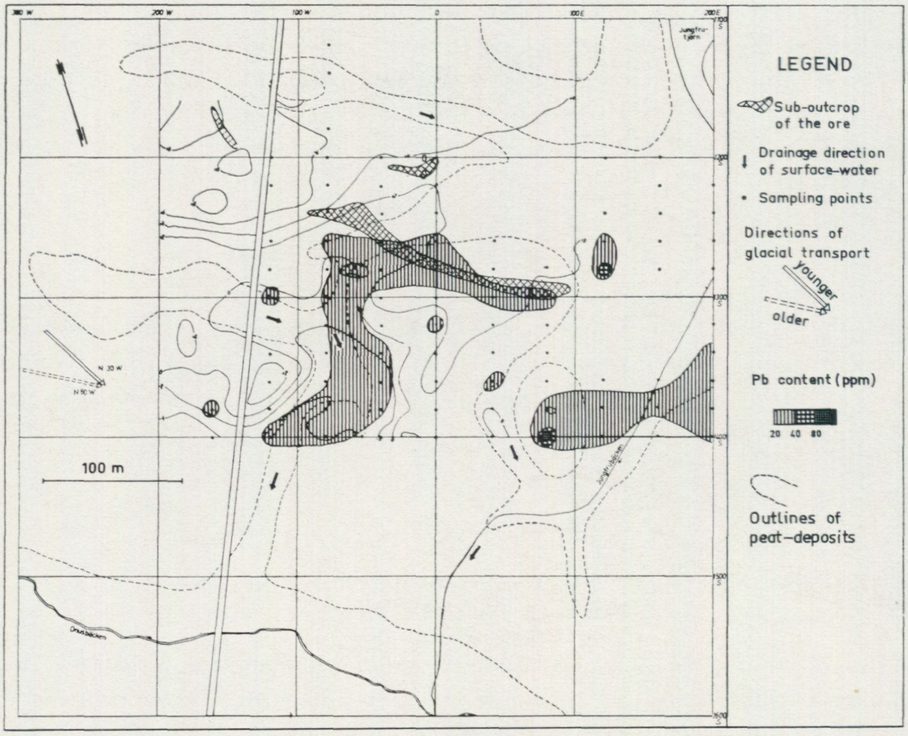


Fig. 4. Distribution of Pb at 0.5 m depth in the <0.1 mm fraction of the till at Norra Norrliden.

RESULTS

The distribution of Pb, Cu and Zn was contoured for the two sampling depths respectively. These elements were found to have surprisingly low concentrations for their position above an ore-body. Nevertheless it was possible to outline weakly anomalous areas for all three elements.

The distribution of Pb at 0.5—0.7 m depth is presented in Fig. 4. Pb contents above 20 ppm have been considered as anomalous. The distribution pattern is characterized by two distinct anomalies and a few scattered ones representing one or two sampling points only. The most conspicuous anomaly covers the central and eastern parts of the ore-body with an elongation to the south over its western end. However, the Pb-values in this anomaly are low, not exceeding 40 ppm. The other anomaly is situated in the south-eastern part of the sampled area with an E—W-trending elongation. Here a maximum of about 80 ppm Pb was found in the western end.

The Pb-distribution at 1.5 m depth is shown in Fig. 5. Two distinct anomalies occur, one immediately to the east of the ore-body and one to the

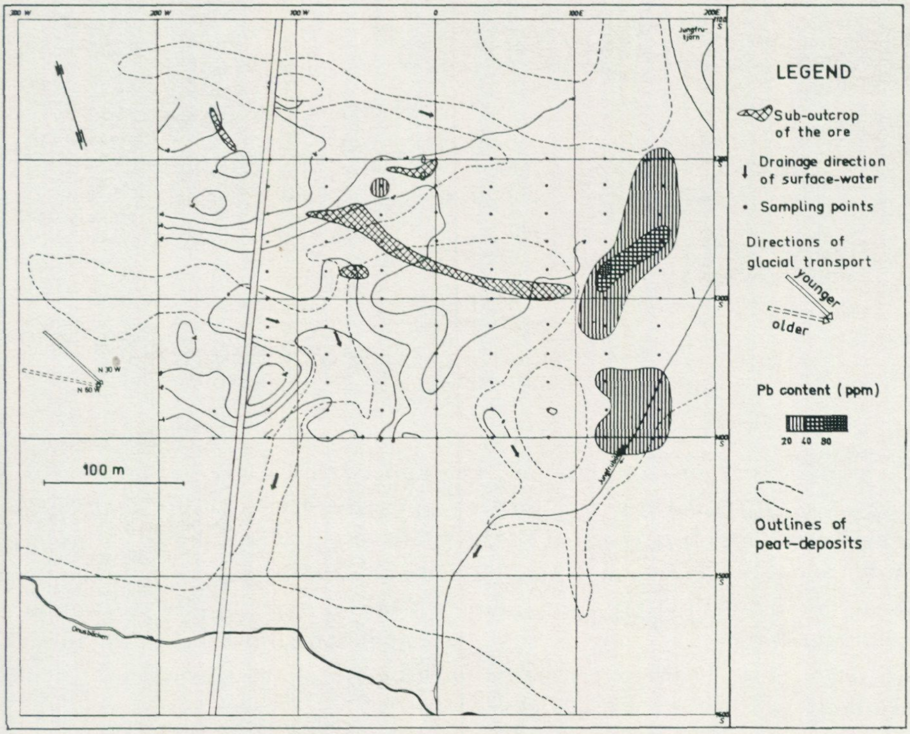


Fig. 5. Distribution of Pb at 1.5 dm depth in the <0.1 mm fraction of the till at Norra Norrliden.

south-east. Both are restricted to the peat-bog in the eastern part of the area. No values above 20 ppm occur directly above the area of the mineralisation except for a single sample north of the western end of the main ore-body. The highest value, 80 ppm Pb, was found in the anomaly immediately to the east of the ore-body.

The distribution of Cu at 0.5—0.7 m depth is presented in Fig. 6. The

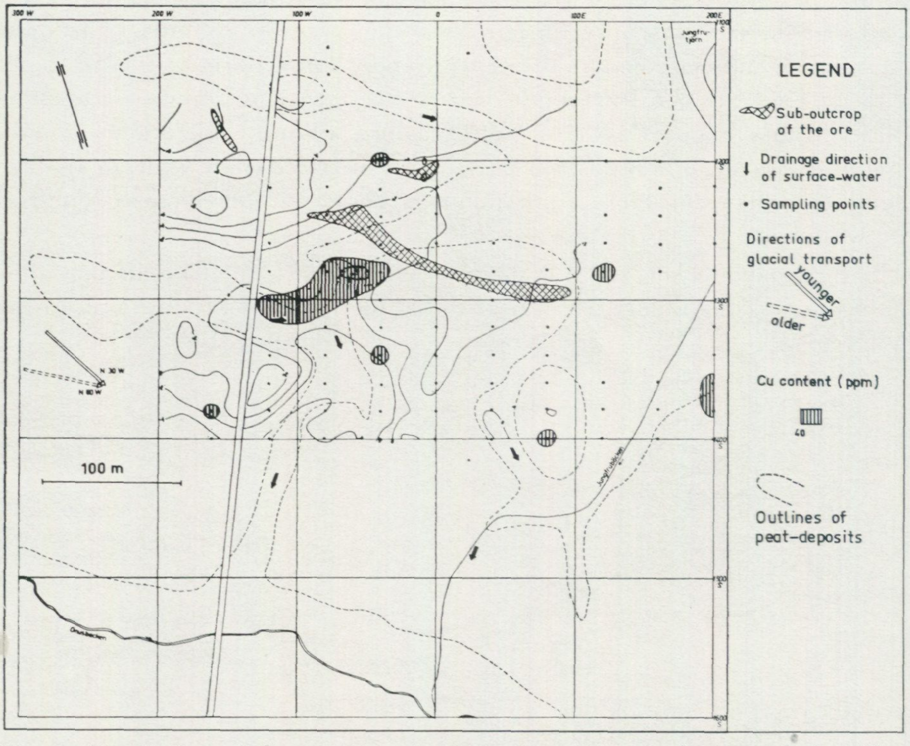


Fig. 6. Distribution of Cu at 0.5 m depth in the <0.1 mm fraction of the till at Norra Norrliden.

Cu content is from 10 to 60 ppm. The upper limit of the background was taken as 40 ppm. Only one distinct anomaly occurs, representing four sampling points. It is situated to the south of the western end of the ore-body. Some scattered single-sample anomalies occur also, but they do not form any distinct pattern. The samples from 1.5 m depth gave Cu contents from 10 to 90 ppm i. e. higher than the upper sampling level. Two anomalies occur (Fig. 7), the one situated to the south of the western part of the ore-body and the other above its eastern end.

The distribution of Zn at 0.5—0.7 m depth is presented in Fig. 8. The Zn content is from 20 to over 240 ppm. The upper background value for

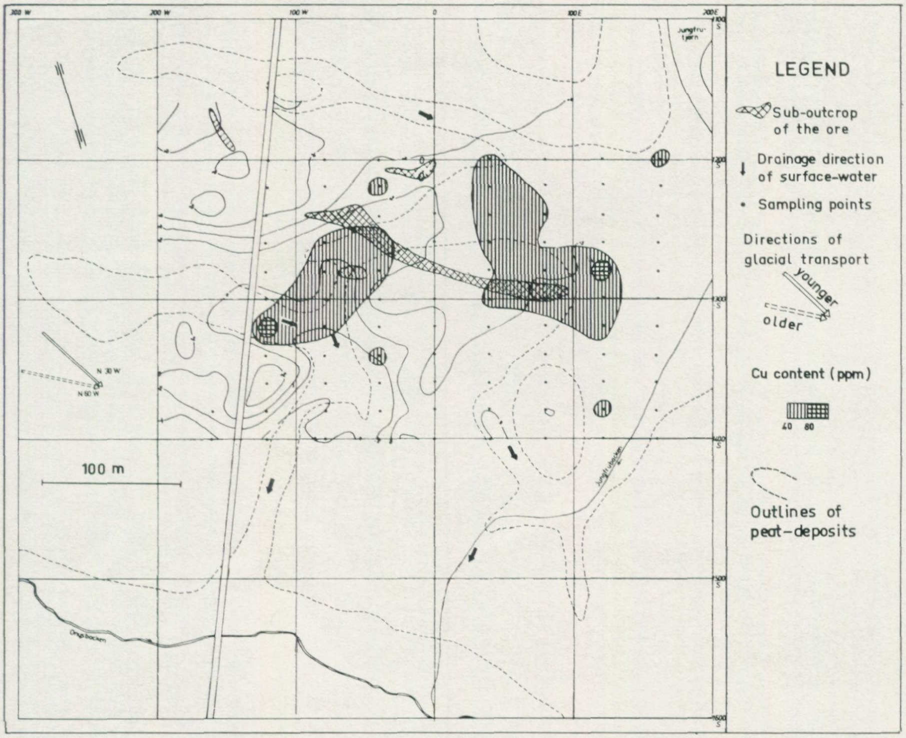


Fig. 7. Distribution of Cu at 1.5 m depth in the <0.1 mm fraction of the till at Norra Norrliden.

Zn is 60 ppm, and the anomalous areas are considerably larger than those for Pb and Cu. The main anomaly covers the western part of the ore-body with an elongation to the south. Two other anomalies occur in the eastern part of the sampled area.

The distribution of Zn at 1.5 m depth (Fig. 9) on the other hand, gives a somewhat different picture. Firstly, Zn content is from 20 to 120 ppm, thus indicating a lower degree of concentration in the till at this level compared with the 0.5—0.7 m level. Secondly, the anomalous areas are not so large, many of the high values forming single-sample anomalies. Two anomalous areas occur in the western part of the area, one above the ore-body and the other in the peat-bog to the south of it. Two other anomalies are located in the peat-bog to the east. Besides these, there are some occasional erratic highs outside the main anomalies.

DISCUSSION OF THE RESULTS

From the results obtained it is possible to draw certain conclusions regarding the mechanisms responsible for the formation of the anomalous

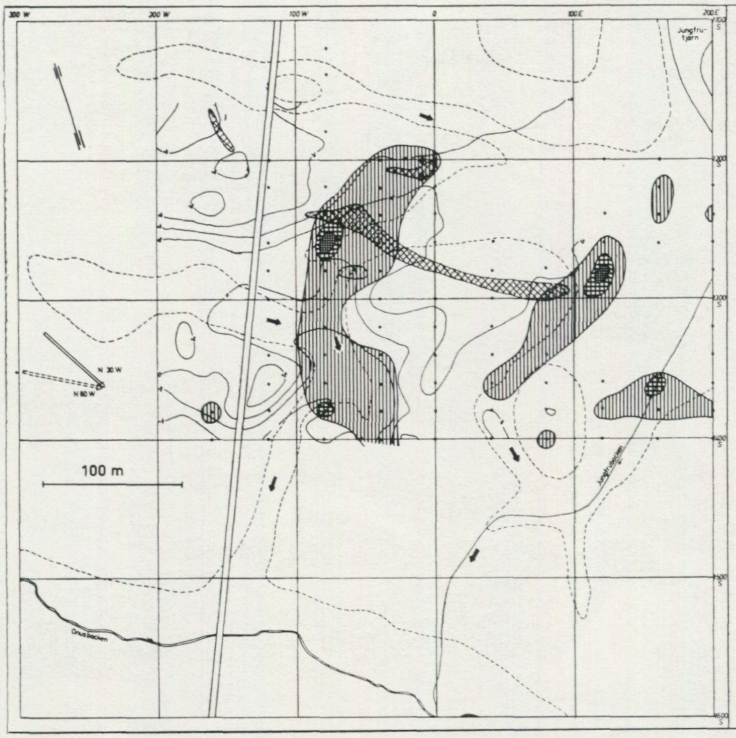


Fig. 8. Distribution of Zn at 0.5 m depth in the <0.1 mm fraction of the till at Norra Norrliden.

patterns within the till. Basically, two processes of formation of the anomalies are possible; by syngenetic or epigenetic dispersion in the till. In the former case the anomalous material would be laid down within the till at the time of its formation by the glacial erosion of the ore-body. By the latter process, anomalous material is introduced into the till after it has been deposited, for example transportation by ground-water or by biogenic activity. Most of the results obtained in this study suggest that the latter processes (hydrochemical and biochemical) were almost entirely responsible for the formation of the anomalies. One of the characteristics favouring this interpretation is the shape of the anomalies. They have a strong tendency to be elongated in the drainage direction downslope from the mineralisation. The concentration of anomalies to the peat-bog in the eastern and south-eastern parts of the sampled area could also be explained by hydromorphic processes. The possibility that ore material has been laid down within the till by glacial erosion is not very likely, neither the low degree of concentration nor the shape of the anomalies favouring this process.

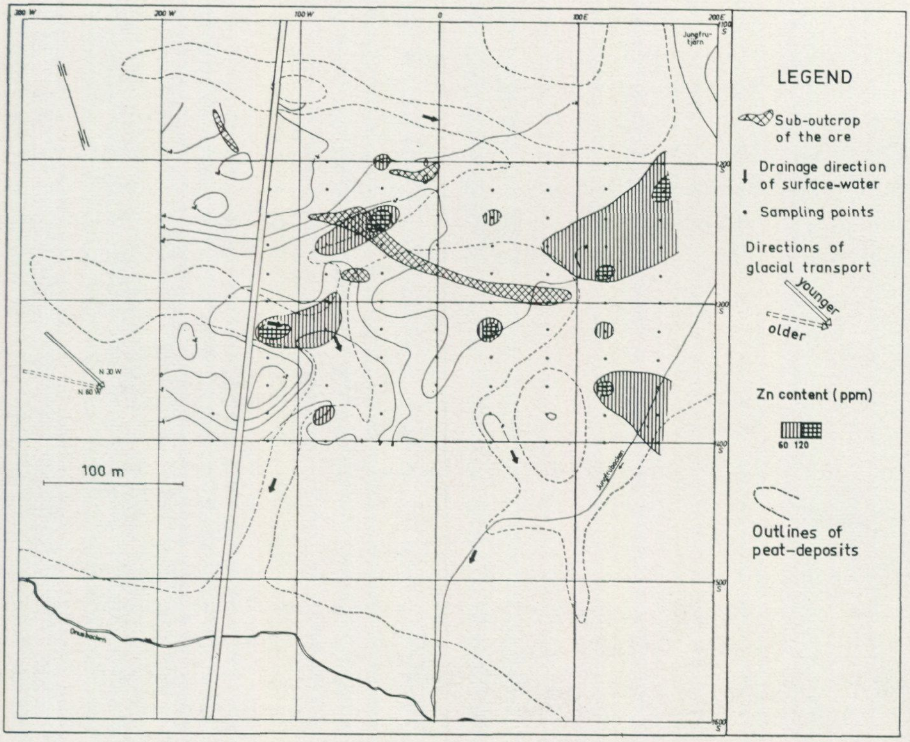


Fig. 9. Distribution of Zn at 1.5 m depth in the <0.1 mm fraction of the till at Norra Norrliden.

The results have also shown that Pb and Zn had a tendency to be more concentrated at the 0.5—0.7 m level than at the 1.5 m level. This is probably a result of biogenic processes combined with retention in the B-horizon. The same phenomenom has been reported by other geochemists (Hawkes & Webb, 1965). The fact that Cu does not show a similar concentration nearer the surface will be discussed later.

INVESTIGATION OF TILL-SAMPLES FROM TEST-PITS

COLLECTION OF SAMPLES

For a detailed investigation of the till, four test-pits were dug to a depth of 3.0—4.0 m on the south side of the ore-body. This location was controlled by the direction of ice-movement so as to allow assessment of clastic dispersion from the ore-body.

The four profiles showed a quite homogeneous till of the composition already described (silty and sandy, low content of coarse material). Only in one of the pits. No. IV, which was dug in a depression could a change be seen near the bottom. Here the till was more pebbly, with a more clay-rich matrix and a slightly pressed appearance.

Samples (1.5—2 kg), were taken from the pits at every 0.5 m, with the exception of No. IV where samples were taken also close to the transition zone. The grain-size distribution of the samples was determined. A special investigation of the rock-types in the gravel fraction (4—8 mm) was carried out. The metal content of the $< 60\ \mu$ fraction was determined spectrographically.

PETROGRAPHIC INVESTIGATION OF THE PEBBLE-FRACTION

Description of the method

In order to determine the different lithologies of the till, pebble-counts were made on each sample. The fraction 4—8 mm was used and 200—300 pebbles were obtained from each sample.

The identification was made with a binocular microscope (6x) under reflected light after washing off the finer fractions on the surface of the pebbles. By also studying parts of the material in thin-section it was possible to recognize five different rock categories: Acid intrusive rocks, volcanic rocks including porphyrites, phyllites, quartzites and crystalline quartz.

About 80 % of the pebbles in each sample could be assigned to one of these categories using the binocular microscope. Thin-section studies further helped to define characteristic features of the different rocks. In combination with available information on the distribution of specific rock-types, as summarized by Gavelin (1955) and Ödman (1957), it was possible to indicate some of the source areas for the material transported by the land-ice (Fig. 10).

Description of the different rock-types

a. *Acid intrusive rocks*

Granitic and syenitic pebbles were easiest to identify because they showed the most marked differences from the other groups. The colour varies between light red and grey. They are generally of medium grainsize, but feldspar porphyritic types with a finer grained matrix do occur. These amount to c. 30 % of the granitic pebbles and show a granophyric intergrowth of quartz and microcline.

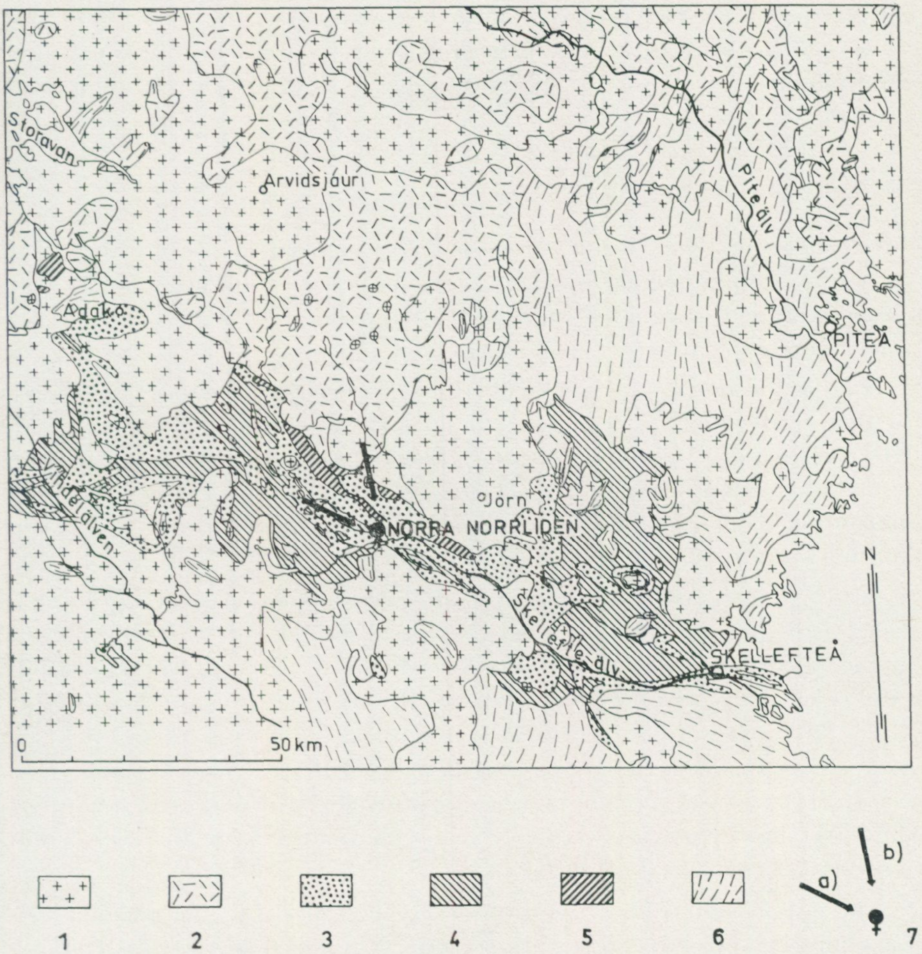


Fig. 10. Simplified geological map of the southern parts of Norrbotten and the northern parts of Västerbotten counties, taken from Gavelin (1955) and Ödman (1957). The map shows the location of the ore deposit at Norra Norrliden and the two directions of glacial transport.
1. Acid intrusive rocks of various age. 2. Arvidsjaur porphyries. 3. Skellefte-volcanics. 4. Sediments of the phyllite series. 5. Vargfors sediments. 6. Other rock types. 7. Location of the Norra Norrliden ore deposit. 7 a). Direction of older glacial transport (from N60°W). 7 b) Direction of younger glacial transport (from N15°W).

Potassium feldspar and microcline perthite dominate. The hornblende is pleochroic in blue and green colours. The biotite is brown. The accessories include: apatite, zircon, sphene and ore minerals (magnetite). Secondary minerals are sericite, chlorite and epidote.

These characters indicate that the acid intrusive rocks in the till originate from the massifs of Sorsele granite and Adak granite 25—30 km north and north-west of Norra Norrliden. A third granite type, the Jörn granite 5—10 km north-east of the sampling area may also be present, it having in part a porphyritic texture (Gavelin, 1955), similar to that observed in some of the pebbles.

b. *Volcanic Rocks*

Two categories of volcanic rocks were recognized, a porphyritic group including pebbles of liparitic, dacitic and andesitic composition, and a more metamorphosed category of acid and intermediate volcanic types (Skellefte-volcanics).

Among the porphyritic rocks, the liparites are the easiest to identfy due to their red-violet or red-grey colour and prominent phenocrysts. The latter are mainly light red potassic feldspars, perthite, microcline and microcline-perthite. They are 2—4 mm in diameter and are often idiomorphic. Quartz phenocrysts are less abundant. They are often corroded and have pyramidal crystal terminations.

A few plagioclase phenocrysts of albitic composition were observed in some of the pebbles. The observed characteristics indicate that this material of the till originates from the liparitic (rhyolitic) derivates of the Arvidsjaur-porphyries, situated 20—25 km north and north-west of Norra Norrliden. Although similar structural and textural features occur in other volcanic series in the area, for example in the Skellefte-volcanics and in the Vargfors series, the predominance of potassium feldspars over albite and the lesser metamorphic alteration favour derivation from the Arvidsjaur-porphyries (Grip, 1935).

The dacitic and andesitic pebbles were identified on the basis of their dark matrix and still darker phenocrysts. Thin-sections revealed that the andesitic types dominate. They have phenocrysts mainly of plagioclase (andesine) and hornblende, the former often zoned. The rocks have been subject to greenschist facies metamorphism with secondary growth of chlorite, sericite, biotite, epidote, amphibole and microcline. Rocks of andesitic and dacitic composition occur in all the three main supracrustal series in this area, namely the Skellefte-volcanics, the Arvidsjaur-porphyries and the Vargfors effusive greenstones.

The first of these series, the Skellefte-volcanics predominates (together with phyllites and graphitic schists) in the Malånäs area. From the regional mapping, however, it is known that in the western part of the Malånäs district (i. e. in the sampling area) basic extrusive are very subordinate. Keratophyric and rhyolitic rocks predominte, often together with clastic agglomerates (Gavelin, 1955). A local origin of the andesitic and dacitic pebbles is therefore not very likely. The most probable source of this material in the till is the vast areas of effusive greenstone belonging to the Arvidsjaur-porphyries and the Vargfors-series 10—15 km north of the sampling area.

The Skellefte-volcanics are of acid and intermediate composition. Most abundant are quartz-porphyric lavas and their pyroclastic derivates. Even-grained, massive or stratified tuffs and tuffites are also frequent in this group. The microscope investigation showed that all these rock-types are more or less metamorphosed and altered into chloritic and sericitic schists.

From earlier work (Gavelin, 1939) it is known that these lithologies belong to the older supracrustal rocks of the Skellefte district, making up the local bedrock of the Malånäs area. They therefore represent the locally derived material in the till.

c. *Phyllites*

The phyllites consist largely of black graphite-bearing phyllite and grey types with mainly quartz, plagioclase, microcline, sericite and chlorite. They are quite widespread in the area, and also in the so-called Vargfors sediments north of the sampling area. Because of the difficulties in identifying these rock-types in the gravel fraction the percentages in Table 1 must be regarded as minimum values (except for sample No. 3 and 12).

d. *Quartzites*

The quartzite pebbles were identified under the binocular microscope mainly by their clastic texture. (Moreover the quartz grains in these pebbles differ from the quartz phenocrysts in the quartz porphyries as they are pale and more rounded). Thin-section studies revealed that a good deal of these pebbles are very similar to the so-called Vargfors sandstones (Gavelin, 1955). Arkoses are also represented.

Most of the pebbles examined have been changed by sericitization and chloritization, which of course makes the classification difficult under the binocular microscope. The true percentage values are therefore likely to be higher than those in Table 1.

The source area of this clastic sediments could be situated 10—20 km north of the sampling area, i. e. from the so-called Vargfors sediments, but the same rock-types are also reported from the phyllites which occur in the vicinity of the sampling area (Gavelin, 1955).

e. *Quartz*

Among the pebbles of the till a few consist of pure crystalline quartz. They are easy to distinguish from all other pebbles.

TABLE 1. Rock-types (%) of the gravel-fraction (4—8 mm) in the pit-samples

Test-pit No.	Sample No.	Sample depth (dm)	Rock-types						Unidentified pebbles	Amount of pebbles
			Acid intrusives	Porphyrites	Skellefte volcanics	Phyllites	Quartzites	Quartz		
I	1	5	31.0	10.6	23.2	8.8	1.8	1.8	22.7	216
	2	10	40.3	8.1	19.9	8.5	4.2	1.7	17.3	236
	3	15	37.6	16.6	23.3	8.7	9.8	4.0	0.0*)	252
	4	20	34.5	11.2	23.9	8.6	1.0	3.0	17.8	197
	5	25	30.0	13.0	26.0	4.0	4.7	3.0	19.3	300
	6	30	36.8	9.5	24.4	8.3	1.6	1.9	17.5	313
II	7	5	26.3	11.7	31.1	10.5	2.9	1.1	16.4	190
	8	10	24.9	11.2	33.2	5.9	1.9	1.9	21.0	204
	9	15	14.2	13.3	36.6	11.6	0.9	1.3	22.0	232
	10	20	12.0	6.2	49.2	5.8	0.0	0.8	26.0	242
	11	25	13.0	5.8	58.9	7.3	0.0	1.5	13.5	203
	12	30	9.7	9.4	64.8	7.5	6.6	2.0	0.0*)	258
III	13	5	34.4	18.3	25.2	5.3	4.6	0.0	12.2	131
	14	10	32.3	16.5	22.8	8.7	3.9	1.6	14.2	126
	15	15	45.5	9.6	19.8	7.8	0.6	0.0	16.7	167
	16	20	42.3	12.8	17.4	7.4	1.3	2.7	16.1	148
	17	25	40.4	11.3	21.1	8.5	2.8	2.8	13.1	176
	18	30	30.2	10.6	27.4	10.1	2.8	0.5	18.4	176
	19	35	15.6	6.1	51.7	7.2	2.2	1.7	15.5	180
IV	20	5	21.3	5.9	33.7	15.4	1.8	2.4	19.5	167
	21	10	20.2	11.1	38.9	6.9	2.7	2.3	17.9	262
	22a	15	10.1	6.0	57.7	6.5	0.6	0.0	19.1	167
	22b	17	10.1	6.7	48.3	9.3	3.8	0.4	21.4	237
	23	20	7.1	8.6	57.6	7.1	1.5	1.5	16.6	198
	24	25	4.3	4.3	60.9	6.1	2.4	0.6	21.4	164

*) All pebbles identified in thin-sections.

The amounts of pebbles counted and the percentages of the different rock-types are presented in Table 1.

Acid intrusive rocks and Skellefte-volcanics dominate, the former with a maximum value of 45.5 % and the latter with 64.8 %. On the other hand there are quite big variations between different samples with respect to these rock-types. This is reflected in the minimum values which are as low as 4.3 % for the intrusive rocks and 17.4 % for the Skellefte-volcanics.

Third largest is the porphyritic category of volcanic rocks ranging from 4.3 % to 18.3 % with most values over 10 %. Taken together these three groups of rocks form the bulk of the gravel-fraction in the till-samples with values from about 65 % to over 75 %.

The fourth largest group is the phyllites ranging from 4.0 % to 15.4 % with most values lower than 10 %.

The quartzites and quartz groups have low values for all samples. They are mostly around 1—4 % and never exceed 10 %.

Unidentified pebbles form the group called "unknown rock-types". The values range from 0—25 %.

The "unknown rock-types" in the gravel-fraction were examined in greater detail in two samples, No. 3 (Pit I, 1.5 m depth) and No. 12 (Pit II, 3.0 m depth). These two samples were chosen because they show marked differences with regard to the percentage of the different rock-types in the gravel fraction. Thin-sections were made of all the unknown pebbles, and the rock-types were determined under the microscope.

The results are included in Table 1. They show that all the unknown pebbles can be referred to the categories of rock-types already identified. Most of the pebbles appear to belong to the Skellefte-volcanic group or to the quartzite group. Only a few were found to belong to the porphyrite types and to the phyllites. No pebbles of acid intrusive rocks were identified.

As a whole the results reinforced the differences between the two samples as far as rock-composition is concerned. Sample No. 3 was found to have 54 % of far-transported rock-types (acid intrusives, porphyrites) and only 32 % of the local rock-types (Skellefte-volcanics and phyllites). The same figures for sample No. 12 are 19 % for far-transported rock-types and 72 % for local rock-types.

The petrographic composition of a till is a reflection of the different rocks and the older till layers that were eroded by the land-ice. With a glacial derivation from the north and north-north-west one can easily explain the contents of acid intrusives and porphyritic rocks in the till. These two rock-types represent the far-transported material. As can be seen from the geological map this material must have been transported at least 10 km (Fig. 10).

The variations of the three dominant rock-types are illustrated in the triangular diagram (Fig. 11). Here the far transported rock-types (intrusive and porphyry) are taken together and plotted against the Skellefte-volcanic rocks and the remaining rock-types. Two concentrations appear in the diagram. The one in the lower right hand corner with samples dominated by the Skellefte-volcanics and with low intrusive values represents eight samples (No. 10, 11, 12, 19, 22a, 22b, 33 and 34). The other samples form a group in the upper part of the diagram, i. e. they are dominated by acid intrusive rocks and porphyrites and are low in Skellefte-volcanics (No. 1, 2, 3, 4, 5, 6, 7, 8, 13, 14, 15, 16, 17 and 18).

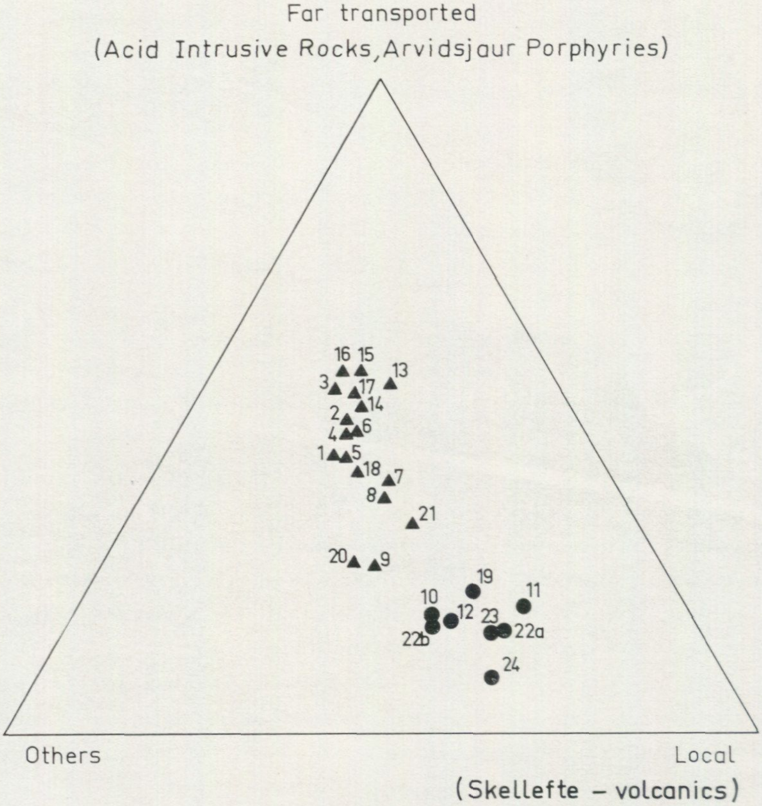


Fig. 11. Triangular diagram showing the distribution of lithology in the till-samples with respect to rock-composition of the gravel fraction.

The variation of the three significant rock-types in the four test-pits are shown in Fig. 12. Here the gravel fraction of each sample is divided into the six petrographic groups and represented by histograms.

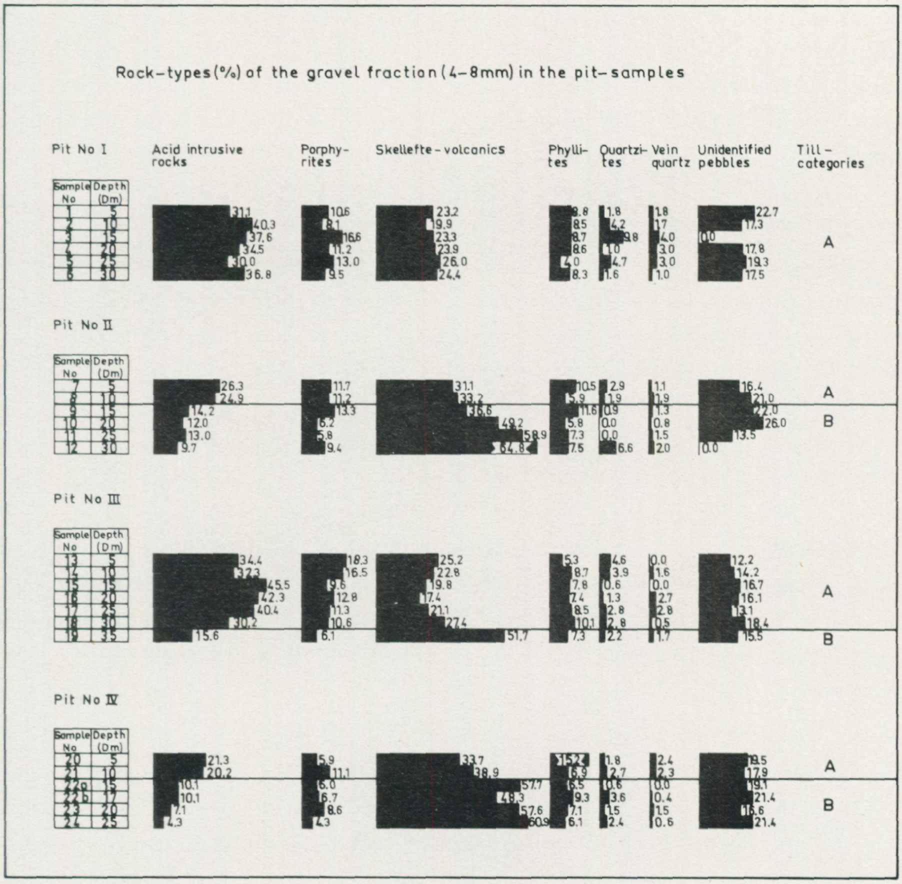


Fig. 12. Histograms showing the vertical distribution of the different rock-types in the gravel fraction of the till from test-pits No. I, II, II and IV.

Test-pit I

The contents of the three rock-types do not change systematically with depth. Granite content is comparably high (30—40 %) as is the porphyrite content (8—14 %). Skellefte-volcanics (c. 20—25 %) are subordinate indicating a dominance of far-transported material.

Test-pit II

The contents of the three rock-types indicate that two categories of till are present.

The two upper samples (No. 7, 8) have intrusive rocks, contents around 25 %, whilst the figures for the three lower samples range from 10 % to 14 % (decreasing downwards).

The porphyrite content is about the same as for pit I in the three upper samples, i. e. about 12 % but decreases to about 6 % in the three lower samples. The contents of Skellefte-volcanics on the other hand, increases from around 32 % (in the upper sample) to around 65 % in the lowermost sample (No. 12) at the 3.0 m level.

Test-pit III

This test-pit was 3.5 m deep. The samples have high intrusive rock contents in the upper part down to the 2.5 m level. The two samples below this level contain more local rock-types. Sample No 19, at the botton of the pit, is dominated by Skellefte-volcanics.

Test-pit IV

Only the two upper samples (No. 20 and 21) have considerable amounts of far transported rock-types (25—30 %). From the 1.5 m level the gravel fraction is dominated by local Skellefte-volcanics and at the bottom of the test-pit the far transported rocks (acid intrusives and porphyrites) have their minimum (8 %).

The results from the pits I—IV indicate that there are at least two types of till in the area. The upper part is rich in intrusive rock and porphyritic pebbles indicating glacial transport more than 10 km from the north and north-north-west. Below this the till is mainly composed of local Skellefte-volcanic material.

As can clearly be seen (Fig. 12) the intrusive and porphyrite group (A) and the Skellefte-volcanic group (B) roughly divide the 25 till-samples into two categories. Intrusive rocks exceed 20 % in group A and are less than 20 % in group B. Skellefte-volcanics on the other hand correspondingly are greater in group B than group A. Another interesting fact is that the porphyrite content varies in the same way as the intrusive rock content. This can be explained when taking the regional geology into account. (Fig. 10). Acid intrusive rocks and porphyrites are both situated in about the same areas in the north and should therefore be subjected to the same glacial transport. One can therefore expect the same variation pattern in the samples with respect to these two rock-types.

The Skellefte-volcanics, on the other hand, represent the local material. The phyllitic schists could be of either local origin or derived from the area of the Vargfors sediments north of the sampling site. However, this latter group of rocks cover large areas north of the Malånäs district, and similar rocks are also found in the local phyllitic series. One could therefore expect a greater proportion of phyllitic schists in the till than has been found.

A possible explanation for the low percentage values is that these schists are easily broken down by the erosion of the ice and are therefore underrepresented in the gravel fraction. Another explanation is that pebbles of this rock-type are difficult to determine using the binocular microscope and might therefore be referred to the "unknown" pebble fraction.

As to the quartzites and vein quartz groups, one can only say that their proportions are low. As far as the quartzite group is concerned this might be due to difficulties in identification. No conclusions can be drawn concerning the source area of these two rock-types. Clastic sediments are represented both in the local phyllitic series and in the Vargfors series north of the sampling area.

GRAIN-SIZE ANALYSIS

Description of the method

Grain-size analysis of a till is in general complicated because of the great range of particles. The fractions of silt and clay are especially problematic as the particles form grain aggregates resulting in erratically high percentages of the sand fraction. The particle-size determinations were based upon the Atterberg scale (Table 2).

The results are plotted in the laboratory directly on a semi-logarithmic diagram on which the size-distributions are presented as cumulative curves.

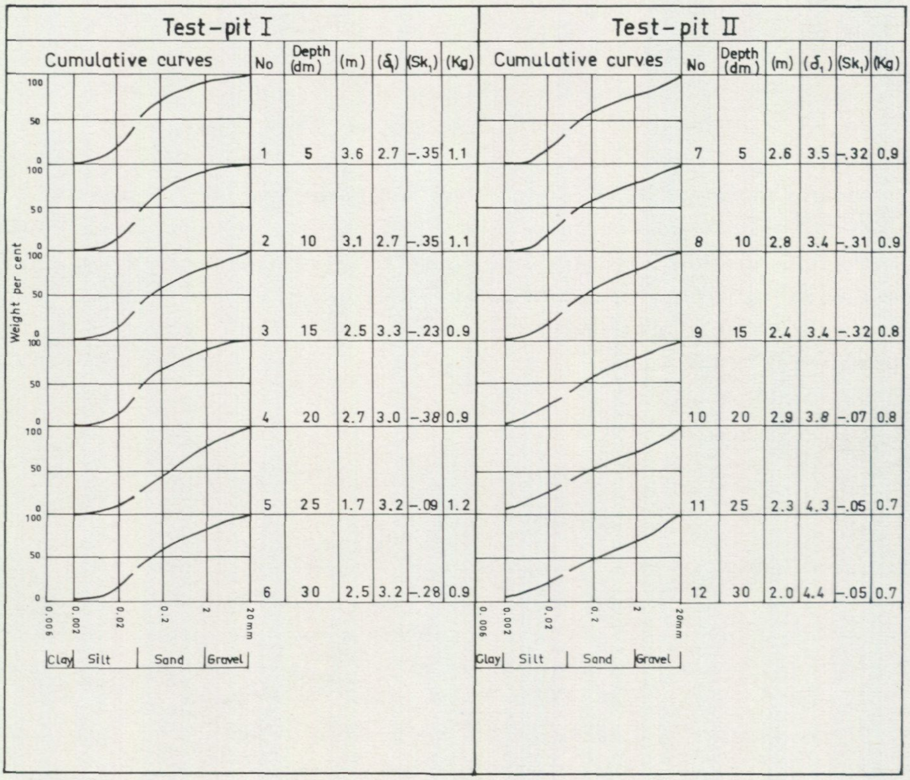
TABLE 2. The Atterberg scale

Swedish nomenclature	Grus	Sand	Mo	Mjäla	Lera
English nomenclature	Pebbles	Sand	Fine sand and silt	Silt and clay	Clay
Grain-size mm	20	2	0.2	0.02	0.02 mm

The results are presented in Table 3. The locations of the four test-pits investigated are shown in Fig. 2. From the shape of the cumulative curves it is possible to divide the till-samples into two groups, one (Group 1) is characterized by more or less S-shaped curves, corresponding to a large proportion of the grain-sizes between 0.2 and 0.02 mm and small proportions of the gravel-sized fraction (20—2 mm) and of the finest fractions.

The other group (Group 2) is caracterized by more or less rectilinear or concave (upwards) curves, which correspond to higher proportions of

TABLE 3. Comulative curves and size-distribution



Test-pit I						Test-pit II					
No	Depth (dm)	(m)	(δ_1)	(Sk_1)	(Kg)	No	Depth (dm)	(m)	(δ_1)	(Sk_1)	(Kg)
1	5	3.6	2.7	-.35	1.1	7	5	2.6	3.5	-.32	0.9
2	10	3.1	2.7	-.35	1.1	8	10	2.8	3.4	-.31	0.9
3	15	2.5	3.3	-.23	0.9	9	15	2.4	3.4	-.32	0.8
4	20	2.7	3.0	-.38	0.9	10	20	2.9	3.8	-.07	0.8
5	25	1.7	3.2	-.09	1.2	11	25	2.3	4.3	-.05	0.7
6	30	2.5	3.2	-.28	0.9	12	30	2.0	4.4	-.05	0.7

the gravel-fraction and the finest fractions, compared to the former group. According to this the samples can be referred to the two groups as in Table 4.

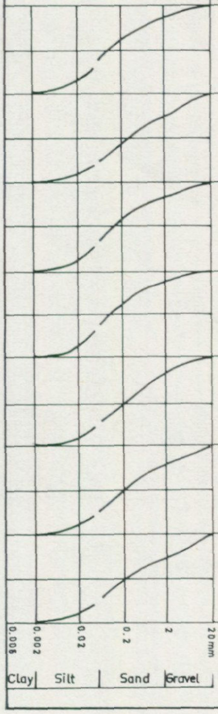
TABLE 4. Grouping of the till-samples from the shape of the cumulative curves

Test-pit No.	Group 1 Sample No.	Group 2 Sample No.
I	1— 6	—
II	7— 9	10—12
III	13—18	19
IV	20—22a	22b—24

It is interesting to note that Group 1 and Group 2 are almost identical with category A and category B respectively, obtained from the study of the lithologies. The only exceptions are samples No. 9 and 22a, which lithologically belong to category B.

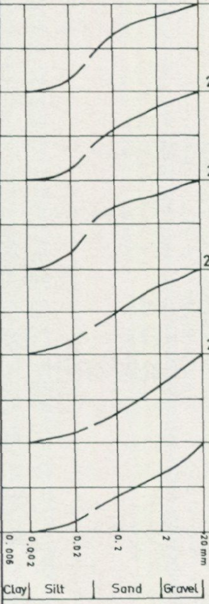
parameters, phi (Ø) — scale (Test-pit I—IV)

Test-pit III



No	Depth (dm)	(m)	(δ_1)	(Sk_1)	(Kg)
13	5	2.7	3.1	-.19	1.1
14	10	1.6	3.2	-.06	0.8
15	15	3.0	3.0	-.09	1.1
16	20	2.0	2.9	-.25	1.1
17	25	2.0	2.9	-.08	0.9
18	30	1.7	3.3	-.14	0.9
19	35	1.6	3.6	-.14	0.8

Test-pit IV



No	Depth (dm)	(m)	(δ_1)	(Sk_1)	(Kg)
20	5	2.8	3.0	-.44	1.0
21	10	2.4	3.2	-.25	0.9
22a	15	3.0	3.3	-.46	1.1
22b	17	2.2	3.6	-.03	0.9
23	20	0.9	3.6	+.14	0.8
24	25	1.0	3.8	+.06	0.7

In order to enable a better study of the correlation between the lithology of the pebble fraction and the grain-size a statistical study of the till samples was carried out.

In studies of size-distribution of sedimentary particles four parameters are most commonly used, namely the mean (m), the standard deviation (σ_1), the skewness (Sk_1) and the kurtosis (Kg).

The phi-scale (Ø) established by Krumbein (1936) is used, in which "Ø" equals the log of the ratio of grain-diameter (mm) to standard grain-diameter (mm).

Since till samples generally have a non-normal distribution the modified formulae proposed by Folk and Ward (1957) were used (Table 5). They are based upon the system elaborated by Inman (1952), which is applicable primarily to sediments having normal distribution of grain-size.

The different percentile values were read directly from the cumulative diagrams.

TABLE 5. Formulae for the four parameters used for determination of sample statistics. The percentile values are given in phi-scale

$$\text{Mean (m)} = \frac{\phi\,16 + \phi\,50 + \phi\,84}{3}$$

$$\text{Standard deviation } (\sigma_1) = \frac{\phi\,84 - \phi\,16}{4} + \frac{\phi\,95 - \phi\,5}{6.6}$$

$$\text{Skewness } (\mathrm{Sk_1}) = {}^1/_2 \left(\frac{\phi\,84 + \phi\,16 - 2\,\phi\,50}{\phi\,84 - \phi\,16} + \frac{\phi\,95 + \phi\,5 - 2\,\phi\,50}{\phi\,95 - \phi 5} \right)$$

$$\text{Kurtosis (Kg)} = \frac{(\phi\,95 - \phi\,5)}{2.44\,(\phi\,75 - \phi\,25)}$$

Parameter values of the samples collected are shown on Table 3. Mean-size (m) ranges from 0.9 to 3.6 phi-units. This means in the mm-scale a range from 0.55 mm to 0.025 mm, i. e. mean-size falls from the medium sand to the very fine sand ranges.

Samples taken from the upper parts of pits No. I, II and IV tend to have smaller grain-sizes than samples from the lower parts.

Standard deviation (σ_1) is a measure of sorting. As wold be expected for till samples it falls within the range of very poor to extremely poor sorting (2.7 ϕ to 4.4 ϕ).

It is interesting to note that the seven most poorly sorted samples are No. 10, 11, 12, 19, 22b, 23, 24. These samples are all taken from the lower parts of pits No. II, III and IV.

Skewness ($\mathrm{Sk_1}$) is a measure of the predominance of coarser and of finer mixtures. Positive values of $\mathrm{Sk_1}$ indicate a predominance of coarser grains and negative values a predominance of finer grains.

The phi-skewness measure is zero for a symmetrical size-distribution. The $\mathrm{Sk_1}$-measures range from +0.14 to —0.46 with most samples on the negative side.

According to Folk and Ward (1957 p. 14) sediments would be classed as very negatively skewed if they have verbal limits of $\mathrm{Sk_1}$ —1.00 to —0.30, and as negatively skewed if they have the limits $\mathrm{Sk_1}$ —.30 to —0.10.

Samples falling within these negative ranges are:

Pit No. I: 1, 2, 3, 4, 6.
Pit No. II: 7, 8, 9.
Pit No. III: 13, 16, 18, 19.
Pit No. IV: 20, 21, 22a.

The remaining samples are classed as nearly symmetrical or positively skewed, i. e. they fall within the verbal limits: $\mathrm{Sk_1}$ —0.10 to +0.10.

They are:

Pit No. I:	5.
Pit No. II:	10, 11, 12.
Pit No. III:	14, 15, 17.
Pit No. IV:	22b, 23, 24.

All samples in test-pit No. I (except No. 5) are negatively skewed or very negatively skewed. The same is also the case for the three upper samples in test-pits No. II and IV. The values of the samples from Pit III do not change systematically with depth.

Kurtosis (Kg) measures the peakedness of the distribution curve.

The maximum value is 1.17 and the minimum value 0.69, i. e. within the lower range of Kg in natural sediments according to Folk and Ward (1957). The variations are unrelated to sampling depth, making it impossible to differentiate the samples on the basis of kurtosis.

GEOCHEMICAL ANALYSIS

Preparation of the samples and analysis

The < 60 μ fraction of the pit-samples was analysed spectrographically in the same way described for the grid-samples from the till. The concentrations of the major elements: Fe, Mn, Mg, Ti, Ba and Ca were determined as cation percentages and the following minor elements were determined in ppm: Pb, Cu, Zn, As, Ag, Bi, Mo, Sn, Ni, Co and Cr. Of these Pb, Cu, Zn, Ni, Cr, Fe, Mg, Ba and Ca had concentrations within the sensitivity of the spectrometer. The content of mercury in these samples has been reported in a separate study by Brotzen and Walker (In Cameron, 1966).

RESULTS

The results of the geochemical analyses are presented in Tables 6 and 7. Table 6 presents the metal contents of the samples from test-pits No. I—IV, i. e. in samples which have been investigated both lithologically and with respect to grain-size. Table 7, on the other hand, presents the metal contents of the samples from test-pits No. 1—7.

The locations of these test-pits are shown in Fig. 2. The samples from these test-pits were only analysed chemically. The tables show the variations of nine elements (Zn, Cu, Pb, Ni, Cr, Fe, Mg, Ba, Ca) in the different test-pits as a function of depth in dm.

The range of Zn content is from 7 to 103 ppm. The most conspicuous tendency in the variation pattern of this element is an increase with depth. This tendency is very clear in test-pits No. I, II and IV (Table 6), and in test-pits No. 1, 3, 4, 5 and 6 (Table 7). However, the variation of Zn con-

TABLE 6. Distribution of heavy metals in the $<60\mu$ fraction of the pit samples

Test pit No.	Sample No.	Sample depth (dm)	Zn (ppm)	Cu (ppm)	Pb (ppm)	Ni (ppm)	Cr (ppm)	Fe (%)	Mg (%)	Ba (%)	Ca (%)
I	1	5	21	23	6	13	30	1.1	0.6	.050	2.1
	2	10	16	20	5	10	24	1.0	0.6	.049	2.1
	3	15	22	24	5	11	22	1.0	0.5	.048	1.9
	4	20	64	53	7	11	22	1.3	0.6	.055	2.2
	5	25	50	48	6	14	36	1.3	0.6	.052	1.9
	6	30	63	36	8	14	26	1.6	0.7	.052	2.1
II	7	5	27	24	5	13	22	1.3	0.7	.046	1.8
	8	10	27	25	6	13	30	1.1	0.7	.045	2.0
	9	15	96	42	9	32	28	3.5	1.0	.055	2.4
	10	20	57	38	6	24	64	2.3	1.4	.055	2.0
	11	25	70	38	8	28	58	2.5	1.6	.060	1.8
	12	30	67	42	8	32	72	3.6	1.8	.064	1.9
III	13	5	52	58	10	17	36	2.5	0.9	.065	2.2
	14	10	40	38	7	18	44	2.0	0.8	.058	2.0
	15	15	43	27	7	12	32	1.4	0.7	.052	2.2
	16	20	35	25	7	14	29	1.7	0.6	.054	2.0
	17	25	59	39	8	15	36	1.7	0.7	.060	2.1
	18	30	34	37	9	15	40	1.8	1.1	.073	2.9
	19	35	67	61	8	20	48	2.8	1.0	.063	2.1
IV	20	5	45	48	8	21	46	2.3	0.6	.046	1.8
	21	10	54	45	10	15	44	2.3	0.8	.045	2.0
	22a	15	42	35	8	17	46	2.1	0.8	.055	2.4
	22b	17	96	69	8	33	80	3.9	2.0	.055	2.0
	23	20	100	76	11	38	70	4.4	1.6	.060	1.8
	24	25	103	67	10	34	74	4.0	1.6	.064	1.9

tent does not change regularly with depth, some samples within the profiles having higher Zn-values than others from deeper levels. Samples with these characteristics occur in test-pit No. I (at 20 dm depth), in No. II (at 15 dm depth), in No. III (at 25 dm depth) and in No. IV (at 17 dm depth). They also occur in test-pits No. 1, 2 and 5 at 30, 20 and 15 dm depth respectively.

It is notable that Zn has a tendency to be more concentrated in some samples from 5 dm depth than at deeper levels. This can be seen for the following test-pits: No. I and III and No. 2, 4, 7.

The distribution of Cu and Pb shows the same characteristics as Zn, but the metal contents of these elements are lower, the Cu content ranging from 4 to 76 ppm and the Pb content from 1 to 29 ppm.

The range of Ni is from 7 to 51 ppm, of Cr from 19 to 118 ppm and of Fe from 1.0 % to 5.0 %. All three elements display increasing metal contents with depth. This tendency is more regular than for Zn, Cu and Pb,

TABLE 7. Distribution of heavy metals in the $<100\mu$ fraction of the pit samples

Test pit No.	Sample depth (dm)	Zn (ppm)	Cu (ppm)	Pb (ppm)	Ni (ppm)	Cr (ppm)	Fe (%)	Mg (%)	Ba (%)	Ca (%)
1	5	11	9	1	15	35	1.7	0.1	.012	0.5
	10	20	13	1	21	54	2.0	0.2	.016	0.5
	15	34	15	5	26	54	2.6	0.4	.011	0.7
	20	37	16	10	34	80	3.7	0.6	.026	0.9
	25	35	25	11	36	84	3.5	0.6	.034	1.0
	30	53	25	13	38	89	3.2	0.5	.039	0.9
	35	49	28	12	40	92	3.4	0.6	.038	0.9
2	5	52	17	10	51	118	5.0	0.7	.023	0.6
	10	45	22	12	33	86	4.4	0.4	.019	0.8
	15	35	19	10	34	88	3.8	0.6	.034	1.2
	20	47	20	12	36	93	4.0	0.6	.030	1.2
	25	41	21	13	37	106	4.2	0.5	.028	1.2
	30	39	16	12	35	103	4.1	0.6	.028	1.2
	35	38	10	10	35	108	4.0	0.6	.032	1.3
3	5	23	4	2	11	19	1.0	0.1	.006	0.5
	10	32	8	4	12	19	1.2	0.2	.009	0.8
	15	37	8	9	14	28	1.1	0.2	.010	0.7
	25	37	8	9	20	34	1.8	0.4	.017	0.9
	35	45	16	29	27	36	2.0	0.4	.016	0.7
4	5	43	25	9	34	76	3.2	0.5	.027	0.7
	10	34	22	9	25	63	3.1	0.6	.029	1.1
	15	33	18	9	27	69	3.5	0.6	.031	1.1
	20	35	22	10	25	62	3.5	0.6	.036	1.2
	25	42	40	12	28	68	3.9	0.6	.045	1.0
	30	49	42	12	31	81	3.9	0.6	.036	1.0
	35	61	46	14	32	80	4.7	0.5	.036	0.9
	40	45	26	9	28	71	3.9	0.6	.032	1.0
5	5	37	23	10	36	68	3.6	0.6	.026	1.0
	10	39	24	9	31	66	3.6	0.6	.030	1.0
	15	52	30	8	24	48	3.9	0.7	.030	0.8
	20	39	24	11	35	83	4.0	0.5	.036	1.1
	25	50	28	13	37	92	4.7	0.6	.039	1.1
	30	51	33	16	42	94	4.5	0.5	.036	1.0
	35	43	25	11	33	83	4.1	0.6	.040	1.2
6	5	31	20	12	22	59	2.4	0.5	.024	0.6
	10	43	28	10	34	84	4.8	0.6	.038	1.0
	15	44	26	12	33	87	4.3	0.7	.040	1.1
	20	45	20	10	30	79	4.1	0.7	.048	1.1
	25	56	32	16	34	87	4.7	0.6	.044	0.9
	30	51	30	12	36	96	4.5	0.8	.044	1.3
	35	52	27	11	27	80	4.4	0.7	.042	1.0
	40	56	33	12	28	75	4.7	0.7	.045	1.0
7	5	62	13	10	22	56	2.4	0.3	.017	0.4
	10	7	8	5	7	40	0.8	0.1	.019	0.8
	15	57	47	9	32	85	4.6	0.5	.034	1.0
	20	57	45	11	32	88	4.8	0.7	.035	1.2
	25	57	31	14	33	87	4.7	0.6	.036	1.1
	30	58	34	14	37	92	5.0	0.6	.031	1.1

only four samples from higher levels having distinctly higher contents of Ni, Cr and Fe than the underlying samples. These four samples are found in test-pits No. IV, 2 and 4, at a sampling depth of 5 dm and in test-pit No. II at a sampling depth of 15 dm.

The range of Mg is from 0.1 % to 2.0 %, of Ba from 0.006 % to 0.073 % and of Ca from 0.4 % to 2.9 %. In most test-pits the contents of these elements do not change systematically with depth, displaying instead rather irregular distribution patterns. Only in test-pits No. II, IV, 1 and 3 do the metal contents have a tendency to increase with depth, following a distribution pattern similar to those of the other elements.

DISCUSSION OF THE RESULTS

The lithology of the pebble-fraction, size-distribution parameters and heavy metal contents are presented in Table 8.

a. Lithological aspects

The samples have been classified as originating from the upper till and the lower till with respect to the rock composition of the pebble fraction (4—8 mm). All samples with 28 % or more of far transported pebbles (acid intrusives and porphyrites), and with less than 40 % of Skellefte-volcanic pebbles have been referred to the upper till. The remaining samples belong to the lower till with the following composition: 23 % or less of far transported and 48 % or more of Skellefte-volcanic pebbles. As can be seen these criteria refer 17 samples to the upper till and 8 to the lower till.

b. Aspects of the size-distribution

Regarding the size-distribution parameters, two of them can be used as indicators of the two tills, namely deviation (σ_1) and skewness (Sk_1). If one studies these two parameters, the samples lithologically referred to the lower till (with the exception of sample No. 22a) can be characterized (using the terminology proposed by Folk and Ward, 1957) as poorly sorted to extremely poorly sorted and nearly symmetrical or positive-skewed. On the other hand those samples that were referred to the upper till in the lithological study have deviation values that are lower than those of the lower till samples (i. e. lower than $\sigma_1 = 3.6$). At the same time they tend to be more negatively skewed than the lower till samples. This means that the degree of sorting is better in the upper till than in the lower till. The skewness values on the other hand, indicate a predominance of finer

TABLE 8. Lithology, size-distribution and heavy metal contents in the till samples

Test-pit No.	Sample No.	Sample depth (dm)	Rock-composition of the gravel-fraction (4—8 mm)			Size-distribution parameters. Phi-scale (Ø).				Distribution of heavy metals in the <60 μ fraction in the till samples									Classification of the till
			Far transported. (%)	Skellefte volc. (%)	Others (%)	Mean (m)	Deviation (σ_1)	Skewness (Sk_1)	Kurtosis (Kg)	Zn ppm	Cu ppm	Pb ppm	Ni ppm	Cr ppm	Fe %	Mg %	Ba %	Ca %	
I	1	5	42	23	35	3.6	2.7	—.35	1.1	21	23	6	13	30	1.1	0.6	.050	2.1	Upper till
	2	10	48	20	32	3.1	2.7	—.35	1.1	16	20	5	10	24	1.0	0.6	.049	2.1	
	3	15	54	23	23	2.5	3.3	—.23	0.9	22	24	5	11	22	1.0	0.5	.048	1.9	
	4	20	46	24	30	2.7	3.0	—.38	0.9	64	53	7	11	22	1.3	0.6	.055	2.2	
	5	25	43	26	31	1.7	3.2	—.09	1.2	50	48	6	14	36	1.3	0.6	.052	1.9	
	6	30	46	24	30	2.5	3.2	—.28	0.9	63	36	8	14	26	1.6	0.7	.052	2.1	
II	7	5	38	31	31	2.6	3.5	—.32	0.9	27	24	5	13	22	1.3	0.7	.046	1.8	Upper till
	8	10	36	33	31	2.8	3.4	—.31	0.9	27	25	6	13	30	1.1	0.7	.045	2.0	
	9	15	28	37	35	2.4	3.4	—.32	0.8	96	42	9	32	28	3.5	1.0	.055	2.4	
	10	20	18	49	33	2.9	3.8	—.07	0.8	57	38	6	24	64	2.3	1.4	.055	2.0	Lower till
	11	25	19	59	22	2.3	4.3	—.05	0.7	70	38	8	28	58	2.5	1.6	.060	1.8	
	12	30	19	65	16	2.0	4.4	—.05	0.7	67	42	8	32	72	3.6	1.8	.064	1.9	
III	13	5	53	25	22	2.7	3.1	—.19	1.1	52	58	10	17	36	2.5	0.9	.065	2.2	Upper till
	14	10	49	23	28	1.6	3.2	—.06	0.8	40	38	7	18	44	2.0	0.8	.058	2.0	
	15	15	55	20	25	3.0	3.0	—.09	1.1	43	27	7	12	32	1.4	0.7	.052	2.2	
	16	20	55	17	28	2.0	2.9	—.25	1.1	35	25	7	14	29	1.7	0.6	.054	2.0	
	17	25	52	21	27	2.0	2.9	—.08	0.9	59	39	8	15	36	1.7	0.7	.060	2.1	
	18	30	41	27	32	1.7	3.3	—.14	0.9	34	37	9	15	40	1.8	1.1	.073	2.9	
	19	35	22	52	26	1.6	3.6	—.14	0.8	67	61	8	20	48	2.8	1.0	.063	2.1	Lower till
IV	20	5	27	34	39	2.8	3.0	—.44	1.0	45	48	8	21	46	2.3	0.6	.046	1.8	Upper till
	21	10	31	39	30	2.4	3.2	—.25	0.9	54	45	10	15	44	2.3	0.8	.045	2.0	
	22a	15	16	58	26	3.0	3.3	—.46	1.1	42	35	8	17	46	2.1	0.8	.055	2.4	Lower till
	22b	17	17	48	35	2.2	3.6	—.03	0.9	96	69	8	33	80	3.9	2.0	.055	2.0	
	23	20	16	58	26	0.9	3.6	+.14	0.8	100	76	11	38	70	4.4	1.6	.060	1.8	
	24	25	9	61	30	1.0	3.8	+.06	0.7	103	67	10	34	74	4.0	1.6	.064	1.9	

...... Ground-water level

grains in the upper till, whilst the grain-size distribution of the lower till tends to be more or less symmetrical. These characteristics evidently reflect the greater derivation distance of the upper till.

However, some samples have size-distribution parameter values that do not fit with the lithological grouping into upper and lower till. Sample No. 22a is more like the upper till with respect to grading, although lithologically it belongs to the lower till. On the other hand, some samples referred to the upper till have skewness values in the same range as the lower till (samples No. 5, 14, 15, 17, 18). These irregularities could be due to local conditions at the time of deposition of the upper till, for example melt-water activity or assimilation of material from the lower till into the upper till. Mean size (m) and kurtosis (Kg) do not display any systematic variation of their parameter values with respect to the two tills. However, on the whole the study of the size-distribution parameters supports the results obtained from the lithological study, i. e. that two tills are present at Norra Norrliden, and that these tills show transitional relationships.

c. Geochemical aspects

The upper till and the lower till are significantly different with respect to the contents of heavy metals in the fine fraction, the lower till samples having about twice as much Zn, Cu, Ni, Cr and Fe as the upper till samples. Pb, Mg, Ba and Ca also tend to be lower in the upper till samples. These differences can be understood if one takes the petrographic composition of the two tills into account. The upper till is dominated by acid intrusive material, and since the contents of heavy metals generally are low in acid intrusives, they also produce tills with low background values of these elements. The lower till, on the other hand is dominated by local rock-types typical for the Skellefte district, i. e. meta-volcanic rocks and sediments of the phyllite series. These lithologies have higher background values of heavy metals than the acid intrusive rocks, which, of course, is also reflected by the metal contents in the tills that they have produced.

However, it is not only the two tills that have influenced the distrbiution pattern of the heavy metals. The results indicate that the drainage has also played an important role. This can be seen in Table 9, where test-pits II and III have higher values of Zn, Cu, Pb, Ni and Fe in the samples at the ground-water level (samples No. 9 and 17 respectively). In test-pit IV, the three lowest samples (No. 22b—24) have maximum contents of Zn, Cu, Ni, Cr, Fe and Mg, probably due to a combination of influences from both the lithology and the drainage. Finally, in test-pit I, the three lowest samples (No 4—6) display increased contents of Zn and Cu. This cannot be explained as an effect of lithology or from hydromorphic processes. A possible explanation for the local enrichment of Zn and Cu in the fine fraction at this location is that this may represent the sole example of anomalies caused by glacial erosion. Chalcopyrite with malachite was identified in one of the pebbles from sample No. 5 (Fig. 13) supporting the hypothesis of clastic enrichment of this locality. Enrichment of heavy metals has taken place at the ground water level in the following test-pits: No. 1 (30 dm depth), No. 2 (20 dm depth), No. 3 (10 dm depth), No. 5 (15 dm depth) and No. 7 (5 dm depth) as can be seen in Tables 7 and 8.

Fig. 13. Chalcopyrite in a pebble from sample No. 5. Test-pit 1. Polished section. Ord. light. × 50.

The same type of enrichment at the 5 dm level as was found for the grid-samples appears also in test-pits No. 1, 2, I and II (Table 6 and 7). As was mentioned in the discussion of the grid-sample anomalies, biogenic processes probably played a role in giving the increased metal contents at this level.

Thus three factors have created the variation patterns of Zn, Cu and Pb in the till. Firstly, the lithological composition of the till, has influenced the background values of the elements. Secondly, the drainage conditions within the area has resulted in dissolution of Zn, Cu and Pb from the ore and locally in the lower till and precipitation of these elements in the till at the ground-water level. And thirdly, biogenic enrichment has occurred in the surface layers.

A study of the three cross-sections, (profiles I, II and III of Fig. 14—16)

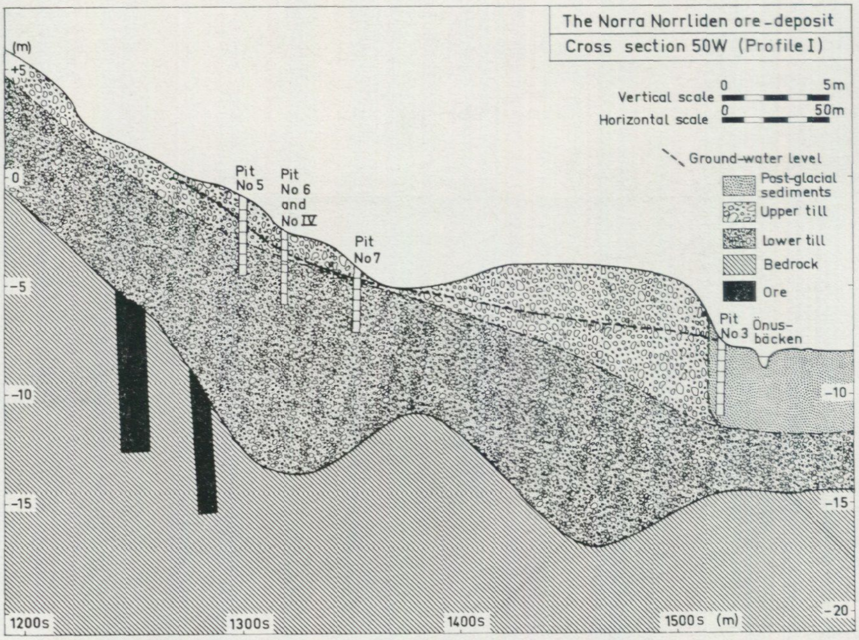


Fig. 14. Profile I through the till over the Norra Norrliden ore-deposit.

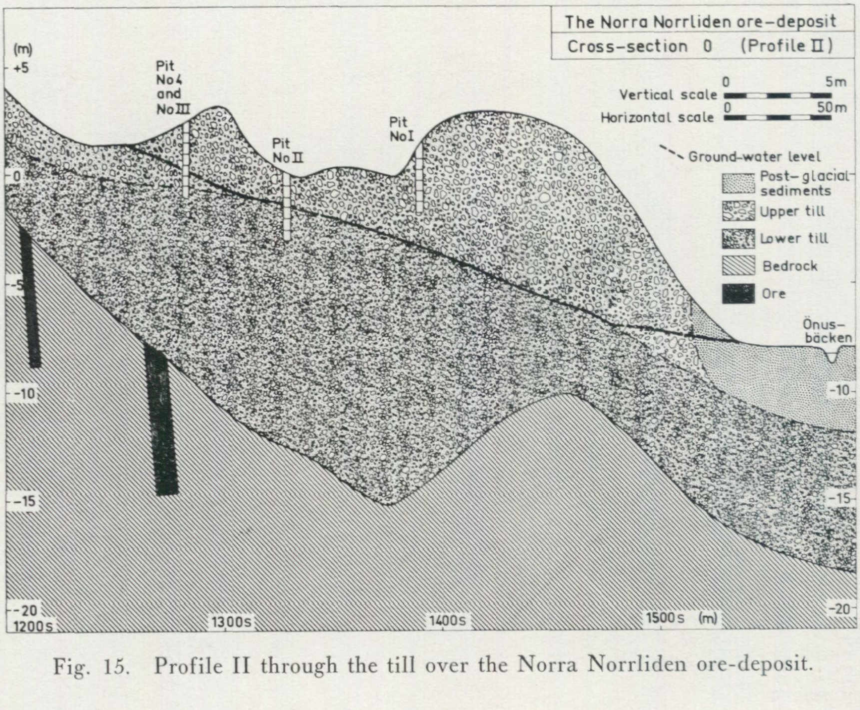


Fig. 15. Profile II through the till over the Norra Norrliden ore-deposit.

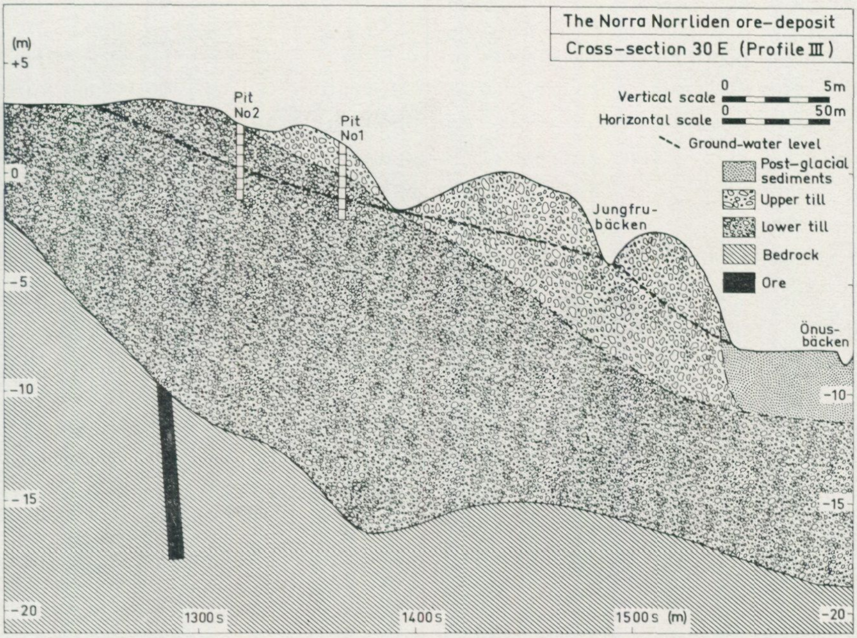


Fig. 16. Profile III through the till over the Norra Norrliden ore-deposit.

shows that the thickness of the till is least along profile I. The groundwater level is also closer to the surface along this profile compared to the other two. These factors together could explain the fact that the grid-sample anomalies of Zn, Pb and to a certain extent Cu (5 dm depth) are correlated to profile I, but not to the other two.

BIOGEOCHEMICAL INVESTIGATION

METHODS OF SAMPLING AND ANALYSIS

The biogeochemical studies involved material from the most common trees within the area namely birch, pine and spruce. Different parts of the trees were sampled, such as twigs, bark, wood, needles, leaves and pine-cones. The humus layer was also sampled. Samples were collected at 20 m intervals along 7 traverse lines: 180W, 100W, 40W, 20W, 20E, 40E and 100E. It was possible to obtain samples at most samples stations using the condition that a sample had to be collected within 5 m of the correct location. The samples were analysed spectrographically for Zn, Cu, Pb, Ni, Co, Cr, Fe, Mg, Ba and Ca.

RESULTS

In general plant material showed only small variations in metal contents with respect to pine, spruce and humus, i. e. the results indicated that these trees had not concentrated more than normal amounts of metals. The only material that revealed abnormally high concentrations of Zn, Cu and Pb was birch-bark, and the discussion will therefore be restricted to this material.

The range of Pb is from 380 ppm to 3200 ppm. The normal abundance of Pb in birch-bark ash, i. e. the background value was about 800 ppm. Samples greater than 1300 ppm have been considered as anomalous.

The range of Cu is from 270 ppm to 1630 ppm. The upper limit of the background values was 800 ppm and the anomalous values were found to start at 1000 ppm. The contrast between birches with normal contents of Cu and those with anomalous values is less than for Pb. This indicates that Cu has a weaker tendency than Pb to be selectively enriched in birch-bark.

The range of Zn is from 0.8 % to 6.6 %. The anomalous values start at

Fig. 17. Biogeochemical anomaly map showing distribution of Pb in the bark ash from birches growing over the Norra Norrliden ore-deposit.

about 4 %, indicating that Zn has a very strong tendency to be selectively enriched in birch-bark, a fact that also has been reported by others (Warren et al. 1952).

DISCUSSION OF THE RESULTS

The anomalous patterns are presented in Fig. 17 to 19. As can be seen all three elements have anomalous values in birches growing above the western end of the ore-body. With regard to Pb (Fig. 17) and Zn (Fig. 19) the anomalies also extend to the south in the drainage direction, while the anomalous pattern of Cu (Fig. 18) is more weakly developed. In the eastern part of the sampled area all three elements have anomalous patterns, and they are also here correlated with the drainage patterns.

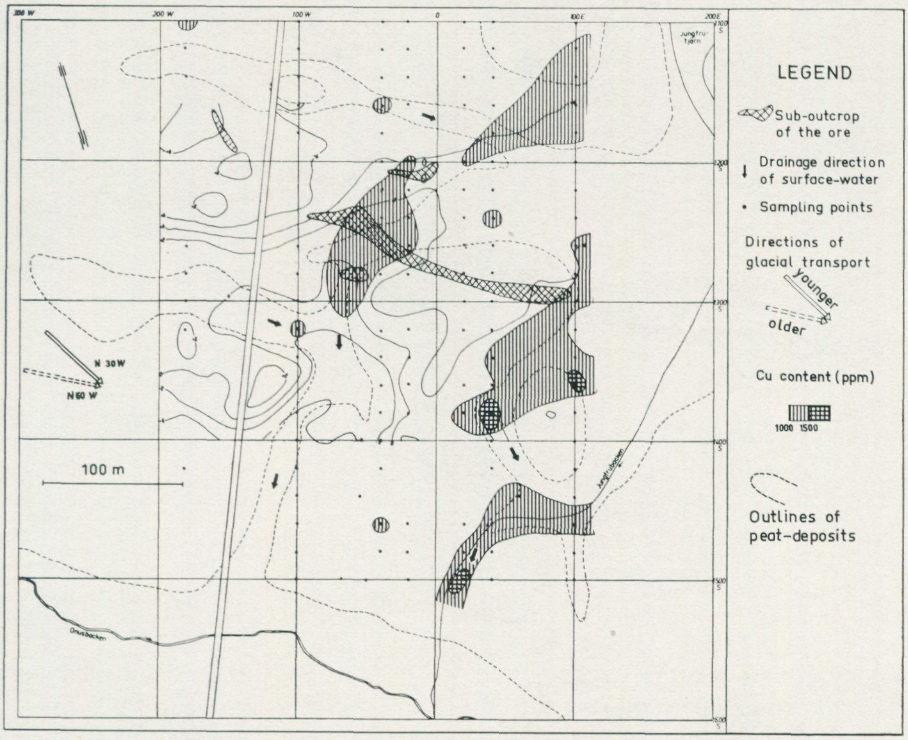


Fig. 18. Biogeochemical anomaly map showing distribution of Cu in the bark ash from birches growing over the Norra Norrliden ore-deposit.

It is of interest to note, that the trees growing above the central part of the ore-body and downslope from it do not contain any anomalous amounts of Zn, Cu and Pb. This corresponds well with the anomalous patterns of the till-samples from 5 dm depth.

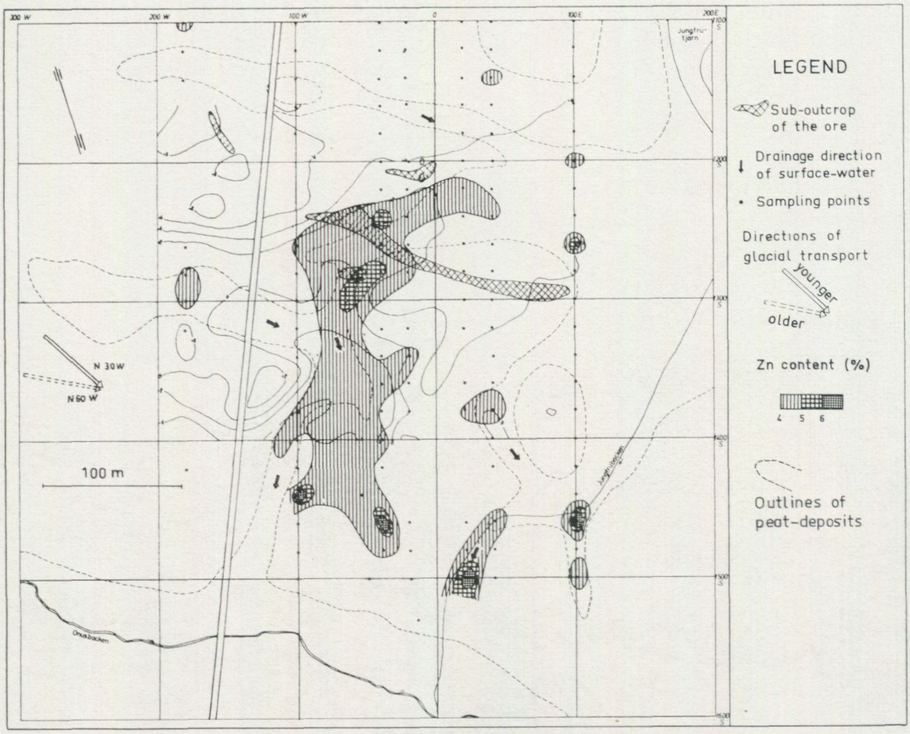


Fig. 19. Biogeochemical anomaly map showing distribution of Zn in the bark ash from birches growing over the Norra Norrliden ore-deposit.

HYDROCHEMICAL INVESTIGATION OF GROUND-WATER AND SURFACE-WATER

Since hydromorphic processes appeared to be responsible for the anomalous patterns of Pb, Cu and Zn in the tills and in the birch-bark, a hydrochemical survey was carried out during the summer of 1969. The purpose of the survey was to measure the contents of these three elements in the different kinds of water (surface-water, water from bore-holes and test-pits) and to investigate their possible relationships to the ore, and to the anomalous geochemistry of the till and the birch-bark.

FIELD PROCEDURE

Samples were taken at 27 points within the area (Fig. 2). Each sampling station was sampled 2 or 3 times during the summer. The sampling layout was concentrated to the area above the ore and down-slope from it.

One set of samples was taken from the ground-water in the till. For this purpose 6 pits were dug to 4 m depth. These pits were arranged in areas where the water-table could be penetrated. The ground-water was sampled immediately after the pits were opened. Into each pit a plastic tube (4 m long, 2″ wide) was then placed, the lower parts of which (0.2 m) were perforated (the holes 2 mm wide) to enable the ground-water to percolate into the tubes. From these the ground-water was then resampled during the summer.

A second set of samples was taken from bore-holes, and a third set (6 samples) from surface-water. Three of these latter samples were taken from the stream Jungfrubäcken, which drains a small lake situated about 150 m north-east of ore-body and passes through the south-eastern part of the area. Two samples were taken from the stream Önusbäcken south of the investigated area, one immediately downstream from the outlet of Jungfrubäcken and one about 220 m upstream from it. Finally, one sample was taken from a small pool of stagnant water near the peat-bog that drains the western end of the ore-body.

The ground-water samples were taken with a rubber tube equipped with a ventilator in one end (Fig. 20) making it possible to pump up water from more than 8 m depth.

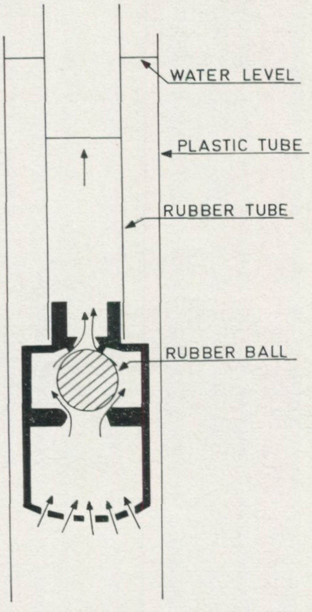


Fig. 20. Sketch of the ventilator attached to the rubber tube showing the movement pattern of the water when the ventilator is pressed downwards. During movement upwards the rubber ball prevents the water from running out.

All samples were filtered and HC1 was added to keep the cations in a soluble form. For determination of pH, conductivity, anions, oxygen and carbon dioxide contents, separate samples were collected.

The temperature of the water and the water-level were measured and the rainfall within the region for each day throughout the summer was obtained from the Swedish Meteorological and Hydrological Institute.

LABORATORY PROCEDURE

Laboratory processing involved measurement of pH, conductivity, Cl^-, HCO_3^-, SO_4^{2-}, CO_2, O_2, Cu, Pb, Zn, Fe, Mn, Mg, Ca, K, Na and Al. The cations were determined by the Atomic Absorption method, and the anions by tradition, as was oxygen after adding two reagents in the field (Alkali-iodide-azide and manganese sulfate solution). CO_2 was determined by titration after adding pulverized $CaCO_3$ in the field to a separate sample.

RESULTS

The results are presented in Table 9.

Cu-distribution. — The range of Cu in the samples is from < 5 to 155 ppb (parts per billion). It is of interest to note, that all samples taken from surface-water had contents < 5 ppb.

Pb-distribution. — The range of Pb is from < 5 to 200 ppb. As in the case of Cu, all samples taken from surface-water had contents < 5 ppb.

Zn-distribution. — The range of Zn is from 20 to 6650 ppb. In contrast to Pb and Cu, the two highest Zn-values were found in samples from surface-water. One of them was taken from the stream Jungfrubäcken (6250 ppb) and the other from the small pool of stagnant water south of the western end of the ore-body (6650 ppb).

Temperature. — As was expected the ground-water from the bore-holes had the lowest temperatures, ranging from 4 to 7 C°. The ground-water from test-pits ranged from 8 to 11 C°, and the surface-water from 12 to 16 C°.

Cl^--distribution. — The range of Cl^- is from 2 to 7 mg/l, i. e. very low for all three types of water.

HCO_3^--distribution. — The range of HCO is from 3 to 141 mg/l. There is a very clear tendency for the water from the bore-holes to have higher contents than the water from the test-pits and the surface-water.

SO_4^{2-}-distribution. — The range of SO_4^{2-} is from 0 to 122 mg/l. The highest contents were found in the ground-water from the test-pits.

TABLE 9. Chemical analyses, Temperature (°C), pH and Conductivity of the water samples

Sample No.	Depth (dm)	°C	Cl mg/l	HCO_4^{2-} mg/l	SO_3^- mg/l	O_2 mg/l	CO_2 mg/l	pH	Cu ppb	Pb ppb	Zn ppb	Fe ppb	Mn ppb	Mg ppm	Ca ppm	K ppm	Na ppm	Al ppm	Conductivity μ mho
Water samples from boreholes																			
47088	25	6	—	117	—	—	—	7.9	5	<5	90	900	800	2.8	17.2	2.1	8.1	2.3	350
42037	25	4	3	137	4	0.9	3	7.6	20	20	1450	2330	580	2.3	22.0	3.0	6.7	4.5	368
42035	0	4	4	128	3	0.7	5	8.1	<5	<5	3000	380	350	2.5	16.7	2.7	8.3	4.5	370
47110	8	4	3	136	16	0.0	8	7.5	110	10	700	9000	600	3.3	31.3	2.1	6.5	1.2	451
42028	0	6	7	141	24	0.0	10	7.3	5	<5	380	10000	400	2.4	23.2	2.6	7.6	2.5	460
42029	18	5	3	126	15	0.0	7	7.7	15	200	2930	11740	600	3.0	8.7	3.2	7.8	3.1	389
47115	19	4	3	115	6	1.2	2	7.8	18	<5	460	2420	740	2.6	24.9	2.3	7.5	0.9	375
47112	6	4	3	124	4	0.9	11	7.9	8	8	890	3550	560	2.9	30.8	2.8	5.9	1.4	394
47113	6	5	3	129	6	0.0	8	7.8	7	<5	2130	1750	590	3.4	27.1	2.9	10.0	1.0	450
47111	35	4	3	141	5	4.5	10	8.1	55	<5	90	6800	100	5.4	33.9	1.9	12.9	0.3	500
47114	15	5	3	53	16	2.1	27	8.3	20	<5	1050	6200	100	2.1	10.9	6.6	12.8	6.5	244
47077	15	4	3	128	4	0.0	7	7.8	30	10	140	3500	510	2.9	44.0	3.6	4.3	5.0	470
42038	0	6	7	134	29	0.0	3	8.0	25	<5	340	2600	300	2.7	15.5	3.0	8.2	1.2	370
47087	50	7	—	41	—	—	—	6.7	<5	100	550	5000	850	—	—	2.1	3.2	—	148
42039	55	7	7	81	0	1.1	2	8.2	15	20	300	2500	50	1.4	7.9	2.3	8.2	2.7	220
Water samples from test pits																			
47103	20	8	6	3	93	0.9	57	5.0	58	5	1800	4880	1680	2.2	4.9	4.5	7.6	1.9	254
47104	20	8	5	47	122	3.0	30	6.6	155	100	1030	6200	810	1.4	6.4	1.6	5.6	1.9	164
47102	22	9	5	21	92	4.8	20	6.2	33	43	260	4430	290	0.6	2.0	1.3	4.4	2.8	84
47076	30	11	2	3	6	9.2	7	7.0	10	<5	20	5000	140	0.2	0.6	0.3	0.8	0.7	21
47089	15	9	5	26	83	6.3	22	6.8	50	85	1000	4350	440	2.1	3.6	1.9	5.2	4.0	127
47101	35	9	5	29	44	4.3	15	6.7	25	5	210	2200	100	1.0	2.7	0.8	2.5	1.3	90
Samples from surface water																			
42041	4	13	5	31	8	8.9	16	7.2	<5	<5	130	870	400	0.8	6.4	0.6	1.8	1.0	110
47105	2	12	3	21	9	2.4	39	7.2	<5	<5	6650	1200	350	1.1	2.7	2.0	5.2	1.7	110
47109	2	14	3	32	21	2.9	9	6.8	<5	<5	550	550	70	0.8	12.8	0.9	2.4	2.5	156
47108	1	16	3	37	8	3.9	10	7.4	<5	<5	480	800	95	0.6	14.5	0.8	2.7	0.9	143
47107	1	14	2	35	5	6.5	9	7.1	<5	<5	6250	100	20	1.1	12.3	2.0	8.3	1.9	134
47106	4	15	3	32	8	7.1	8	6.6	<5	<5	550	680	140	0.9	6.3	0.9	2.6	0.9	156

Oxygen content. — The range of O_2 is from 0.0 to 9.2 mg/l. There is a very clear tendency for the water from bore-holes to have lower contents than the water from test-pits and the surface-water.

pH. — The range of pH readings is from 5.0 to 8.3. All samples from bore-holes (except one) had readings above 7.0, whilst all samples from test-pits had readings on the acidic side (except one sample, that had pH = 7.0). The surface-water had readings on both the acidic and the basic side within the range that is normal for this type of water.

Distribution of Fe, Mn, Mg, Ca, K, Na and Al. — The distribution of the major elements (cations) is characterized by higher contents in the ground-water when compared with the surface-water. This tendency is very clear for Fe (water from bore-holes and test-pits) and for Ca (water from bore-holes).

Conductivity. — The highest readings were found for the ground-water from bore-holes, which is explained by the higher contents of the major elements in this water.

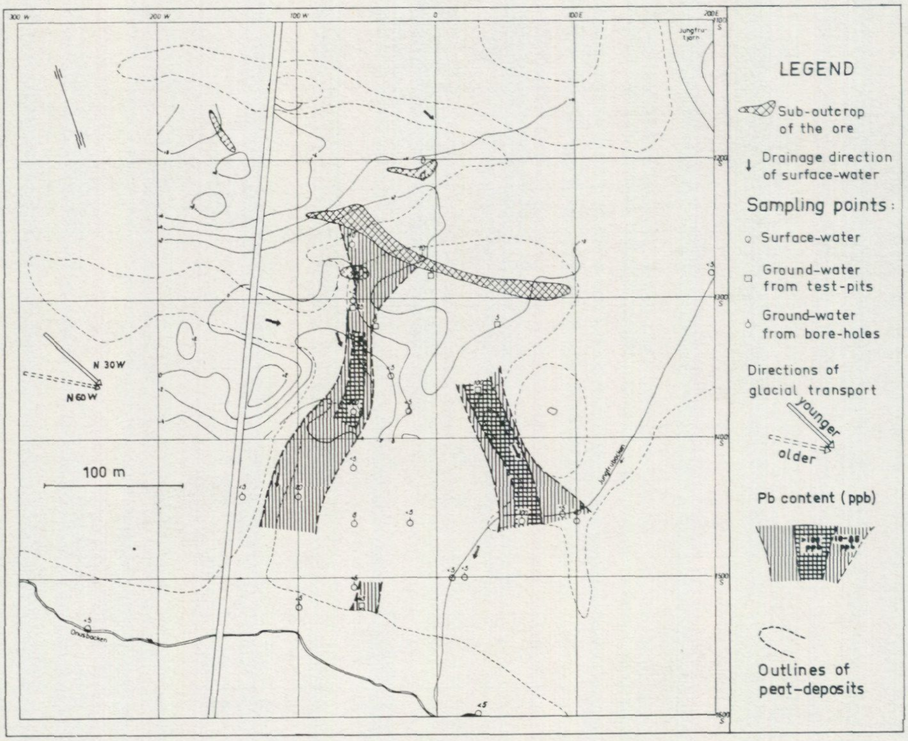


Fig. 21. Trends in the Pb content of ground-water from bore-holes and test-pits.

DISCUSSION OF THE RESULTS

The distribution patterns of Pb, Cu and Zn in the ground-water samples are discussed here.

The highest Pb values in the ground-water are found along the two drainage channels extending southwards from each end of the ore-body (Fig. 21). By contrast, samples taken above the central part of the ore-body and down-slope from it, had Pb contents of less than 10 ppb. Using the criterion that Pb values above 10 ppb are anomalous, which compares well with the results from Russian investigations (Y. Y. Boghelski, 1957) of ground-water anomalies arond complex (Pb, Cu, Zn) ore deposits, the western drainage structure contains five anomalous samples. Of these, one is a test-pit sample (No. 5) containing 85 ppb Pb, whilst the remaining four were taken from bore-holes. Within the eastern drainage structure three samples have anomalous values. One of them, containing 100 ppb Pb, was taken from test-pit No. 1, and the remaining two from bore-holes.

The Cu contents of the ground-water samples have been regarded as anomalous above 25 ppb, which corresponds well with results reported from hydrochemical prospecting for Cu in Russia (Brodsky, 1956). Along

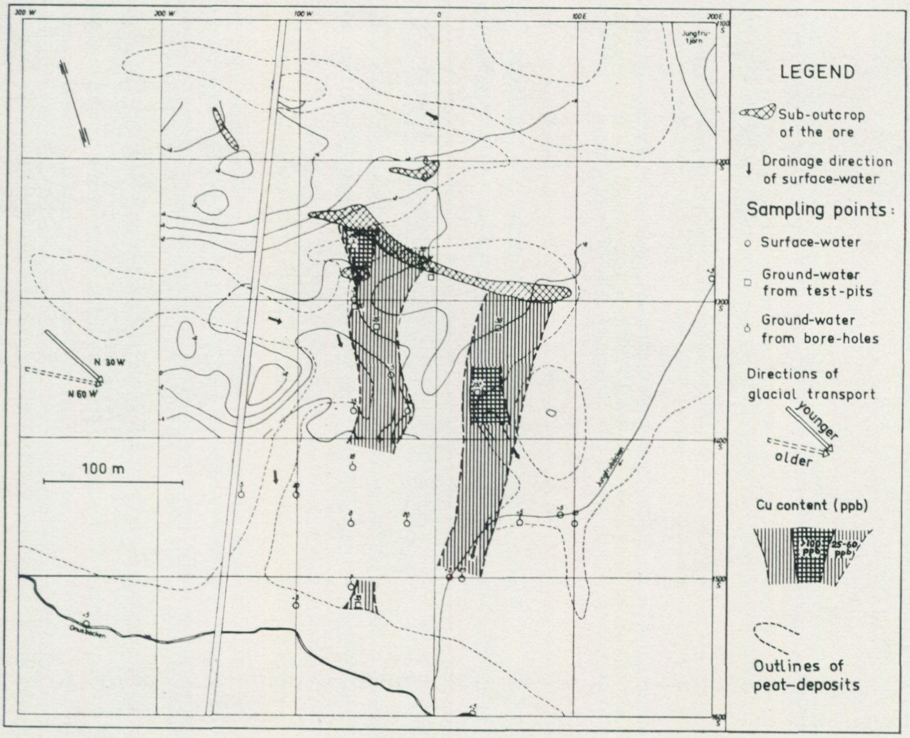


Fig. 22. Trends in the Cu content of ground-water from bore-holes and test-pits.

the western drainage structure (Fig. 22) five samples are anomalous, two of these are pit samples, one from test-pit No. 5 (50 ppb Cu) and the other from test-pit No. 6 (25 ppb Cu). Along the eastern drainage structure three samples are anomalous, two of which are from test-pits (No. 1, 155 ppb Cu and No. 2 58 ppb Cu).

The distribution of water samples with high Zn contents forms a much wider anomalous patter than that of Pb and Cu (Fig. 23), although the highest contents are concentrated in the two drainage structures. According to Russian investigations of Zn in waters around different complex ore bodies (Brodsky, 1956), contents in the range from 40 to 500 ppb are anomalous. If these figures are applicable to the ore-body at Norra Norrliden, the Zn anomalies must be regarded as very strong.

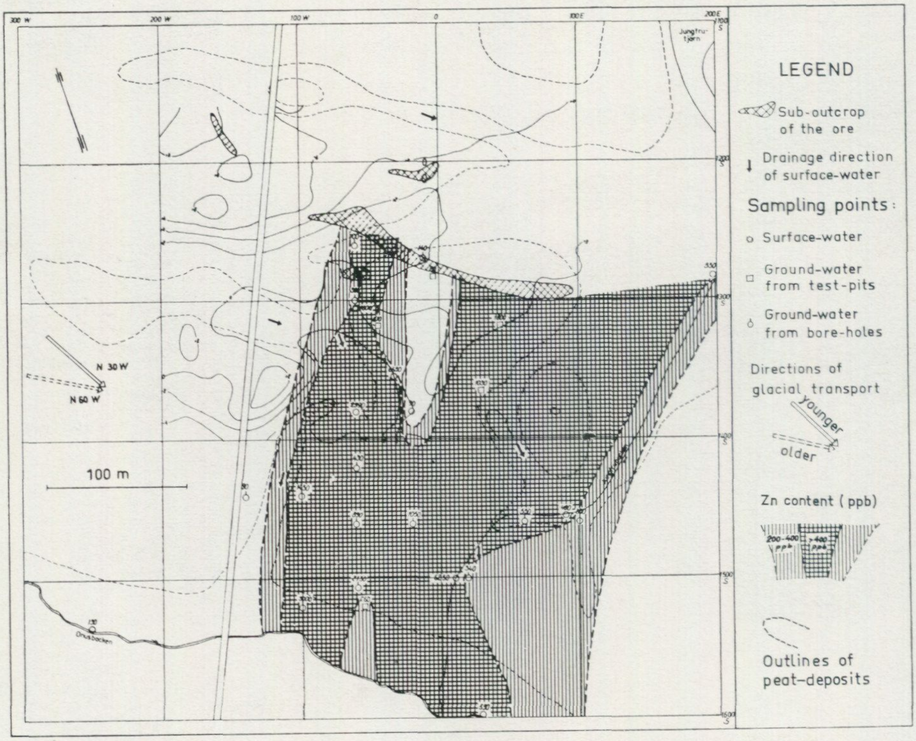


Fig. 23. Trends in the Zn content of ground-water and surface-water.

The high mobility of Zn in natural waters in combination with the fact that Zn is the most abundant element in the ore (up to 14 % Zn) are two of the most probable explanations of the strong anomalies. As a whole, there is a general tendency for both test-pit water and bore-hole water to have anomalous amounts of Pb, Cu and Zn along the same drainage structures.

A probable explanation of the fact that the ground-water anomalies have developed southwards from the external ends of the ore-body could be that the contents of Pb, Cu and Zn have maximum values there. Consequently, the central (and most narrow) part of the ore-body should affect the ground-water (that is passing through and over it) to a much less extent than the external parts.

Another explanation is that ground-water movement is greatest in the two drainage channels affecting the ends of the ore-body, whereas the central part form a local nearly horizontal divide. The water sampled there (at a depth of 4 m) would not generally have had contact with the till/ore interface (at 6 m), but such deeper water would contribute by influx to ground-water in the drainage system.

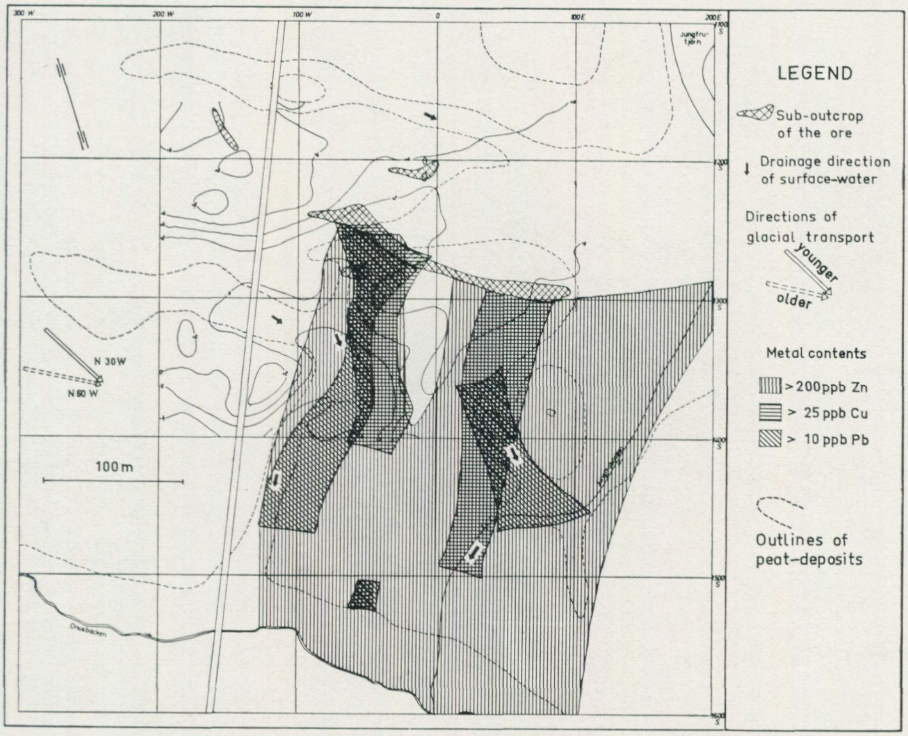


Fig. 24. Hydrochemical anomalies of Zn, Cu and Pb over the ore-deposit at Norra Norrliden.

SYNTHESIS

The combined anomalous patterns of Pb, Cu and Zn in the different materials are presented in Fig. 24—27.

The distribution pattern of anomalous Pb, Cu and Zn in ground-water (Fig. 24) indicates a displacement of the three elements down-slope from the external ends of the ore-body along two drainage channels. Zn has much higher contents in the ground-water and the surface-water than Cu and Pb, interpreted as a reflection of the higher mobility of this element and of the higher Zn contents in the ore compared to the other two elements.

The combined anomalous distribution patterns of the three elements in birch-bark ash (Fig. 25) are closely correlated to those in the ground-water. Zn has a stronger contrast to the background values compared to Cu and Pb, which fits well with the higher contents of this element in the ground-water. However, this also indicates a higher tendency for Zn to be selectively enriched in birch-bark compared to the other two elements.

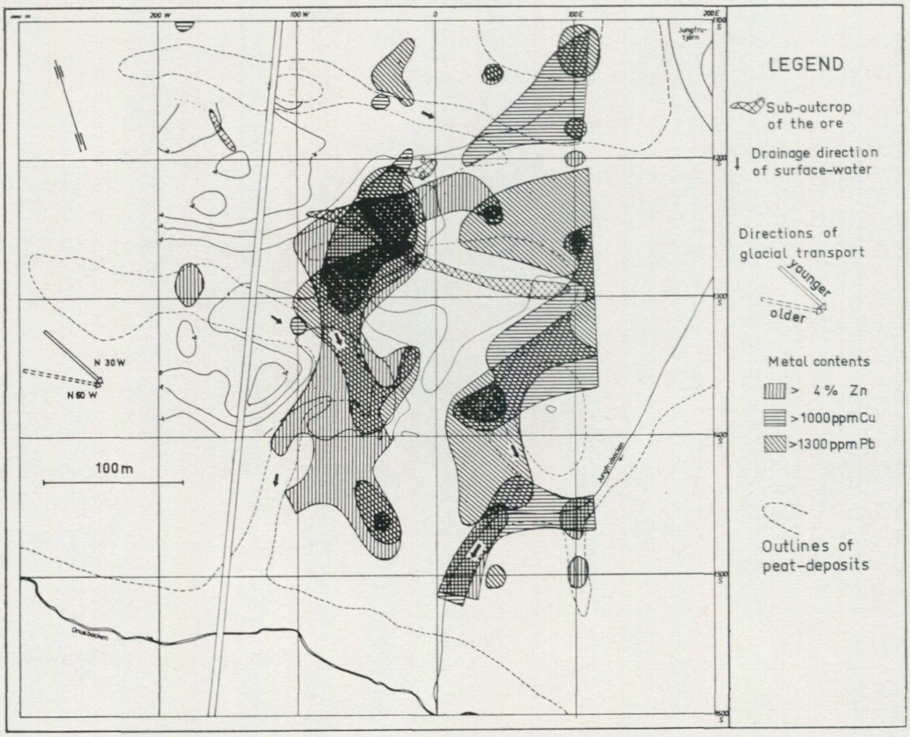


Fig. 25. Distribution of anomalous amounts of Zn, Cu and Pb in birch bark ash at the Norra Norrliden ore-deposit.

Cu, in spite of the relatively high contents in the ground-water, has a less well developed anomalous pattern in birch-bark, and the general contents of Cu are lower compared to the other two elements. The fact that movements of inorganic constituents into the plant is selectively controlled in such a way that some elements are freely admitted while others are impeded to a greater or lesser degree has been reported previously (e. g. Hammett, 1928).

The anomalous patterns of Pb in birch-bark are also closely correlated with those of the ground-water. Although Pb is the least mobile element of the three in water, the anomalous patterns in birch-bark are very distinct and have a strong contrast to the background values.

The anomalous patterns of Pb, Cu and Zn at 1.5 m depth in the till (Fig. 26) is affected by the presence of two till-beds, as already has been discussed. Because of this complicating factor the combined anomalous patterns of the three elements at this sampling depth are not so well correlated with those in the ground-water or in the birch-bark.

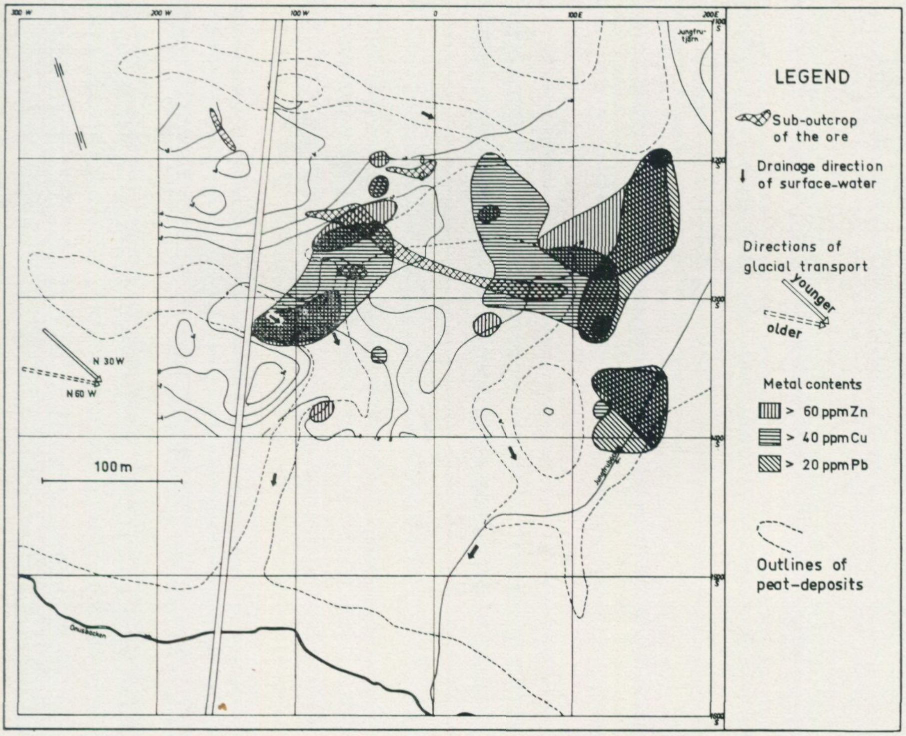


Fig. 26. Distribution of anomalous amounts of Zn, Cu and Pb in the <0.1 mm fraction of glacial till at 1.5 m depth, Norra Norrliden.

The anomalous patterns of the three elements in the till samples from 0.5 m depth (Fig. 27) on the other hand, are very well correlated with those in both the ground-water and the birch-bark. This strongly favours the possibility that hydromorphic and biogenic processes are the dominant factors in creating the anomalous patterns at this sampling depth. The fact that Cu displays the weakest anomalous patterns of the three elements indicates that this element does not take part in the biogeochemical cycle to the same extent as Zn and Pb. As far as birch is concerned, this was also indicated by the low Cu contents in the bark.

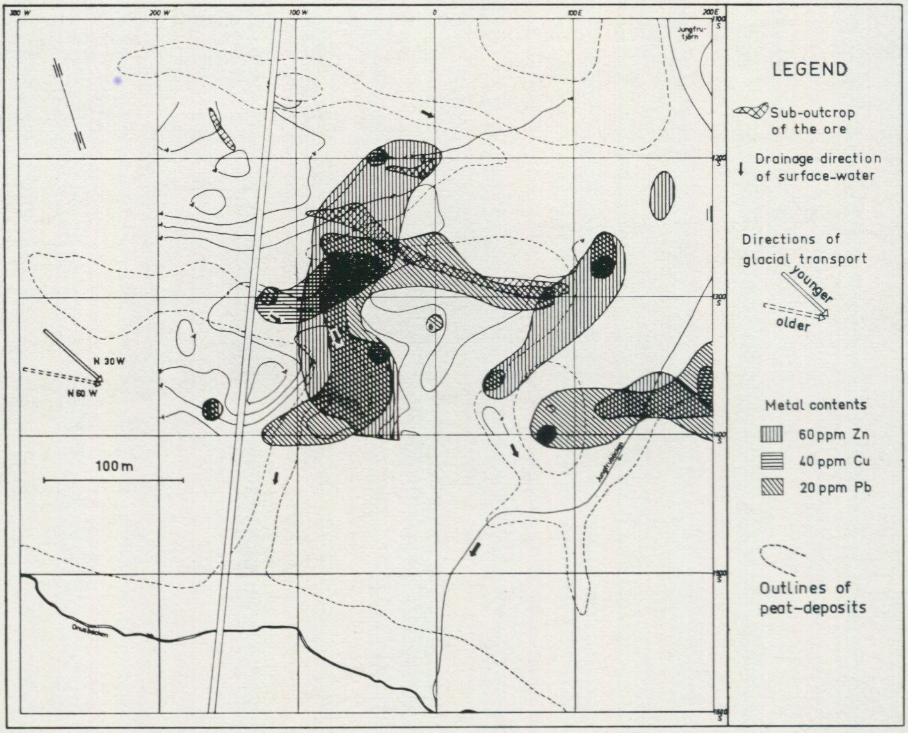


Fig. 27. Distribution of anomalous amounts of Zn, Cu and Pb in the <0.1 mm fraction of glacial till at 0.5 m depth, Norra Norrliden.

SUMMARY AND CONCLUSIONS

The purpose of the investigation was to study the anomalous patterns of Pb, Cu and Zn in different natural materials above a complex sulphide ore-body, and to explain the processes responsible for these anomalous patterns. The basic reason for the study, however, was to contribute to a clearer understanding of geochemical distribution patterns of significance for ore-prospecting. The following four observations and conclusions can be made:

1. The anomalous patterns of Pb, Cu and Zn in ground-water were correlated to two drainage structures down-slope from the ore-body. Only Zn showed anomalous contents in surface-water.

2. Birch-bark was found to be the best plant material for analysis to determine effectively the hydromorphic distribution of Pb and Zn from the ore. Cu, on the other hand, was found to be less enriched in this plant material, although anomalous patterns correlatable with those in the ground-water were also found for this element.

3. The anomalous patterns in the till, although weak, have a positive correlation to those of the ground-water for samples from 0.5 m depth, while samples from 1.5 m depth have irregular anomalous patterns. Biogeochemical processes have probably been active in creating the anomalous patterns at 0.5 m depth, while those at 1.5 m depth have become complicated due to the presence of a lower till with significantly different background values of heavy metals compared to the upper till. As a whole, the anomalous patterns of Pb, Cu and Zn at different levels of the till were weak and would easily escape attention during a geochemical prospecting program.

4. The results indicate that hydrochemical and biogeochemical methods may usefully supplement soil surveys, especially in areas where the latter have proved negative despite other evidence (e. g. stream sediment anomalies) for the existence of complex sulphide ore-bodies.

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