Heavy minerals from placer deposits in the County of Norrbotten, northern Sweden, and their provenance

GÖRAN GRANATH

Granath, Göran, 1978 04 15: Heavy minerals from placer deposits in the County of Norrbotten, northern Sweden, and their provenance. *Bulletin of the Geological Institutions of the University of Uppsala,* N. S., Vol. 7, pp. 111—175. Uppsala. ISSN 0302-2749.

This study is concerned with the composition of some placer deposits found along the main rivers and the coast of the County of Norrbotten, Sweden. Attempts to explain their provenance are also made. For these purposes, the size distribution, the mineralogical composition, and the trace-element content of magnetite were investigated. As the heavy mineral species differ in density and other physical properties, they will be enriched differently under different hydraulic conditions, which renders a judgement concerning the provenance impossible. Therefore some concomitant variable has to be found to which the mineralogical variables may be related. By regressing the original variables onto such a concomitant variable, new variables are found in the residuals, which give a better geological explanation. These new variables can now be treated together with the other data in the hope of finding out the provenance of the minerals. As will be seen, the three main areas — the Pite, Lule, and Kalix areas — differ considerably in composition, especially in the trace-element content of magnetite. Inside each area, there are also differences, and the results often, but not always, correspond to the known bedrock. Especially samples taken in glaciofluvial material can be difficult to interpret.

Göran Granath, Department of Mineralogy and Petrology, Institute of Geology, University of Uppsala, Box 555, S-751 22 Uppsala, Sweden, 16th February, 1978.

Contents

C'est la profonde ignorance qui inspire le ton dogmatique. Jean de la Bruyère (1645—1696)

Introduction

The area of investigation is situated in the eastern part of the County of Norrbotten in northern Sweden (Fig. 1). This county is the largest in Sweden with an area of 98 909 km^2, or slightly bigger than Scotland and Wales together. Geographically it can be divided into three regions: along the coast and along the lower parts of the main rivers,

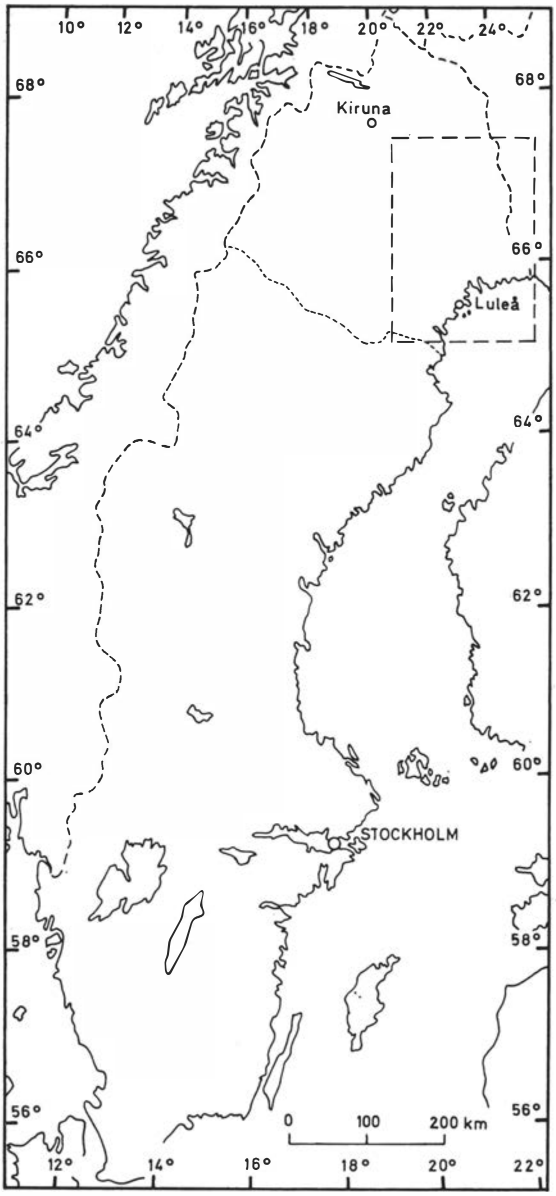


Fig. 1. Location of the investigated area.

there are fairly flat plains which are to a great extent brought under cultivation; the main central part which consists of forested hilly areas and vast mire-complexes in between; and finally the mountain region along the border to Norway which, to a great extent, lies over the tree-line. The forests mainly consist of boreal coniferous species (*Pinus silvestris*, *Picea abies*), with birch as the most important second element (*Betula verrucosa* and *pubescens*). The population is sparse (well under 300 000) and more than two thirds live in the coastal region. Three languages are spoken in this county: apart from Swedish, Finnish in the easternmost parts and Lappish in the far north and in the mountain areas.

The aim of the investigation

The aim of this work was mainly to investigate the heavy mineral placers, i.e. sand bodies enriched in minerals with a density greater than 2,90 to reveal their mineral composition, and, if possible, to determine the provenance of the minerals. Several authors have worked on heavy minerals in sediments before; notable are the classical works of Russel (1937), Rittenhouse (1943), and van Andel (1950). These authors, however, did not work on placers but merely on grab-samples taken directly from the river bottoms. Among authors working on the problems of different density of different mineral-species Briggs (1965) and Hand (1967) may be mentioned. Among studies dealing with multivariate statistics on heavy mineral data, Imbrie & van Andel (1964), Kelley & Whetten (1969), and Rice et al. (1976) may be mentioned. The statistical methods used in this work, however, are to a great extent different from those used by the above authors as will be discussed later on.

Little is published about heavy minerals in Norrbotten even if Linnaeus described a placer at Harads, when he made his famous journey to Lapland in 1732. There is, however, an outstanding paper by Ljunggren & Sundborg (1968) treating heavy mineral deposits in the valley of the Lule River. They studied enriched heavy mineral deposits and discussed the hydrodynamical enrichment and sorting of such minerals and also provided size curves for different mineral species. It was this paper that inspired the present author to continue the work on heavy minerals in the main river valleys and along the coast of Norrbotten.

Geological setting of the area

Bedrock geology

The whole area of investigation is underlain by bedrock of Precambrian age. However, as outcrops are scarce, and younger dikes of kimberlite occur in the Kalix Archipelago and on some promontories, there is a possibility that such dikes also exist on the mainland but are hitherto not found.

The total area of the Precambrian in Norrbotten amounts to 82 720 km² or about one fifth of the whole area of Sweden. Ödman (1957) divided the Precambrian in Norrbotten into two major formations, or cycles, viz. the Svecofennian Cycle and the Karelian Cycle. In his opinion, the Svecofennian Cycle is the oldest, and, in age and in geological character, comparable to the oldest Precambrian formations in Västerbotten, south of the present map area. The Svecofennian is believed to be of the same age as the basement formations in central Sweden and south-western Finland.

According to Welin (1970), the Svecofennian and Karelian rocks are two synchronous facies, and not two orogenic cycles, with the Svecofennian facies to the SW and the Karelian facies to the NE. Using modern Rb-Sr methods he has found the development of the rocks thus: first a period of deposition of supracrustal rocks between ca 2 100 to 1 900 million years ago. After this, a period of intrusion and deformation occurred, between 1 900 and 1 775 million years ago followed by a final period of deposition and intrusion, with a widespread volcanic activity, from 1 775 to 1 540 million years ago (Welin ibid., Welin et al. 1971).

To the west, the Precambrian is overlain by younger rocks of Eocambrian to Silurian age, belonging to the Caledonian mountain range (Ödman ibid.).

The following description of the bedrock of the investigation area follows Ödman (ibid.). The condensation of his rock types into sixteen major types agrees with that of Fromm (1965) (Fig. 2).

1. Acid, red microcline granites. — These granites are Late Karelian in age and cover the largest part of the area. Most extensive is the Lina Granite and smaller areas consisting of the very similar Arjeplog and Palja Granites. These granites are always mapped together. The Lina Granite is a medium grained homogeneous rock of reddish colour. It is dominated by quartz, microcline, and plagioclase. Biotite is almost always present and hornblende has been reported present up to 10 %. Pyroxene may be present and of the accessory minerals which are usually rare (less than 4 %), the following ones are noted: epidote, sphene, magnetite, apatite, zircon, and rutile.

2. Edefors Granite (incl. Edefors Syenite). — The Edefors Granite and Syenite covers a fairly large area in the parishes of Edefors and Jokkmokk. The granite is a bright red or brownish, medium grained rock, characterized by small spots of accumulated dark minerals. The predominant constituents are quartz, microcline, plagioclase, hornblende, and biotite. Pyroxenes are sparse. The hornblende is usually grass-green but can also be of a bluish variety. The pyroxenes consist mainly of a greyish-green to colourless diopside. Among the accessory minerals epidote, sphene, zircon, apatite, and magnetite may be noted.

The greyish-green or brownish forms of the Edefors Syenite are coarse to medium grained, homogeneous rocks. They are dominated by microcline perthitically intergrown with oligoclase or albite. Quartz is present but usually in small amounts. The dark minerals are usually hornblende, pyroxene, and biotite. The pyroxene, which is a diopsidic augite, is to a large extent altered to dark-green hornblende. The accessory minerals are the same as in the granite. The age of the above rocks is Late Karelian.

3. Perthite granite. — This granite occurs, in the area of this investigation, only SW of Tärendö and in a thin band east of that place. It is of a special type called Kompelusvaara Granite. It is a red homogeneous rock, consisting of microcline-perthite, plagioclase, and quartz. Dark minerals are rare, only some amount of hornblende and biotite but no pyroxene occurs. Of the rare accessory minerals the following may be noted: sphene, magnetite, apatite, and zircon.

4. Augen granites. — The augen granites which could have influence on the sediments in the area are of two types: the Late Svecofennian Revsund Granite and the Late Karelian Degerberg Granite. The Revsund Granite occurs in an area just south of Älvsbyn. It is a medium grained light-grey rock, but with its augenstructure not as well developed as in the typical Revsund Granite further south. Microcline and quartz dominate, but epidote and sphene are usually present.

The only, for this investigation, relevant locality of the Degerberg Granite is at Buddbyn just north of Boden. It consists of microcline, plagioclase, and quartz and very few accessory minerals.

5. Other granites. — The only other "true" granite relevant to this investigation, is the Arvidsjaur Granite and its local variety, the Porjus Granite. It occurs along the Pite River, mainly on the southern side, from about Moskosel and down to near Älvsbyn. The Porjus Granite occurs in a smaller area along the river Stora Luleälv between Porjus and Vuollerim. These granites are medium grained red quartz-microcline granites with albite or oligoclase. They contain an average of 1 % hornblende with bluish green pleochroism, and about 2 % biotite. The accessories usually consist of magnetite, sphene, apatite, and zircon. Epidote has also been found.

6. Syenites. — Syenite occurs in two areas, namely in a small area along the Lule River south of

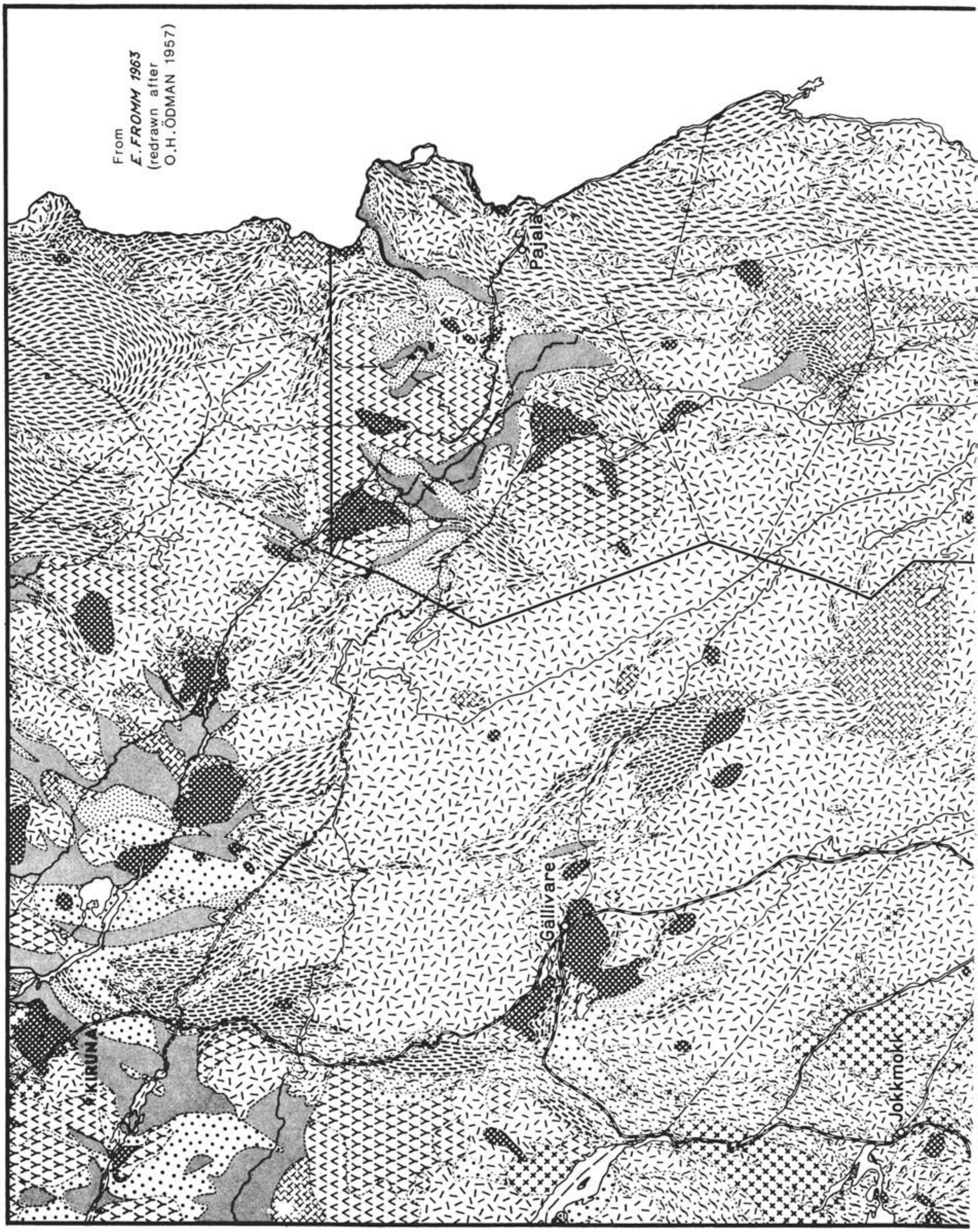
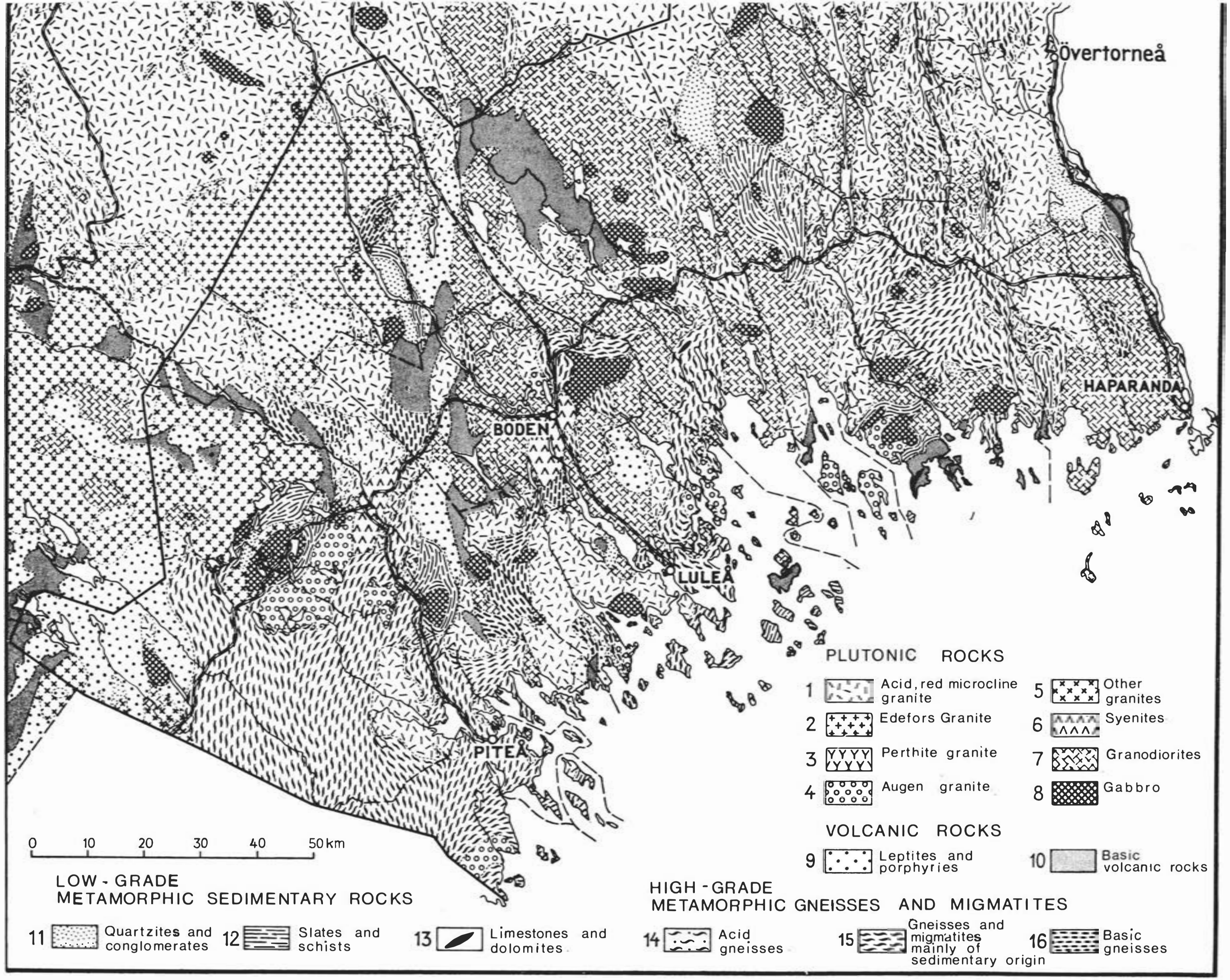


Fig. 2. A slightly simplified map of the Precambrian rocks in the investigated area, after Ödman (1957). The figures in the legend correspond to those in the text. The map is taken from Fromm (1965).


Övertorneå
HAPARANDA
BODEN
LULEÅ
PITEÅ
PLUTONIC ROCKS
1 Acid, red microcline granite
2 Edefors Granite
3 Perthite granite
4 Augen granite
5 Other granites
6 Syenites
7 Granodiorites
8 Gabbro
VOLCANIC ROCKS
9 Leptites and porphyries
10 Basic volcanic rocks
0
10
20
30
40
50km
LOW-GRADE METAMORPHIC SEDIMENTARY ROCKS
11 Quartzites and conglomerates
12 Slates and schists
13 Limestones and dolomites
HIGH-GRADE METAMORPHIC GNEISSES AND MIGMATITES
14 Acid gneisses
15 Gneisses and migmatites mainly of sedimentary origin
16 Basic gneisses

Boden, and in a greater area north of Tärendö. The Boden Syenite has already been described together with the Edefors Granite. The Pajala Syenite, as the syenite north of Tärendö is called, is as typically developed a coarse to medium grained massive rock, varying from brown to brownish red in colour. According to Geijer (1931) diopsidic augite, hornblende, and biotite occur together with oligoclase, microcline, and quartz.

Among the accessory minerals, which can reach well over 10 % by volume, epidote, zircon, apatite, sphene, and magnetite can be found. The magnetite is usually fairly rich in titanium.

7. Granodiorites. — These consist of the Arvidsjaur Diorite and the diorites of the Haparanda "Series". The Arvidsjaur Diorite lies too far to the south for being of any influence to the sediments of the Pite River. The diorites of the Haparanda "Series" on the other hand are crossed both by the Lule and the Kalix River. They are Early Karelian in age. They are low in quartz but fairly rich in oligoclase or andesine plagioclases. Hornblende is very common, up to 59 % as in one case NW of Gäddvik. The accessories consist of sphene, magnetite, epidote, apatite, and rutile, but zircon is rare.

8. Gabbro. — Gabbro occurs all over the area, usually in fairly small massifs. The gabbros usually carry much plagioclase and pyroxene. Olivine is sometimes common but hornblende is always sparse. Among the acessories magnetite and apatite are noteworthy.

9. Leptites and porphyries. — These are of acid dacitic, keratophyric and liparitic composition. The dacites, which are closely connected to the liparites, occur in an area around Laver, 40 km WNW of Älvsbyn, and in a small area at the coast between Piteå and Luleå. They consist of a microgranitic-microgranophyric groundmass with grains of plagioclase. The keratophyres occur in most of the Svecofennian supracrustal areas. Their feldspars consist mainly of albite but potash feldspar may also occur. The accessories are usually biotite with some hornblende and pyroxene adjoining it. The liparites are the areally most extensive rocks of the acid volcanics. They are much alike the above rocks, only with more quartz, and a strict limit between liparites on one hand, and dacites and keratophyres on the other, seems to be difficult to draw.

10. Basic volcanic rocks (incl. the Bälinge Porphyrite). — The basic volcanic rocks are of dacitic, andesitic and basaltic composition. It is to these rocks that the porphyrites of the Bälinge "Series" are usually assigned. The basic volcanics either belong to the Kiruna-Arvidsjaur "Series" of Early Svecofennian age or to the Lapponian of Early Karelian age. The Bälinge "Series" is considerably younger, but although older than the Late Karelian intrusive rocks. Those rocks belonging to the Kiruna-Arvidsjaur "Series" are found in the same areas as the above mentioned leptites and the Arvidsjaur Granites. One area runs as a narrow band from a point east of Älvsbyn up to Svartlå south of Edefors; smaller areas occur scattered along the Pite River upstream from Älvsbyn. Another rather extensive area is situated along the Tärendö River north and east of Tärendö. The Lapponian basic volcanics are found north of the above area around Lauttakoski and on some promontories south of Kalix and Töre. The Bälinge Porphyrite occurs in a fairly large area from a point 30 km upstream from Råneå along the Råne River and reaches 40 km further. Not very much is written about the mineralogy of the rocks of the Kiruna-Arvidsjaur "Series" in the areas around and north of the Pite River, and the same is valid for the Tärendö area, even though there is one report from there (Eriksson 1954). The rocks consist of albite or oligoclase and amphiboles. Of accessory minerals sphene, apatite, magnetite, and pyroxene can be noted. Much more is published about the Lapponian rocks at Lauttakoski and at the coast. The basic volcanic rocks at Lauttakoski consist of hornblende and plagioclase, and the accessories of sphene, magnetite, and pyrite (Shaikh 1972).

In conjunction with basic metavolcanics there is a narrow band of basic intrusive rocks described as leucodiabase. It contains deposits of soapstone with a remarkably high magnetite content (up to 15 %). The basic intrusion consists of plagioclase, hornblende, and augite as main minerals, and scapolite, biotite, magnetite, apatite, and sphene as accessory minerals. This composition varies, however, considerably (Shaikh 1972). The Bälinge Porphyrite is of two types: plagioclasic and uralitic. The plagioclase is relatively basic (20—40 % An). Among other minerals hornblende and biotite may be noted, and as accessory minerals microcline, quartz, and epidote are found.

11. Quartzites and conglomerates. — Most of the quartzites in the area are of Early Karelian age, i.e. Lapponian. At first we have the quartzites of the Vakko and Vargfors "Series", situated west of Gällivare and north and east of Kiruna. But these quartzites can hardly have influenced the sediments of this investigation. Then there is a fairly extensive quartzite area NW of Tärendö, more or less enclosing the basic volcanics of Lauttakoski. This area also contains some conglomerates. Another area of quartzites occurs along

the Lule River south of Edefors to Svartlå. Generally, however, the quartzites should have very little influence on the content of heavy minerals in the sediments. After the Lapponian Epoch, the Bälinge "Series" was developed. The type locality is at Bälingsberget, on the southern side of the Lule River opposite Nederluleå church. It consists mainly of a conglomerate with balls of Early Karelian and Svecofennian rocks, and with a groundmass consisting of plagioclase, biotite, and hornblende. This locality is in detail described by Åhman & Ödman (1952). Several other small localities of the Bälinge Conglomerate also exist in the vicinity.

12. Slates and schists. — These are mostly of Svecofennian and Lapponian age and occur in an area west and south of Älvsbyn and north of Morjärv and SW of Överkalix. These rocks are often rich in graphite and sulphides, but their influence on the mineralogy of the placers is probably almost nil.

13. Limestones and dolomites. — There is relatively little limestone and dolomite in the area. Most of them occur in connection with the basic volcanics. As carbonate rocks do not usually carry much heavy minerals, their influence on the sediments of this investigation could probably be neglected.

14. Acid gneisses. — The acid gneisses are high-grade metamorphic transformation products from acid leptites, porphyries etc. Therefore, they are fairly rich in quartz. They occur in a smaller area NW of Älvsbyn and in a larger area north of Jokkmokk. Their essential minerals are quartz, feldspar, muscovite, and biotite. Of accessory minerals sillimanite, andalusite, cordierite, garnet, and chrome-bearing mica can be noted.

15. Gneisses and migmatites, mainly of sedimentary origin. — These rocks occur in a large area south of Älvsbyn and Piteå down to the border of Västerbotten and in narrow bands stretching north-south, north of Luleå and north of Kalix, all the way up to Pajala. The latter are Late Karelian and the former Late Svecofennian in age.

16. Basic gneisses. — These are high-grade metamorphic transformation products of basic eruptive rocks of the types described under 10. They are poor in quartz and fairly rich in heavy minerals as the basic volcanic rocks are. In addition to the other gneisses they carry amphiboles and pyroxenes.

Quaternary geology

Most parts of the area are described by E. Fromm (1965) regarding the Quaternary geology. Among later descriptions, that of Daniel of the Moskosel area (upper Pite River), and Fagerlind's of the Pajala area (upper Kalix River), may be mentioned (Daniel 1975; Fagerlind 1975).

A short description of some of the main features of the Quaternary development of the area, according to Fromm (o.c.) is as follows:

1. The oldest Quaternary deposit in the area is the interglacial, or early interstadial, peat at Ale, about 25 km north of Luleå (Fromm 1960), and interglacial, or interstadial, varved clays and silts resting on an older till at Boden. Other loose deposits, older than the final stages of the last glaciation, are not known.

2. The till mainly consists of rather uniform types. The most common till is characterized by the size fractions medium sand and fine sand. The boulder content is low in the northernmost parts of the area; elsewhere it is medium and sometimes high.

In some coastal areas, a special type of till is common, the "Kalix till" (Sw. "Kalixpinnmo"; Beskow 1935; Hoppe 1948).

The petrographic composition of the till, expressed as the content of different rocks among the boulders, is to a large extent dependent on the local bedrock. Rock types with a large areal distribution, however, occur in appreciable amounts at great distances from their outcrops.

3. The ice movement during a major stage of the last glaciation was from NNW, and then from the west. In the northern parts of the area the latter movement came from the SW. After deglaciation of the eastern districts, the ice movement reassumed its direction from NW or NNW. Deglaciation of the western area then took place. At the ice border below the highest shore line, small terminal moraines ("annual moraines") were formed in the same area as the previous ice movement.

According to the traces of lateral and extramarginal drainage channels, the ice in the northernmost part of the area seems to have been split into separate ice bodies.

4. Glaciofluvial deposits are represented by typical eskers, and by flat sand or gravel plains. Some of the latter are delta deposits at the highest lateglacial shore line of the Baltic. Above this, the eskers are small and usually covered by a thin layer of till, suggesting a subglacial formation (Fig. 3). Lateral drainage channels, and other traces of melt water drainage, e.g. rock canyons ("kursu-valleys") are rather common above the highest shore line.

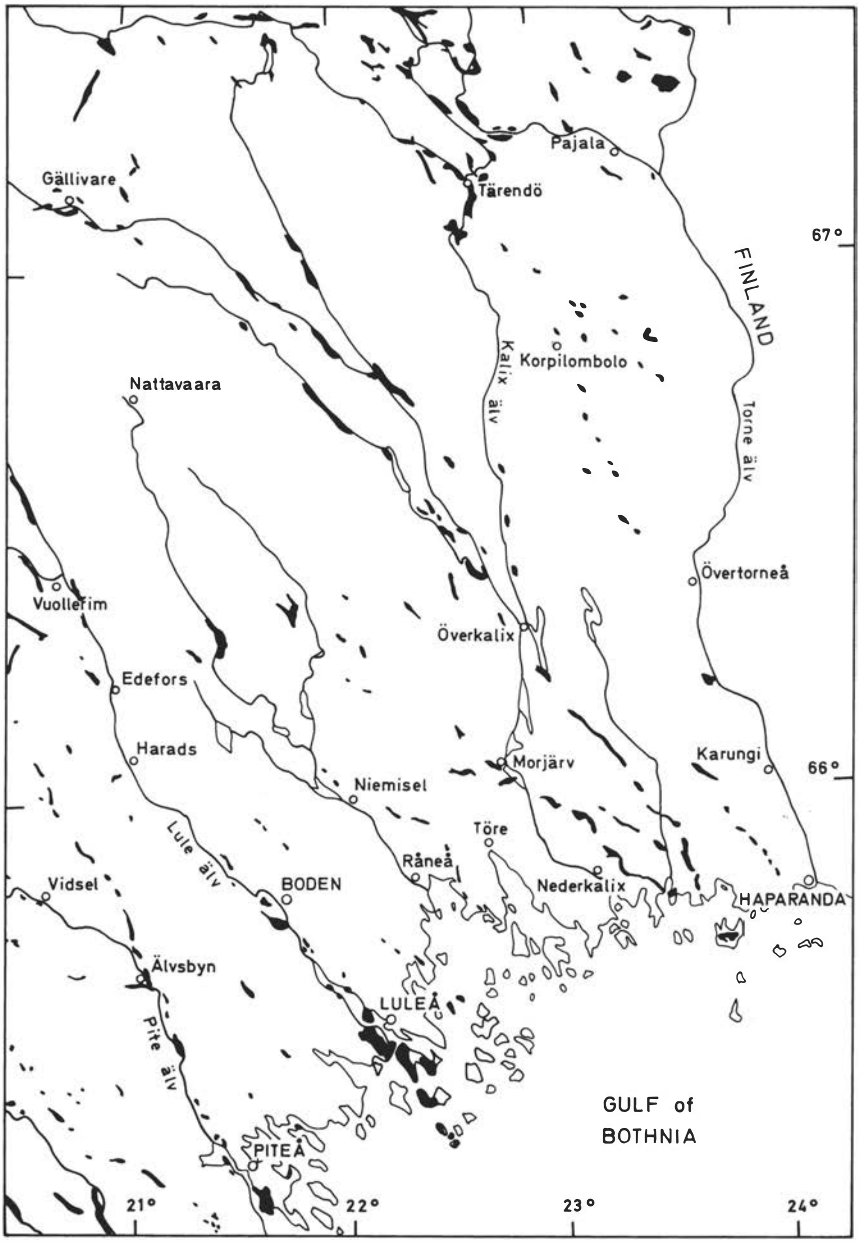


Fig. 3. Distribution of glaciofluvial deposits in the investigated area. Scale 1:1585000.

5. The ice recession from the area was rather rapid. There are indications of a retreat of the ice in the areas, submerged by the late-glacial Baltic, of 300—400 metres per year (Möller 1962 a, b). The final evidence of glacial activity is a drainage varve in the glacial clays of the Lule and Pite River valleys, possibly reflecting catastrophic drainage of ice-dammed lakes in the Muddus district, NW of Vuollerim.

6. Using pollen and diatom analyses, the ice recession has been dated to the transition between the Yoldia and Ancylus stages of the Baltic, and is contemporary with the latest part of a *Betula* zone in the pollen diagrams, before the Boreal *Pinus* maximum. The absolute age can be estimated to be about 7 000 B.C. In Norrbotten, the glacial varved clays are too indistinct to permit varve measurements.

7. The highest late-glacial shore line in Norrbotten is the level of the Baltic during the retreat of the land ice from the area. In the SW, the shore line is situated 240 metres above the present sea level and in the NE 170 metres. It is marked by the upper limits of the traces of wave-washing in till, delta plains and mouths of glaciofluvial lateral drainage channels at the former sea level.

8. The shore level at the transition between the Ancylus Lake and the Litorina Sea in the central part of the area is 102 metres above the present sea level. The present land elevation measured at gauges and old water marks is 0,9 cm/year.

9. Coarse sediments outside glaciofluvial deposits and river valleys are mainly the product of the shore processes below the highest shore line of the Baltic. Dunes occur in two different areas: late glacial "fossil" dunes on glaciofluvial sand and gravel at the highest shore line or at still higher levels in the northern part of the area and recent or sub-recent dunes near the present coast.

10. Fine grained sediments occur to a very limited extent above the highest shore line as sediments in ice-dammed lakes etc. The silts and clays are far more widespread below the highest shore line.

11. The loose deposits in the river valleys below the highest shore line are, from the bottom to the surface of the sediment plains:

a. Till or glaciofluvial sediments

b. Glacial and post-glacial silts and clays

c. Deltaic fine sand and sand deposited at the river mouth in earlier stages of the land elevation, and forming sand plains into which the river has cut its present course.

12. The peat lands of the area, about 25 % of the land area, are soligenous mire complexes, with extensive fen areas and more restricted bog vegetation.

13. The frost activity is characteristic of a northern, boreal climate, but not of arctic or subarctic environments. In spite of the high latitude, there is no permafrost.

Present hydrography

In the area of investigation there are three major drainage basins, namely those of the Pite, Lule, and Kalix Rivers and one smaller, belonging to the Råne River. The latter will not be considered here as the samples from there were withdrawn for geographical reasons.

The Pite River. — The Pite River is the southernmost, and the smallest of the three major rivers. It has been described by Hoppe (1969) and Nilsson (1972). The area of the basin is 11 093 km^2 and has a lake-percentage of 6,9. The mean elevation of the area is 510 meters. The lenght of the basin is 350 km with an average width of only 31 km; and the length of the river from Skierfajaure, at an altitude of 450 m, to the sea is 240 km. However, from Skierfajaure to Gaskajaure at an altitude of 856 m, there is a further 60 km.

The general direction of the river is NW to SE and the average slope 1,9 per mille. The river is not controlled by dams except at Sikfors, about 30 km from the mouth. Here, the mean discharge has been calculated to be 161 m^3/sec. The river has only one tributary of importance, namely Varjisån, which is about 50 km long. The source area is located in the southern Caledonides of Norrbotten with peaks reaching over 1 500 m. The uppermost region consists of moderately large lake areas with small rapids between the lakes. Below this area, the river reaches the forest region, and changes character completely. It falls from an altitude of 427 m to 48 m at Bredsel, which is situated 80 km from the mouth. Here, the river runs in a narrow valley with long stretches of smooth water interrupted by substantial rapids of which Storforsen, 110 m high, is the most imposing. Below Storforsen, at Bredsel, the river changes character again and takes on a sluggish aspect. Still the results of fluvial activity are marked by high steep sandy river-banks etc. At Bölebyn, 10 km from the mouth proper at Pitsund, the river reaches the sea level through a small delta. The last stretch is composed of two bays: Svensbyfjärden and Pitefjärden.

The Lule River. — The Lule River is, according to discharge, the second river in Sweden with a mean discharge of 510 m^3/sec. The basin which is situated north of the Pite River, with only some small basins in between at the coast, has an area, above Boden, of about 25 000 km^2. It has a mean altitude of 680 m, a lake content of 8,4 % and a runoff of 21 l/sec. and km^2. The length of the river is 450 km from Virihaure, at an altitude of 579 m, to the sea. The general direction of this river is NW to SE and the average slope is 2,2 per mille. The Lule River's water system is to almost all of its elevation controlled by dams. Above Vuollerim the river forms two tributaries: the Stora and Lilla Lule älv. The system of smaller tributaries is very extensive but none is worth mentioning specially. Both the Stora and Lilla Lule älv have their source areas in the mountain region. The Stora Lule älv rises at Sitasjaure, at an altitude of 616 m, with contributing smaller lakes even higher up; there is also another source area around Virihaure with smaller lakes at an altitude of almost 1 000 m. The source area of the Lilla Lule älv lies to the south with many small lakes among the mountains situated up to more than 1 000 m above sea level. These lakes then discharge via small streams into Lake Saggat at Kvikkjokk (alt. 303 m). Both tributaries form vast areas of elongated lakes, some of them more or less man-made, in their upper reaches. At Porjus and Jokkmokk, the Stora and Lilla Lule älv, respectively, change character, as was the case with the Pite River. They then pass through the forest region with stretches of smooth water interrupted by sizeable waterfalls, now dammed. At Vuollerim the rivers unite and continue to Laxede power station, about 100 km from the mouth; thereafter it reaches an altitude of only 19 m. Downstream from here, the river becomes sluggish with sandy banks etc. in the river. The last rapid is at Boden, now dammed; after this point sea level is almost reached. At Unbyn there is a small delta, and then several bays and bights open up until the sea is reached just east of Luleå. The heavy damming of the water system has, of course, influenced recent sedimentation severely, and made any meaningful sampling above Vuollerim difficult. The Lule River has been described by Nilsson (1972).

The Kalix River. — The basin of the Kalix River is situated north and east of that of the Lule River, with the basin of the Råne River protruding in between them in the southern part. The Kalix basin is only slightly smaller than that of the Lule River, with an area of 23 600 km^2. The lake percentage is 4,0 and the mean runoff 12,1 l/sec. and km^2. The length of the main stream is 455 km and the mean discharge is 286 m^3/sec. at Kalix at the river mouth. The source area of the Kalix River proper is situated in the Kebnekaise Massif with peaks reaching well over 2 000 m above sea level. Within the source area, the river consists of two tributaries: the Kalix River and the Kaitum River, of which the latter lies to the south. The Kaitum River is also longer and has a higher discharge, and should therefore be considered the main stream. In the mountain region, unlike the two former rivers, the lake content is fairly small and they mostly run through narrow valleys. In this area the general direction is approximately west to east and they slope up to more than 4 per mille. The rivers enter the forest with little change in character, and unite at Lappeasuando 40 km SE of Kiruna. After this point, the general direction is WNW-ESE until Tärendö, where it is northsouth all the way to the coast. The character of a typical north-Swedish forest river, with slow water interrupted by rapids, continues to Överkalix. South from there (alt. 36 m), a system of long lakes begins, with small rapids between them, almost all the way down to the mouth. There are several important tributaries to the river, of which the Tärendö River, the Lina River, the Lansån River and the Ängesån River are worth mentioning. The Tärendö River is the only bifurcation in Sweden of any importance, and it contributes almost as much water, from the Torne River, into the Kalix River as the main stream itself. The Ängesån River is the longest of the tributaries, with a length of 210 km and with a basin area of 6 780 km^2. Another thing worth mentioning is that the Kalix River is not dammed at all. The Kalix River has been described by Hjorth (1971) among others.

Methodology

Field methods

In all, 110 samples from placer-like deposits were collected, containing between 0,1 and 98,6 % total of heavy minerals. Only 86 of these were used; some of the poorest samples were deleted.

The samples were usually taken just at the water's edge on the beach (i.e. the summer-water-level, as all sampling was made in August), but

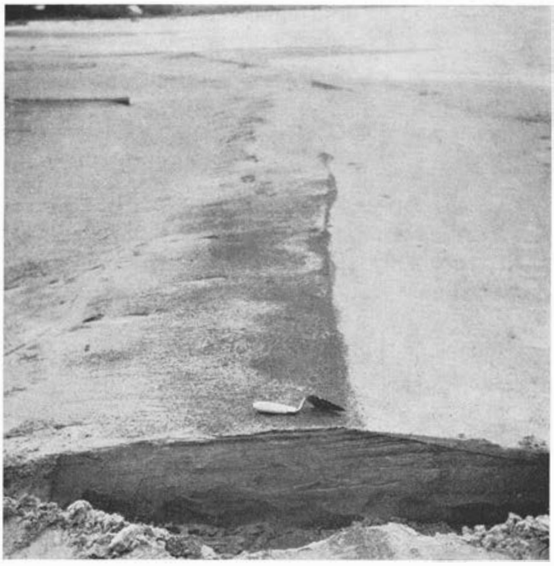


Fig. 4. Thin layers of heavy minerals near Gammelstad.

at some localities samples were taken higher up on the beach as well. And in one case, a sample (30101) was taken from the bottom of the Lule River (Bergnäset) at a depth of about 0,15 m. This was, however, not from a placer in true sense, but is was, nevertheless, included in the analysis. By means of a palette-scraper, the samples then were carefully scraped off the underlying layer of light minerals. Great caution was taken to get the sample out of just one layer, i.e. the same sedimentation unit. In some cases the layers were only about 1 mm thick, in which case a small brush was of greatest use. About 100—500 g were collected thus, the amount depending on the size of the placer, and the patience of the collector. The samples were put into plastic-bags, which were then sealed and marked. In some cases trenches were dug, in a direction perpendicular to the water's edge, in order to study the succession of the layers (Fig. 4). However, attempts to collect from lower-lying layers were unsuccessful.

The sampling location was then noted carefully, i.e. the distance from, and height over the water's edge. These measurements were made by means of measuring-tape and ruler. Sometimes a surveyor's tube had to be used in order to pin-point the height over the waterlevel correctly. The sampling-sites were plotted on Ordnance-survery maps (scale 1:50 000 or 1:100 000) or, where sampling-density was great, on copies drawn from Economical maps (scale 1:10 000). In a few cases sketch-maps had to be surveyed and drawn on the spot. Each sampling-site is described in the appendix.

Laboratory methods

Pretreatment of samples. — In the laboratory the samples were dried at 105°C for several hours. Thereafter they were washed in diluted acetic acid for several times, and carefully decanted. Thus most of the clay-size fraction also was removed. The reason for using acetic acid is that it does not destroy apatite, which was considered an important mineral in this investigation. Furthermore, the samples were found to be almost free from ferrogeneous coatings so treatment with oxalic acid was not necessary. After washing, the samples were again dried.

Size analysis. — The samples were split down to 50—100 g in order to get a suitable portion for sieving. The sieve-analysis was carried out in 1/2-phi steps from 1,5 to 4 phi on original samples (i.e. no treatment except washing and drying). Each fraction was then weighed on a Mettler-balance, and in some cases, grain-size curves were plotted and the values for the mean, sorting, and skewness were calculated. Further, the weights in percent for each size class in all samples were punched on cards for further statistical treatment.

The methods of size analysis and the classical ways of evaluation of the results can be found in many textbooks on sedimentary petrology (i.e. Krumbein & Pettijohn 1938, Müller 1967, Parfenoff, Pomerol & Tourenq 1973).

Separation by gravity. — In order to obtain the fraction of a sample with a density greater than 2,90—3,96, which is what is usually meant by the heavy mineral fraction, a separation by gravity is necessary. Several methods exist, as elutriation, panning and separation by heavy liquids. The latter method is by far the most used and gives, if carefully performed, the most distinct separation. The basic principle is, that if mineral grains are put into a liquid with a given density, the particles heavier than the liquid will sink and those lighter will float. The problem is to get liquids that have the densities in question. Several such exist but

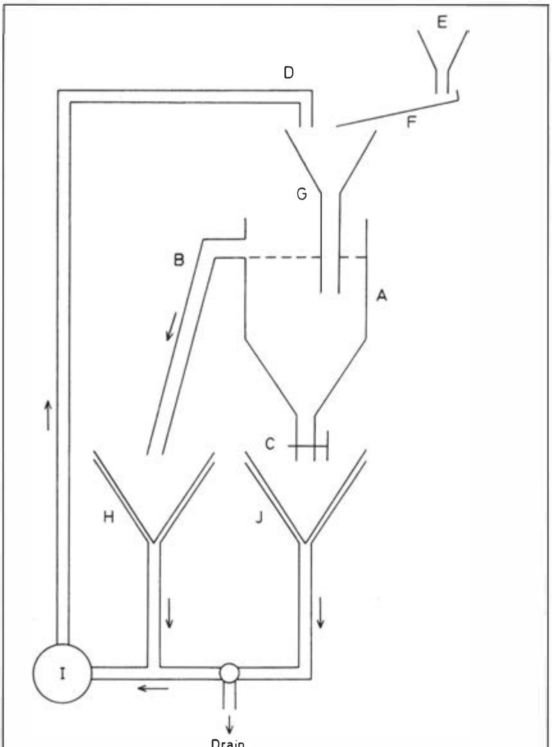


Fig. 5. Apparatus for continuous separation of mineral grains. See text for explanation.

they are expensive and mostly very toxic. In this case, tetrabromethane ($C_2H_2Br_4$) with a specific gravity of 2,95 was used. It has the advantage of being the cheapest of them all, and of having a gravity which coincides with that of the limit between heavy and light minerals.

In this investigation a modification of an apparatus for density separation by means of heavy liquids, originally designed by M. P. Jones, was used (Jones 1965) (see Fig. 5). The apparatus works continuously, and it is especially well suited for fairly large samples, about 50 g in this case. It consists of a separation-funnel (A) with an overflow (B), and a stopcock (C) at the bottom. The funnel is filled with heavy liquid which continuously is supplied to the funnel through the pipe (D). Mineral grains are poured into funnel (E) and are slowly conveyed by the vibrating flute (F) down through funnel (G). This funnel reaches well below the level of the liquid, and as there is a considerable circulation in the liquid, because of the continuous supply of new liquid, the grains are effectively stirred. As there is an outflow through (B), the light grains will eventually pass this way, and collect on a nylon-filter placed in funnel (H). The liquid drains through the filter and is pumped by a piedestaltic pump (I), up through (D), into (A) again. At regular intervals (depending on the amount of heavy minerals) the stopcock (C) is opened and the heavy minerals collected on a nylon-filter in funnel (J).

When a separation is ready, both fractions are washed carefully, several times, in acetone and dried in a fume-cabinet. Both fractions are weighed and the weight percentage of the heavy fraction is calculated and punched on cards.

Magnetic separation. — Magnetite is, at least in northern Sweden, one of the most common and important heavy minerals (up to 74,5 weight per cent of the heavy fraction). As it can be easily separated by magnetic methods, and such a separation is desirable in order to cut down the number of opaque grains before microscopic examination, this is the next step in the treatment. A handy device that is simple to use and with which ferro-magnetic minerals can be selectively separated is Wilke's pocket-magnetic separator, used in this work. The magnet is described by Kneuper (1957) and Müller (1967). The magnetic residue is continously checked under a binocular microscope for purity; the process is repeated, if necessary, up to ten times. Magnetite samples from tills, which were obtained from the Geological Survey of Sweden, were also processed in the same way in order to get the highest possible purity before atomic-adsorption analysis for trace elements.

Microscopic analysis of heavy minerals. — In order to get quantitative relationships between different species of the heavy minerals, a microscopic examination was performed. The heavy fractions were split in a microsplitter until a suitable amount for the slide was left. The grains were strewn onto a heated microscope-slide smeared with Lakeside-cement, and a cover-glass was put onto the slide. The slides were then surveyed in order to find out the most common minerals over all samples, and those which seemed to be able to distinguish between different sampling areas. The minerals thus selected were: opaques, amphiboles, garnet, epidote, diopside, enstatite-hypersthene, kyanite, brookite-rutile, apatite, zircon, monazite, and zoisite.

The different slides were also checked for sorting by size of the grains, and it was found, by the micrometer-eyepiece, that the size intervals never spanned over more than about one phi. For the quantitative estimation the point-counter method of Glagolev and Chayes was chosen (Chayes 1956, Carver 1971).

The analysis was made by a Swift automatic point counter. Against using this method it could be argued that the grains are not uniformly thick, and hence a percentage by volume is not obtained. However, with the narrow phi-intervals and with rather constant relations of the thickness of the different mineral species, fairly good relative volume percentages could be obtained. This method will also not decrease the robustness of the correlation matrix in the statistical treatment of the results.

The results were recalculated into percentages, and punched onto cards.

Trace-element analysis of magnetite. — The trace-element content of magnetite can, at least in many cases, be used as a key to the provenance of the magnetite (cf. Theobald et al. 1967, Frietsch 1970). An advantage is that the density of magnetite is unaffected by the content of the various trace-elements, at least in a hydraulic sense. The most sensitive method, available for this work, was atomic-adsorption spectrometry. For a description of the method the reader is referred to Angino & Billings (1967) and Zussman (1967). The samples were dissolved and then analysed on the Perkin-Elmer A. A. spectrometer at the Institute of Geology at the University of Uppsala.

Eight elements were analysed, namely: cobalt, nickel, copper, chromium, zinc, manganese, vanadium, and titanium. The results were then punched on cards. In addition to the placer-magnetites, 23 magnetite samples from tills were analysed. In parallel with the above analyses, the magnetites were also analysed on the spectrograph at the Geological Survey of Sweden in Stockholm, but the results were disappointing, probably because of the high iron content of the samples.

X-ray analysis. — An attempt was made to make a semiquantitative analysis of the heavy mineral fractions by X-ray analysis (Pryor & Hester 1969). The results were disappointing owing to the great many species present and the high ilmenite content (fluorescense of iron compounds). However, in some cases the X-ray diffractograms could be of some value in identifying a number of species under the microscope. The three magnetites with the most extreme trace-element composition were also analysed by X-ray diffraction, and their cell-edges calculated. However, the results showed that the differences were well below the limits of probable error.

Complementary analyses. — The above extreme magnetites were also analysed by the electron microprobe for titanium and vanadium. Here also, the results were rather obscure.

Statistical methods

Introduction. — With a multitude of data as in this case (3190 units of information of which 2494 are used), where the observations and variables are related to each other in a rather complicated way, the investigation has to rely heavily on statistical methods.

As in all work of this kind, basic statistics of the data has to be done, i.e. means, standard deviation, testing of normality, correlations and so on. But the results obtained from such analyses, although necessary for a general description of observations and variables, would not reveal very much of the underlying structure, at least not in this case. The approach to the solution of this problem is by multivariate analysis. There are many types of multivariate methods in statistics, and those relevant to this work will be reviewed in the next part of this section. The problem arises which methods are, at least in theory, feasible. Two main strategies exist: the "statistical zap" and the "statistical shotgun" (Brower & Veinius 1974). "The statistical zap" is an approach, advocated by Reyment (Blackith & Reyment 1971, Reyment 1972, 1974), in which one applies one single method to the data to determine one single structure. To investigate several types of structure, one uses several techniques. In the "shotgun"-technique on the other hand, a series of different methods are used to the data set, in trying to reveal all possible types of structure hidden therein. Both methods have their virtues. For the "zap", it is simplicity (hence low computer costs), while the "shotgun" has an assurance of finding even quite subtle structures in the data. In this investigation, with three main types of variables and three main areas with observations, something like "zapping with a shotgun" was found to be a way of revealing structures. It means that one uses several methods of analysis between and within each type of data; so the whole multivariate statistical investigation becomes a network of interlocking analyses between and within the units of data (Fig. 7). The strategy will be presented step by step later (p. 130).

General review of multivariate statistical methods used

In this review no univariate methods are presented, as they could be found in any statistical textbook. Except canonical correlation and procrustes rotation, the methods used are quite familiar to the common user of multivariate statistical analysis. In some cases complete programs have been used, but in most cases the calculations have been made using the GENSTAT language (Nelder et al. 1977). It gives the user, in a fairly convenient way, freedom to build his own program, or chain of programs to suit a special problem.

Multiple regression. — Although strictly a univariate method, multiple regression will be briefly summarized here, because so many multivariate techniques are based on, or used together with it. The problem is to find the best function of the form

$$Y = b_1 x_1 + \ldots + b_p x_p,$$

(where Y is a random variable dependent on the p variables $x_1 \ldots x_p$) to predict the mean value of y from the x's. This is done by least squares estimation, minimizing the residual sum of squares. This leads to a set of linear equations in the b's, the normal equations, of the form

$$\mathbf{Sb} = \mathbf{c},$$

where $\mathbf{S}$ is the matrix of sums of squares and products of the x's and $\mathbf{c}$ is the vector of sums of products of the x's and y's. For a more complete discussion of multiple regression see for example Morrison (1967) or Davis (1973).

Principal components analysis. — The principal components analysis (PCA) of a dispersion matrix is one of the most frequently used multivariate methods, and perhaps the most straightforward. Its aim is to condense a set of variables to a set of new variables, fewer in number and uncorrelated with each other. In doing so, one hopes to reveal meaningful results out of the new variables which otherwise were hidden in the "jungle of data". The method consists simply of calculating the latent roots and vectors of a dispersion matrix.

If $\mathbf{R}$ is the dispersion matrix, the mathematical problem consists in finding the vector $\mathbf{a}$, that maximizes the quadratic form $\mathbf{a}'\mathbf{R}\mathbf{a}$ subject to the constraint that $\mathbf{a}'\mathbf{I}\mathbf{a} = 1$. This implies finding a vector that satisfies $\mathbf{R}\mathbf{a} = \mathbf{l}\mathbf{a}$, where $|\mathbf{R} - l\mathbf{I}| = 0$, and l are the latent roots and $\mathbf{I}$ an identity matrix. The last equation has p roots, and to each corresponds a different vector. Since $\mathbf{R}$ is positive definite the roots are all positive, and when they are arranged in order, the largest root corresponds to the first principal component $\mathbf{a}'\mathbf{x}$, the second largest root corresponds to the second largest component and so on. Further, the variances of the principal components are equal to the corresponding values of l, the latent roots of the matrix $\mathbf{R}$.

The method of principal components has a simple geometrical interpretation. The equation $\mathbf{x}'\mathbf{R}^{-1}\mathbf{x} = K$ represents an ellipsoid in p dimensions. In fact, if the x's are variates with a multivariate normal distribution, these ellipsoids are the contours of equal probability density (centred on the common mean).

The calculations involved in finding the principal components are then precisely those necessary to find the principal axes of the ellipsoid, in order of length.

The original data matrix $\mathbf{X}$ can be standardized into a matrix $\mathbf{Z}$ and be premultiplied by the matrix of latent vectors $\mathbf{V}$ to get the roster of factor scores: $\mathbf{F} = \mathbf{Z}\mathbf{V}$. These scores may then be plotted to get a view of the mutual geometrical position of the observations (samples). For a more detailed description of PCA see among others: Cooley & Lohnes (1971), Marriott (1974), and Jöreskog et al. (1976).

Canonical variates analysis. — Canonical variates analysis (CVA) is used to discriminate between groups, especially when the number of groups exceeds two. The first step is to compute two different dispersion matrices: the within-groups sums of squares and products matrix $\mathbf{W}$, and the between-groups sums of squares and products matrix $\mathbf{B}$. The canonical variates are then found from the latent roots l and vectors of the determinantal equation $|\mathbf{B} - l\mathbf{W}| = 0$. The latent vectors corresponding to the equation are found from $(\mathbf{B} - l\mathbf{W})\mathbf{v} = 0$ and are the p-component vectors $\mathbf{v}$, and p is the number of variables in the groups. The latent vectors can be used to discriminate between groups, and by postmultiplying the matrix of the vectors $\mathbf{V}$ by the matrix of group means $\mathbf{M}$ the canonical variate means are obtained: $\mathbf{C} = \mathbf{M}\mathbf{V}$. The vectors can also be used to obtain the canonical variate scores: $\mathbf{F} = \mathbf{Z}\mathbf{V}$ where $\mathbf{Z}$ is the standardized data matrix. These scores, when plotted, can be used to allocate each observation to a group, and misclassified observations can thus be detected. For more detailed descriptions of CVA see: Reyment & Ramdén (1970), Blackith & Reyment (1971), and Marriott (1974).

Canonical correlations. — Canonical correlations analysis is related to CVA but instead of dealing with groups of observations canonical correlations deal with groups of variables. The method is, in fact, a generalization of multiple regression, such that the relationship between one set of variables $x_1 \ldots x_p$ and another $y_1 \ldots y_q$ is considered. Now, knowing the dispersion matrix of the complete set of $p+q$ variables, it is possible to calculate the correlation of any given linear combination of the x's with a linear combination of the y's. Of all the possible pairs of combinations, one has the maximum correlation. This correlation is called the first canonical correlation and the corresponding pair of linear combinations of the x's and the y's are called the first canonical variables. The second canonical correlation and variables are similarly defined by the pair of variables, uncorrelated with the first pair, that have maximum correlation, and so on until p pairs of canonical correlations and variables have been defined ($p \leqq q$).

Technically the calculations are quite complex, but briefly it begins with calculation of the total dispersion matrix of the $p+q$ variables: $\mathbf{R}$. This is partitioned into four blocks, thus

$$\mathbf{R} = \begin{pmatrix} \mathbf{R}_{11} & \mathbf{R}_{12} \\ \mathbf{R}'_{12} & \mathbf{R}_{22} \end{pmatrix}.$$

The submatrices $\mathbf{R}_{11}$ and $\mathbf{R}_{22}$ refer to the sets of x's and y's respectively, while submatrices $\mathbf{R}'_{12}$ and $\mathbf{R}_{12}$ represent the interaction of all the variables of the two sets. If $\mathbf{a}'\mathbf{x}$ and $\mathbf{b}'\mathbf{y}$ are two linear functions of the x's and y's respectively their correlations are $\mathbf{a}'\mathbf{R}_{11}\mathbf{a}$, $\mathbf{b}'\mathbf{R}_{22}\mathbf{b}$, and $\mathbf{a}'\mathbf{R}'_{12}\mathbf{b}$. Then it is required to maximize $\mathbf{a}'\mathbf{R}'_{12}\,\mathbf{b}$ subject to $\mathbf{a}'\mathbf{R}_{11}\mathbf{a} = \mathbf{b}'\mathbf{R}_{22}\mathbf{b} = 1$. This leads to the determinantal equation:

$$|\mathbf{R}'_{12}\mathbf{R}_{11}^{-1}\mathbf{R}_{12}\mathbf{R}_{22}^{-1} - l\mathbf{I}| = 0.$$

Here $\mathbf{I}$ is an identity matrix, and l is the undetermined multiplier in the maximization, and is the square of the correlation between the two sets.

To each canonical correlation there are two sets of corresponding coefficients, and these are found by solving the simultaneous equations:

$$\mathbf{R}'_{12}\mathbf{R}^{-1}_{22}\mathbf{a}'\mathbf{R}'_{12} - l^2\mathbf{a}'\mathbf{R}_{11} = 0,$$
$$\mathbf{R}'_{12}\mathbf{b}\mathbf{R}^{-1}_{11}\mathbf{R}'_{12} - l^2\mathbf{R}_{22}\mathbf{b} = 0.$$

The two sets of coefficients may each be premultiplied by the standardized data matrix and plotted against each other.

Then a correlation coefficient of 1,00 will show all observations on a diagonal line and one of 0,00 will show them scattered all over. For more information about canonical correlation see: Blackith & Reyment (1971), Cooley & Lohnes (1972), and Marriott (1974).

Procrustes rotation. — Procrustes rotation deals, like canonical correlation, with two different sets of variables of the same observations, but the technique is entirely different. — Suppose there are n observations and p, respective q, variables in the two sets. The sets have then been analysed by some multivariate method, i.e. PCP, CVA, etc. The resulting matrices of scores then give for the first set the coordinates of points $P_i(i = 1 \ldots n)$, and for the second set $Q_i(i = 1 \ldots n)$. The first matrix is called $\mathbf{X}$, and the second $\mathbf{Y}$, and the configuration corresponding to $\mathbf{Y}$ is translated, orthogonally rotated (including reflections), and isotropically stretched until $M^2_{pq} = (P_iQ_i)^2$ is minimized, where M^2_{pq} is the residual sum of squares. The correct translation is merely to move $\mathbf{Y}$ until its centroid coincides with the centroid of $\mathbf{X}$. After translation, the next step is to find the rotation and reflection; this is a function of the singular value decomposition of $\mathbf{Y'X}$. Stretching and contraction may, or may not, be needed.

With least-squares scaling, analysis of variance relates the values of $\mathbf{X}$ and fitted $\mathbf{Y}$, thus:

$$\text{Trace }(\mathbf{X'X}) = \text{Trace }(\mathbf{Y'Y}) + M^2_{pq} \cdot$$

The recidual sum of squares, or criterion value, M^2_{pq} gives a measure of the lack of fit for the rotation, and the lack of fit for each observation can also be obtained from it. The plot of the rotated $\mathbf{Y}$-coordinates gives a synthesis of the two sets of variates.

Very little is published yet about procrustes rotation but Gower (1971) and Banfield & Harries (1975) are worth mentioning.

Description of data

Introduction

As mentioned earlier, the data consist of three groups of variables: size-data, including total weight of heavy fraction; heavy mineral "volume percentage" (except for magnetite where weight percentage was used); and trace-element content of magnetite expressed in ppm. The total number of observations is 86, and of variables it is 29, so there are totally 2 494 pieces of information.

Accuracy of data. — There is little to say about the accuracy of the size data, since the methods are so simple and more or less "foolproof" if only common sense is respected during the laboratory work. The data obtained from the microscope, on the other hand, can easily contain quite large errors as they are completely dependent on the human factor and thus influenced to some extent by subjectivity. Therefore, it is important that the same person carries out the analysis. The number of grains counted was about 300, which number is usually used for general purpose investigations of this type. Below 300, the probable error increases rapidly, whereas above 300 it decreases slowly (Dryden 1931, Carver 1971). However, data of rare minerals (or extremely abundant) are less accurate, and for instance, a mineral with the abundance of 1,0 % has a probable error of 0,39 % at the 50 % confidence level. To get down to a probable error of 0,1 % about 500—600 grains have to be counted. In this investigation the lowest abundance recorded is 0,3 % which gives a probable error of 0,21 %, a seemingly worthless piece of data. One has to count about 1 500 grains to get a probable error of 0,1 %, and over 5 000 grains to reach a probable error of 0,05 %. A check was made by deleting those minerals with many values around and under 1,0 %, but it altered the results of the multivariate statistical analyses very little, so all variables were used, but not too much attention should be payed to the loadings of the variables with many small values. Also the tenths of per cent which were constantly recorded could well have been deleted, but their influence is also negligible. The values of magnetite content are also quite accurate for the same reason at those of the size data. Trace-element values obtained by atomic-adsorption spectrometry, as mentioned earlier, also seemed to be satisfactory and, by far, much more accurate than data obtained from emission spectroscopy. Of course, there may be some hidden faults, but several samples were

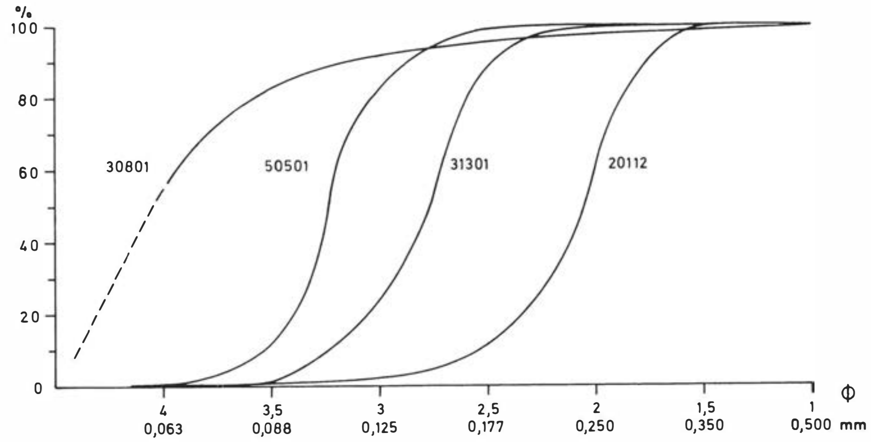


Fig. 6. Grain-size distribution of some of the samples.

run twice in the A. A. spectrometer and the results were more or less in agreement with each other.

Size data

The size data, which comprise seven size classes and the total heavy mineral content, do not show any areal trends, and hence only represent the energy-level of the beach, and, of course, it is also dependent on the parent material to some extent. See Fig. 6 for some size curves, and Table I for basic statistics of size data.

Table I. Basic statistics of size data.

Variable	Mean (%)	Standard deviation (%)	Maximum (%)	Minimum (%)
1,0—1,5 Φ	1,20	2,66	12,36	0,00
1,5—2,0 Φ	8,58	10,70	39,34	0,00
2,0—2,5 Φ	20,67	16,14	63,85	0,78
2,5—3,0 Φ	35,63	14,74	65,43	3,47
3,0—3,5 Φ	25,32	17,84	71,17	0,24
3,5—4,0 Φ	7,08	7,80	32,08	0,02
> 4,0 Φ	1,87	5,95	54,47	0,00
Amount of heavy minerals (%)	66,90	22,01	98,50	13,90

Heavy mineral data and description of the various minerals

As mentioned earlier the heavy minerals, except magnetite, are recorded in a sort of volume percentage, which in this investigation was considered to be sufficiently accurate. The heavy minerals, on the contrary to the size data, show marked areal trends, even if they are considerably masked by the physical factor, i.e. the hydraulic or "energy" influence. How attempts were made to eliminate this factor will be discussed in the next chapter. A brief description of the various minerals follows, in alphabetical order. Basic statistics is found in Table II.

Table II. Basic statistics of heavy mineral data.

Variable	Mean (%)	Standard deviation (%)	Maximum (%)	Minimum (%)
Opaques	33,50	13,35	75,00	11,80
Amphiboles	17,11	8,99	35,40	0,70
Garnet	25,16	11,49	62,60	2,80
Epidote	5,43	4,02	21,00	0,60
Diopside	1,28	1,49	8,40	0,00
Enstatite-Hypersthene	3,83	2,74	12,40	0,00
Kyanite	1,40	1,45	6,50	0,00
Brookite-Rutile	3,27	2,23	9,10	0,00
Apatite	0,91	0,95	4,00	0,00
Zircon	0,58	0,73	3,40	0,00
Monazite	6,77	4,14	17,70	0,70
Zoisite	0,71	0,81	3,30	0,00
Magnetite	35,90	21,01	74,50	1,60

Amphiboles. — The amphiboles consist mainly of hornblende and, adjacent to schistose areas, of members of the tremolite-actinolite series. Other amphiboles may also be present, but in very small concentrations. Since it is fairly difficult to distinguish between green hornblende and actinolite, all amphiboles were recorded together. The hornblendes are usually of the green variety even if brown hornblende was observed. Hornblende has a density of 3—3,5, depending on the iron content, and a hardness of 5—6. It is fairly brittle but still survives mechanical transport surprisingly well. The grains are usually elongated and subangular, and sometimes they are also indented. Hornblende occurs in all magmatic rocks and in amphibolites and some gneisses. It is rare in sedimentary rocks as it is easily altered chemically. The minerals of the tremolite-actinolite series are very similar to hornblende, except that tremolite is much paler in colour and they are more fibrous than hornblende. Probably, the minerals of the latter series do not survive transport as well as hornblende, depending on their more fibrous nature. Tremolite-actinolite occur mainly in metamorphic schists and serpentinites, so it is unfortunate that they are so alike hornblende when their provenance is so different.

Apatite. — Apatite is a rather rare mineral in the placers, never more than 4 % of the non-magnetic fraction, depending on its brittleness. It has a density of 3,1—3,55 and a hardness of 4,5—5. It usually has the form of elongated prisms or tabular crystals, and the colour is mostly milk-white. Apatite occurs in many igneous rocks, for example granites, pegmatites, gabbros, and carbonatites. It may als occur in some gneisses.

Brookite and rutile. — These minerals were recorded together for practical reasons, because they are much alike under the microscope, their chemical composition is the same and their provenance agrees to a great extent. Their densities vary between 3,9 and 4,2, and 4,2 and 5,5 for brookite and rutile, respectively. The values of hardness are 5,5—6,0 for brookite and 6,0—6,5 for rutile. The colour of brookite varies from amber-yellow to maroon and the grains usually occur as tablets. Rutile is usually brownish- to yellowish-red, and the grains are usually prismatic but can sometimes be completely rounded. Both minerals are rather resistant to mechanical abrasion, which makes them quite common in the sediments (up to 9,0 % of the non-magnetic fraction). Brookite occurs as vein-deposits formed from leaching of gneisses, or schists, by hydrothermal solutions. It may also occur as an accessory mineral in certain igneous rocks. Rutile is mostly a product of regional metamorphism and it is also widespread too as an accessory mineral in igneous rocks.

Diopside. — Diopside is not as frequent in the placers as one would suppose (under 8,4 % of the non-magnetic fraction). It is a pyroxene with a density of 3,5 to 3,6 and a hardness of 5—6, and it is rather brittle. The grains are usually rounded, occasional angular grains are encountered, and they are colourless to green. The provenance is mostly from gneisses and mica-schists, but it can also occur in peridotites and kimberlites.

Enstatite and hypersthene. — These pyroxenes are grouped together as they form a continuous series, and are rather alike under the microscope, and have the same provenance. Their densities vary between 3,3 and 3,7 and the hardness is 5,0—6,0. Enstatite is usually colourless to brownish, while hypersthene always has shades of brown. The grains are usually prismatic, but may be rounded with the cleavage still clearly visible, and they are fairly resistant to transportation. They occur in gabbros, andesites, dacites, and also in high-grade metamorphic rocks.

Epidote. — Epidote is a fairly common mineral in the placers of Norrbotten; it occurs in all samples and the maximum value is 21 % of the non-magnetic fraction. It has a density of 3,4—3,5, a hardness of 6, and it is resistant to mechanical abrasion, almost as resistant as garnet. The grains are usually irregular, elongated and angular to subangular. The colour varies from yellowish-green over pistachio-green to brownish-green. It is a typical mineral of low- and medium-metamorphic rocks, and of skarns.

Garnet. — Garnet is well represented in the placers of Norrbotten with amounts of up to 63 % by volume of the non-magnetic fraction. Most of the garnets, if not virtually all, are more or less pure almandine, although it can be very difficult to distinguish between different garnets under the microscope. Almandine has a density of 4,1 to 4,3, hardness of 7, and is resistant to mechanical abrasion. The grains are usually equidimensional, more or less rounded and colourless to pink. Almandine usually originates from schists and gneisses, but is also reported in some granodiorites, rhyolites and pegmatites.

Kyanite. — Kyanite is not so common in the sediments as one would expect, possibly due to its brittleness. The mineral has a density of 3,6—3,7 and a variable hardness; on the (100) face it is 4—5 and on the (010) face it is 7. The grains usually consist of elongated tablets, seldom terminated, but sometimes the crystals may be bent. They are mostly bluish but can also be colourless, pale green or greyish. Kyanite is the product of medium-grade regional metamorphism of aluminium-rich rocks, and it occurs in schists and gneisses.

Magnetite. — Magnetite is one of the most common species in the sediments, and it can occur in amounts reaching 75 % of the heavy fraction. It has a density of 5,2 and a hardness of 5,5—6. The grains are usually equidimensional and angular, but in some cases they can be extremely well rounded, and the colour is black. Magnetite is an opaque mineral, rather difficult to recognize even in polished sections under the microscope, but easily detected even with a weak magnet. Magnetite occurs in a great number of rocks, as a minor accessory mineral in igneous rocks, as magmatic segregation deposits, in contact-metamorphic deposits and also in schists and gneisses. Titanium-rich magnetite, titano-magnetite, is derived from basic and ultra-basic rocks.

Monazite. — Monazite is common in the placers of Norrbotten. It occurs in all samples, and the maximum value recorded is nearly 18 % of the non-magnetic fraction. It has a density of 5—5,3 and a hardness of 5, but it is brittle. The colour is usually pale yellow, but the grains can also be almost colourless or brownish yellow. They are usually well rounded but grains with its crystal shape visible exist. Although monazite has a high density it behaves, strangely enough, like minerals with much lower density in a hydraulic sense. The mineral is usually "over-represented" on low-energy beaches and "under-represented" on high-energy beaches. This might be explained by the mineral being brittle and not surviving in a high-energy environment. Monazite occurs as a minor accessory mineral in intermediate and high-grade metamorphic rocks derived from argillaceous sediments. It is less abundant in metamorphic rocks formed from arenaceous sediments. It is especially common in pelitic schists, gneisses, and migmatites of upper subfacies of the amphibolite facies and in the granulite facies. It may occur in magmatic rocks ranging in composition from diorite to muscovite granite and also in associated pegmatites, greisen and vein quartz; it is also abundant in many carbonatites (Overstreet 1967).

Opaque minerals. — Opaque minerals, other than magnetite, form a considerable part of the Norrbotten placers, with values up to 75 % of the non-magnetic fraction. By studying a couple of polished sections, it was found that almost all the grains consisted of ilmenite except for some which were hematite or pyrite. Ilmenite has a density of 4,4—4,8, a hardness of 5,6 and it can survive long streches of transport. The grains are usually tabular, sometimes rounded and black in colour. Ilmenite principally occurs in gabbros, diorites, peridotites, and syenites. It is also found as an accessory mineral in other igneous rocks, gneisses, garnet-rich amphibolites and other crystalline schists.

Zircon. — This mineral is not so common in the placers of Norrbotten as in many other placers around the world, and the maximum value is just over 3 % by volume of the non-magnetic fraction. Zircon has a density of 4,6—4,7, hardness of 7,5 and it is fairly resistant to mechanical action. The grains usually consist of very characteristic elongated prisms, which are colourless or greyish. The origin of zircon is usually from acid igneous rocks and their pegmatites, but it may also occur in some metamorphic rocks.

Zoisite. — Zoisite is akin to epidote in many respects, and should perhaps have been recorded together with that mineral. It is also much less common than epidote in the sediments of Norrbotten. It has a density of about 3,3, hardness of 6, and it is rather brittle. The grains consist of short prisms, more or less rounded, and the colour is usually grey but can also be yellowish or greenish. Zoisite has the same provenance as epidote, i.e. low- and medium-grade metamorphic rocks, and skarns.

Among other heavy minerals present but not recorded the following may be noted: andalusite, sillimanite, sphene, and tourmaline. It was found that sphene was fairly common in some areas, and it might have been better to record it instead of zoisite.

The values of density and hardness in the description of the different minerals were taken from Parfenoff et al. (1973).

Trace-element data in magnetite

The entry of trace-elements into a mineral is governed by several factors of which the temperature and pressure, the physical properties of the elements, and the chemical environment are important. Reviews of the theories of the laws governing the entry of trace-elements into minerals are given, among others, by Shaw (1964) and Taylor (1965). Magnetite as a member of the spinel group, is composed of 8 atoms of divalent four-coordinated iron, 16 atoms of trivalent six-coordinated iron, and 32 atoms of oxygen per unit cell (Palache et al. 1952). To allow diadochic substitution, an element must have a size, at the valence and coordination state, similar to that of the element to be replaced. Rankama & Sahama (1950) put an approximate size limitation on diadochic substitution of ±15 % of the size of the element being replaced. A brief description of the elements analysed, in alphabetical order, follows. See Table III for a summary of basic statistics.

Table III. Basic statistics of trace-element data from magnetite.

Variable	Mean (ppm)	Standard deviation (ppm)	Maximum (ppm)	Minimum (ppm)
Cobalt	51	18	99	0
Nickel	64	31	153	0
Copper	23	15	93	0
Chromium	461	137	846	262
Zinc	134	48	358	41
Manganese	1209	389	2509	619
Vanadium	1106	239	1810	663
Titanium	5458	3039	16620	1560

Chromium. — Chromium has a maximum value of 846 ppm and a mean value of 460 ppm in the placer magnetites of Norrbotten. According to Frietsch (1970) the chromium content in magnetites from basic magmatic rocks in northern Sweden can reach values of 2000 ppm, with a mean value of 690 ppm for these rocks. In syenite-porphyries of northern Sweden the values are 800 ppm and 230 ppm, respectively. Cr^{3+} has an ionic radius (0,63 Å) very similar to that of Fe^{3+} and associates, therefore, with ferric iron. Cr^{3+} has, however, a low electronegativity value, and a high relative total bonding energy value, and will, consequently, in a crystal lattice, be preferentially incorporated to Fe^{3+}. According to Frietsch (ibid.), the magnetite in the early magmatic differentiates in Norrbotten is relatively rich in chromium relative to other rocks.

Cobalt. — Cobalt is one of the sparser trace-elements in the placer magnetites. It has a maximum value of 99 ppm and a mean value of 51 ppm. In the basic magmatic rocks of northern Sweden Frietsch (ibid.) reports a maximum content of 420 ppm and a mean content of 200 ppm Con in the magnetites. In the syenite-porphyries the values are 100 and 60 ppm, respectively. Co^{2+} is intermediate in size (0,72 Å) between Fe^{2+} (0,75 Å) and Mg^{2+} (0,66 Å), and replaces these elements in a crystal lattice. The cobalt content of the upper lithosphere is, according to Shaw (1964), 27 ppm, thus in all placer magnetites, except one, there has been a considerable enrichment of cobalt in the magnetite.

Copper. — Copper is the rarest of the trace-elements investigated, with a maximum value of 93 ppm and a mean of only 23 ppm. Frietsch (ibid.) reports constantly higher values; a maximum of 140 ppm and a mean of 60 ppm for the basic magmatic rocks, and 80 and 40 ppm, respectively, for the syenite porphyries. Cu^{2+} is in size (0,72 Å) similar to Fe^{2+} and should enter the magnetite lattice, but Cu^{2+} has higher values for electronegativity and ionization potential than Fe^{2+}, meaning that the Fe-O bond is more ionic than the Cu-O bond. Copper is depleted in most of the analysed magnetites, as the copper content of the upper litosphere is 70 ppm (Shaw ibid.).

Manganese. — Manganese belongs to the more abundant trace-elements in the magnetites of the placers, with a maximum value exceeding 2500 ppm and a mean of 1209 ppm. In the basic magmatic rocks of northern Sweden the maximum lies at 2000 ppm and the mean at 500 ppm; the values for the syenite-porphyries are 800 and 200 ppm, respectively. However, there are stratified iron ores in northern Sweden with a maximum value of 7200 ppm and the iron ores at Kittilä in northern Finland contain up to 2700 ppm manganese (Frietsch ibid.). The manganese values, in this investigation, are generally lower in the Kalix River samples, than in the other.

Mn^{2+} which has a somewhat larger ionic radius than Fe^{2+} is known to substitute this ion in magnetite. The relative total bonding energy for Mn^{2+} and Fe^{2+} is almost equal, pointing to a similarity between these ions, but Mn^{2+} has, compared to Fe^{2+}, lower values for electronegativity and ionization potential, and the Mn-O bond is thus more ionic than the Fe-O bond. The manganese content in the upper lithosphere is about 1000 ppm (Shaw ibid.), so the values for the placer-magnetites are usually near or somewhat above this value.

Nickel. — Nickel is slightly more abundant than cobalt in the magnetites from the placers in Norrbotten, with a maximum value of 153 ppm and a mean of 64 ppm. The values reported by Frietsch (ibid.) are usually higher; so, for example the basic magmatic rocks contain up to 420 ppm nickel with a mean of 180 ppm and the syenite-porphyries have the values of 160 and 90 ppm, respectively. The nickel-content of the upper lithosphere is about 80 ppm (Shaw ibid.) which lies close to the values obtained in this investigation. Nickel behaves similarly to cobalt in combination with magnetite, but it has a slightly smaller ionic radius (0,69 Å) compared to cobalt (0,72 Å). The magnetites of basic intrusives are generally richer in nickel than those of acid or intermediate intrusives. It should also be mentioned that the nickel values from Norrbotten, both placers and rocks, show lower figures than those obtained from magnetites of comparable rocks in other parts of the world.

Titanium. — Titanium is the most abundant of the trace-elements investigated; in fact, it should perhaps be termed a minor element, with a maximum of 16620 ppm and a mean of 5458 ppm in the placer-magnetites. Frietsch (ibid.) reports values, from the basic magmatic rocks, with a maximum of 27000 ppm and a mean of 8600 ppm, while the values of the syenite-porphyries are 9000 and 3900 ppm, respectively. Ti^{4+} is intermediate in size (0,68 Å) between Fe^{3+} and Fe^{2+}. Ti^{4+} has the same electronegativity value as Fe^{2+} but lower than that for Fe^{3+}. Ti^{4+} has a lower ionization potential value and a higher value of the relative total bonding energy than Fe^{2+} and Fe^{3+}. The magnetite found in basic and ultrabasic intrusives is always comparatively rich in titanium. The titanium content in the magnetites from the placers may also be dependent upon ilmenite-lamellae in the magnetite grains, but such could not be detected with an electron microprobe or with a microscope; they may, however, be very thin and thus not detected (Lindh 1972). The titanium content of the upper lithosphere is about 10000 ppm (Shaw ibid.), so it seems to be slightly depleted in magnetite.

Vanadium. — The vanadium content of the placer-magnetites has a maximum value of 1810 ppm and a mean of 1106 ppm. According to Frietsch (ibid.), the vanadium abundance has a maximum value of 4000 ppm and a mean of 1850 ppm in the basic magmatic rocks; the corresponding values for the syenite-porphyries are 1250 and 1000 ppm, respectively. The content of vanadium in the upper lithosphere is about 100 ppm (Shaw ibid.), so vanadium always seems to be enriched in the magnetites investigated. Vanadium, mostly occurring as V^{3+}, has almost the same ionic radius (0,74 Å) as Fe^{2+} but is larger than Fe^{3+} and is consequently captured in Fe^{2+} positions while it enters late Fe^{3+} positions. V^{3+} has a lower value of electronegativity and ionization potential, and a higher relative total bonding energy than Fe^{3+}.

Zinc. — This element occurs in amounts of up to 358 ppm, with a mean of 134 ppm, in the placer-magnetites. In comparison, Frietsch (ibid.) reports a maximum of 800 ppm and a mean of 260 ppm in the magnetites from the basic magmatic rocks; the values of the syenite-porphyries are 100 and 60 ppm, respectively. In the upper lithosphere the zinc content is about 40 ppm, according to Shaw (ibid.), so it seems that zinc is enriched in most magnetites. Zn^{2+} being of the same size (0,74 Å) as Fe^{2+} should substitute this ion in a crystal lattice. The lower value for the ionization potential, and the somewhat higher value of the relative total bonding energy for Fe^{2+} indicates that this element forms more ionic bonds than zinc.

Most of the above elements show some areal trends in the placer-magnetite samples. Most of the above information about magnetite was gathered from Frietsch (ibid.) and some also from Fleischer (1965) and Theobald et al. (1967).

Evaluation of the data

Introduction

In an investigation like this, all the statistical methods described earlier can be used in several combinations so that they will finally build up a network of combinations as in Fig. 7. Of course, as will be seen later, some methods, or combinations of methods, will give more meaningful results than other.

A principal problem in this study is that the various mineral species have differences in density, shape, resistance to transport and so on. This causes some minerals to be overrepresented and others to be depleted. To get any meaningful results out of the heavy mineral data, one has to find either some concomitant variables outside the set of ordinary variables, or to find some hidden variables inside the set of data. In the first case, the concomitant variables should be variables representing the same physical properties as mentioned above, and these should be highly correlated with the original variables. In the second case, the latent vectors are taken and analysed for vectors whose scores could serve as concomitant variables. The matrix of $(n \times k)$ vectors of concomitant variables is hereafter called $\mathbf{K}$, where n is the number of samples or observations, and k is the number of concomitant variables. In the first case, with the "external" set of concomitant variables, multiple regression (in the case of only one additional variable), or canonical correlation is used. The second case, with an "internal" set of concomitant variables, is much the same as that which occurs in biological sciences where the first latent vector often reflects differences in growth or age (cf. Burnaby 1966; Jolicoeur 1963; Reyment & Banfield 1976).

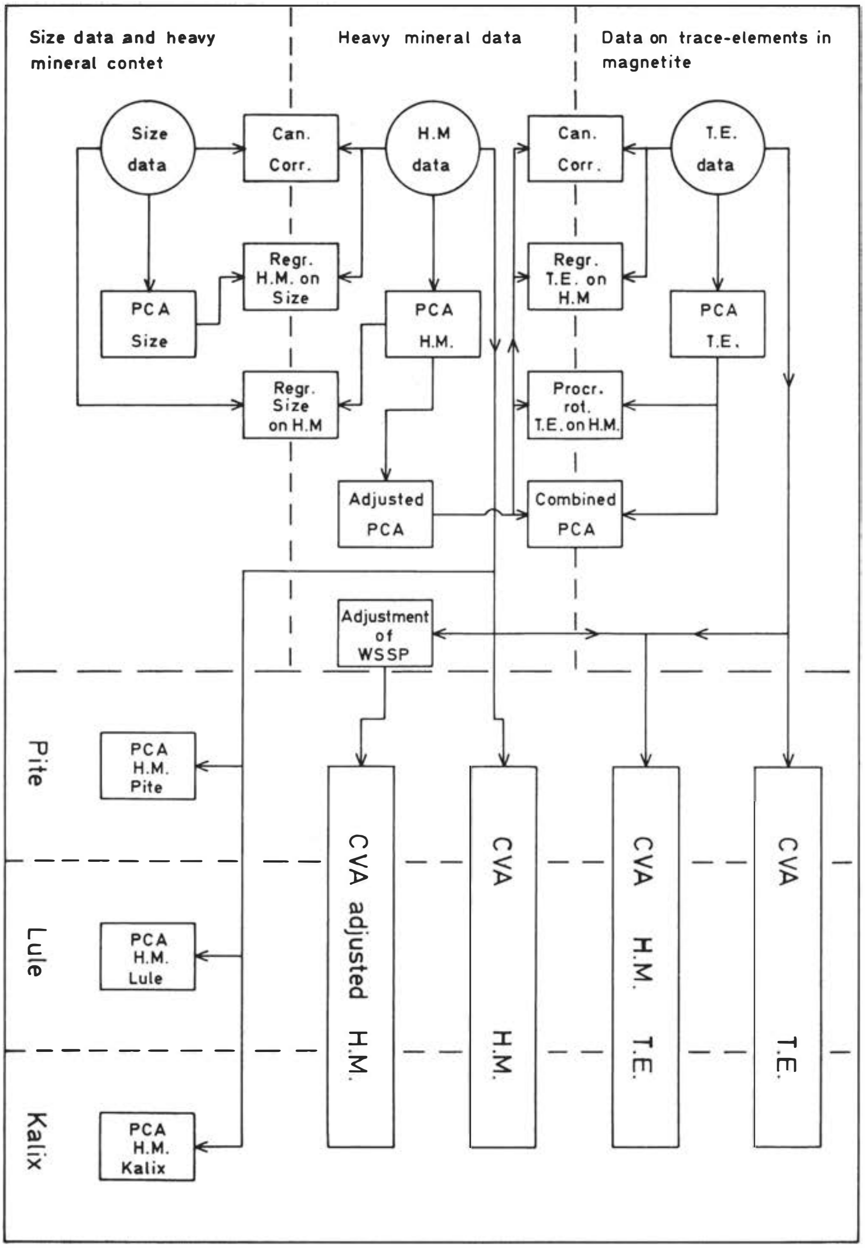


Fig. 7. Diagram showing some possible combinations of multivariate statistical methods. PCA = principal components analysis, CVA = canonical variates analysis, WSSP = the within sums of squares and products matrix.

Results of principal components analysis

A natural starting-point for an investigation of this nature is to accomplish a principal components analysis on each of the three types of variables. To obtain a distribution as normal as possible, the variables were transformed thus: the size-groups and the mineral species with a mean under 5 % were transformed by the square-root transformation; those with a mean above 5 % were given an angular transformation:

$\arcsin \sqrt{\frac{x}{100}}$.

The trace-element data were logarithmically transformed, as it is well known that the abundance of the elements is usually logarithmically distributed (Ahrens 1954).

As the size and heavy mineral data are expressed as percentages, the data form a closed system, which gives too high values of correlation or covariance. The well known example is when there are only two variables, which of course must be completely negatively correlated. Chayes (1960, 1970), Chayes & Kruskal (1966), Darroch (1969), and Zodrow (1976) suggest methods to overcome this problem, but the methods are tedious and rely on various approximations and assumptions. To see whether the dispersion matrices in this work were severely distorted by the closure, some variables were simply deleted to obtain an open system. It was found that the closure of the data rarely changed the dispersion matrices, and the transformation of the data also "opened up" the systems to some extent. The data, therefore, were used as they were, after transformations, and dispersion matrices were calculated, from which the latent vectors and roots were drawn, and the matrix of latent vectors, **V**, was then scrutinized in hope of finding some structure in it. Also, the factor scores were calculated to obtain the relationship among the samples.

Table IV. Principal components analysis of size data.

Latent roots:	3,13	1,77	1,22	0,74	0,59	0,28	0,22	0,05
% of variance:	39,06	22,06	15,27	9,29	7,41	3,47	2,76	0,67
Latent vectors:	I	II	III	IV	V	VI	VII	VIII
Variable:								
1,0—1,5 Φ	—0,12	—0,27	—0,75	—0,20	0,31	0,47	—0,04	0,05
1,5—2,0 Φ	—0,50	—0,16	—0,05	0,19	0,17	—0,41	—0,55	0,43
2,0—2,5 Φ	—0,51	0,05	0,13	0,07	—0,31	0,34	0,51	0,49
2,5—3,0 Φ	0,10	0,59	0,05	—0,67	0,05	0,06	—0,24	0,36
3,0—3,5 Φ	0,50	0,01	—0,13	0,25	0,41	—0,26	0,38	0,55
3,5—4,0 Φ	0,38	—0,36	0,37	0,12	—0,10	0,54	—0,42	0,31
$> 4{,}0$ Φ	0,16	—0,56	—0,12	—0,50	—0,47	—0,38	0,12	0,16
Amount of heavy minerals (%)	0,22	0,34	—0,50	0,38	—0,62	—0,01	—0,21	0,11

Principal components analysis of size data. — The principal components or latent vectors are presented in Table IV. The first component gives a "sinusoidal impression" with low significant values among two of the coarser fractions and high significant values among two of the finer fractions. The heavy mineral content does not seem to have much influence on this component. This component attempts to divide the samples in a coarser- and a finer-grained part. Its dependence on the hydraulic energy in the environment of deposition is doubtful. It rather suggests differences in the nature of the parent material in different parts of the area. The second component is highly loaded in the medium-sized class with low loadings in the finest classes. Also the total amount of heavy minerals shows some influence here. The component suggests an influence of skewness.

The third component shows numerically high values for the coarsest size class and the total amount of heavy minerals, and this might imply some dependence on hydraulic energy. By examining the correlation coefficients between this component and different mineral abundances, it is found that two of the densest minerals, opaques and magnetite, have the highest negative correlation, −0,45 and −0,42, respectively. The highest positive correlations fall on two of the less dense minerals, amphiboles and epidote, with values of 0,44 and 0,45, respectively. It is thus clear that the component is to a great extent dependent on energy, even if it contains more information, which is not obvious or makes any geological sense. The components of higher order are difficult to interpret and probably contain noise to a great extent. The factor scores of the samples do not show any special areal trends and are largely without significance for this work.

Principal components analysis of heavy mineral data. — The principal components are presented in Table V. The first component with a third of the total variance in the system, shows usually high positive values for the denser minerals and high negative values for the lighter ones. This immediately suggests a dependence on density. However, there is one notable exception, namely monazite, which is one of the densest minerals, but shows a rather high negative value. This implies that the first component is not entirely dependent on density, and, if one wishes to adhere to the assumption that this component is the component dependent on physical factors, other physical criteria than density must also be con-

Table V. Principal components analysis of heavy mineral data.

Latent roots:	4,34	1,41	1,32	1,08	1,00	0,79	0,75	0,64	0,50	0,49	0,35	0,30	0,03
% of variance:	33,42	10,81	10,13	8,31	7,68	6,09	5,76	4,90	3,83	3,78	2,72	2,33	0,25
Latent vectors:	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
Variable													
Opaques	0,39	—0,29	—0,20	—0,06	—0,19	—0,08	—0,21	—0,22	0,14	0,01	—0,32	—0,20	—0,65
Amphiboles	—0,40	—0,08	—0,08	—0,06	0,06	0,03	0,29	—0,27	0,13	—0,32	0,11	0,60	—0,41
Garnet	0,27	0,51	0,32	0,12	0,09	—0,02	0,10	0,40	—0,15	0,05	0,24	0,07	—0,53
Epidote	—0,35	—0,04	0,19	—0,11	0,13	0,43	0,25	—0,10	0,36	0,29	0,17	—0,52	—0,21
Diopside	—0,28	0,15	—0,04	—0,14	—0,32	0,36	—0,58	0,25	0,03	—0,47	0,09	—0,10	—0,07
Enstatite-Hypersthene	—0,32	0,01	—0,13	—0,29	—0,34	—0,00	—0,13	0,15	—0,29	0,68	—0,09	0,26	—0,12
Kyanite	—0,25	—0,18	—0,25	0,44	0,05	—0,47	—0,24	0,26	0,32	0,14	0,40	—0,07	—0,10
Brookite-Rutile	—0,11	—0,04	—0,14	—0,54	0,70	—0,21	—0,17	0,25	—0,05	—0,07	—0,15	—0,07	—0,08
Apatite	—0,16	—0,34	0,45	—0,15	—0,33	—0,32	0,31	0,44	0,11	—0,20	—0,28	—0,09	—0,00
Zircon	0,04	—0,52	0,27	0,37	0,31	0,44	—0,22	0,21	—0,16	0,11	—0,14	0,26	—0,05
Monazite	—0,33	—0,02	—0,25	0,31	0,04	—0,04	0,23	—0,02	—0,67	—0,19	—0,13	—0,39	—0,17
Zoisite	—0,17	—0,03	0,60	—0,06	0,05	—0,33	—0,38	—0,50	—0,24	0,02	0,18	—0,08	—0,06
Magnetite	0.28	—0,45	—0,10	—0,34	—0,11	0,07	0,14	0,07	—0,29	—0,08	0,68	—0,06	0,01

sidered. Other criteria mentioned earlier are brittleness and shape. However, in the case of monazite the shape can not be the erratic factor. Freise (1931) calculated the durability of monazite ("Transportwiderstand"), together with several other heavy minerals, and found out that its value was very low. This means that monazite tends to survive more easily in low-energy environments than in high-energy ones. The first component, in fact, suggests that monazite is more dependent on durability than density in its sedimentological behaviour. If the natural logarithm of the durability of the different minerals is taken and multiplied by their density, a plot can be made of the values against the first component which shows a swarm with a fairly good correlation (Fig. 8). Hence the first component might be used as a concomitant variable for "internal" estimation of the "geological factors", i.e. sorting out the physical factor. We can also conclude that about one third of the variation is dependent on physical factors. The second component, with almost 12 % of the total variation, shows a high positive value for garnet and high negative values for zircon, apatite and magnetite. The component seems to divide between metamorphic and igneous parent rocks in general. Any further conclusions are difficult to draw.

The third component, with almost 10 % of the total variation, shows three marked negative values, namely zoisite, garnet, and apatite. The component might reflect the grade of regional metamorphism in the source area. The fourth component, with almost 9 % of the total variation, shows marked high positive figures for kyanite and monazite, and a high negative value for brookite and rutile. It is very difficult to interpret as also the rest of the components seem to be.

The value of the whole analysis in this state is not particularly great, so some adjustments have to be made as will be seen later on.

Comments on regional PCA of heavy mineral data. — Principal components analyses were carried out on the three different areas based upon the correlation matrices for the three areas. The matrices agreed to a great extent even if discrepancies occur, as was also the fact with the loadings. So, for instance, the first heavy mineral component among the Pite samples (the "physical" component) is distorted because of a general lack of opaques and magnetite.

Regional principal components analysis of trace-elements in magnetite. — In the case of trace-element data of magnetite, the dispersion matrices varied considerably. But to understand the results of the PCA of all areas together better it is advisable to first consider each area separately. The till samples are also included and are considered as a separate area. The different PC loadings can be found in Tables VI—IX. Not only are the first few latent vectors of interest here but also the vector representing the smallest latent root, i.e. the root with the smallest possible variance (Jöreskog et al. 1976). This vector represents the linear equation whose values, when multiplied with the original data, should yield scores as near zero as possible. The deviations from zero could be regarded as residuals which represent lack of fit of the equation. The loadings of the last vector represent a constant state which lies outside the

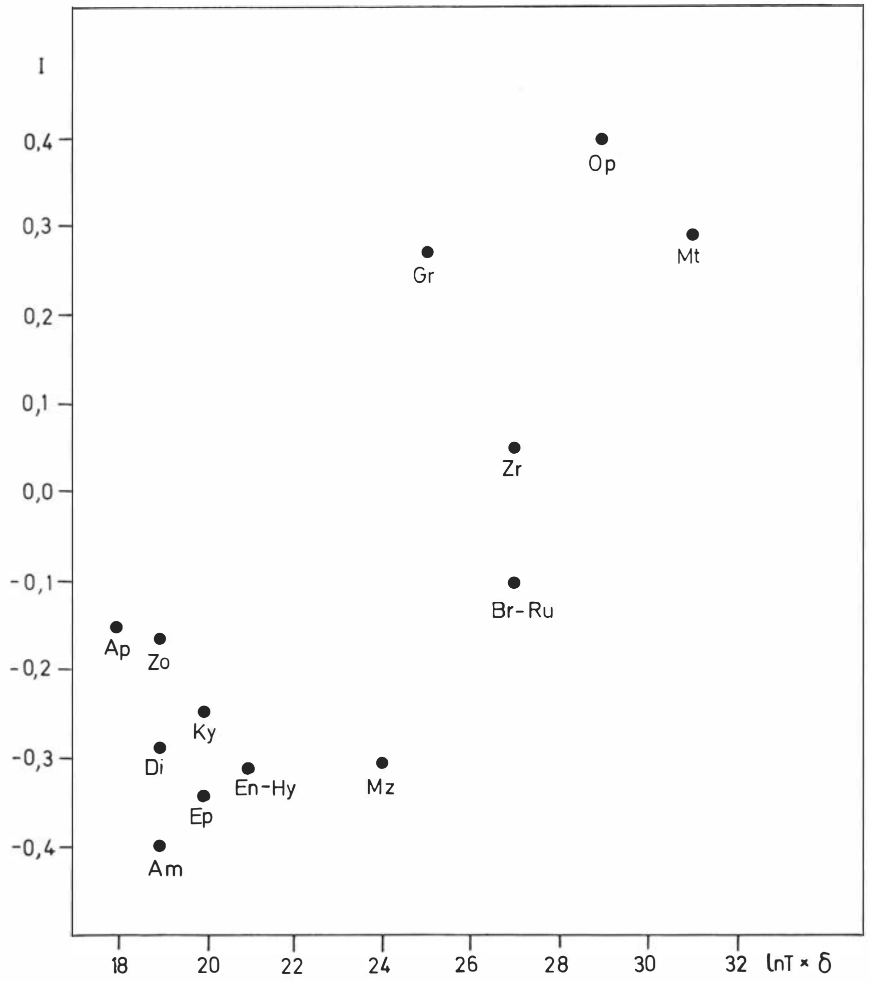


Fig. 8. Heavy mineral data plotted against the first principal component (I) and the durability-density factor (lnT × δ), r = 0,79. Am = amphiboles; Ap = apatite; Br-Ru = brookite and rutile; Di = diopside; En-Hy = enstatite-hypersthene; Gr = garnet; Ky = kyanite; Mt = magnetite; Mz = monazite; Op = opaque minerals; Zo = zoisite; Zr = zircon.

Table VI. Principal components analysis of trace-elements in magnetite: the Pite samples.

Latent roots:	3,53	1,34	1,17	0,93	0,69	0,30	0,03	0,01
% of variance:	44,16	16,72	14,64	11,60	8,67	3,77	0,37	0,07
Latent vectors:	I	II	III	IV	V	VI	VII	VIII
Variables								
Cobalt	0,25	—0,31	0,35	0,31	0,77	0,13	—0,06	—0,07
Nickel	0,25	—0,49	0,22	0,35	—0,59	0,43	—0,05	—0,02
Copper	0,07	0,46	—0,14	0,84	—0,07	—0,21	—0,04	0,03
Chromium	—0,38	—0,52	—0,02	0,20	—0,05	—0,54	0,47	—0,16
Zinc	0,43	—0,34	—0,31	—0,07	—0,04	—0,52	—0,54	0,21
Manganese	0,52	0,07	—0,01	—0,08	0,01	—0,05	0,65	0,54
Vanadium	—0,09	—0,22	—0,83	0,12	0,22	0,43	0,11	0,02
Titanium	0,51	0,12	—0,15	—0,12	—0,05	—0,09	0,21	—0,80

Table VII. Principal components analysis of trace-elements in magnetite: the Lule samples.

Latent roots:	2,22	1,97	1,34	0,90	0,65	0,47	0,33	0,12
% of variance:	27,80	24,64	16,72	11,27	8,15	5,82	4,13	1,49
Latent vectors:	I	II	III	IV	V	VI	VII	VIII
Variables								
Cobalt	0,25	—0,55	—0,07	—0,28	0,00	0,30	0,66	—0,18
Nickel	0,21	—0,51	—0,29	0,08	0,17	—0,72	—0,12	0,21
Copper	0,08	0,18	0,57	—0,63	0,37	—0,31	0,07	0,06
Chromium	—0,06	0,55	—0,39	—0,05	—0,16	—0,35	0,61	0,15
Zinc	—0,46	—0,03	—0,10	0,28	0,80	0,10	0,21	—0,02
Manganese	—0,56	—0,27	0,11	—0,18	—0,27	0,10	0,06	0,69
Vanadium	—0,10	0,06	—0,64	—0,62	0,15	0,20	—0,35	—0,05
Titanium	—0,59	—0,17	0,06	—0,12	—0,28	—0,34	0,02	—0,64

Table VIII. Principal components analysis of trace-elements in magnetite: the Kalix samples.

Latent roots:	2,23	1,65	1,48	1,15	0,66	0,42	0,26	0,14
% of variance:	27,91	20,72	18,52	14,38	8,27	5,25	3,22	1,72
Latent vectors:	I	II	III	IV	V	VI	VII	VIII
Variables								
Cobalt	0,21	0,25	0,57	0,37	—0,11	0,52	—0,38	—0,08
Nickel	—0,25	0,36	—0,43	—0,19	—0,67	0,16	—0,33	0,07
Copper	—0,06	—0,49	0,23	0,40	—0,66	—0,26	0,20	0,04
Chromium	—0,56	0,28	0,19	0,00	—0,03	0,14	0,47	—0,57
Zinc	0,42	0,39	—0,28	0,32	—0,10	0,18	0,62	0,26
Manganese	0,52	0,32	0,12	—0,17	—0,19	—0,54	—0,08	0,50
Vanadium	—0,36	0,47	0,24	0,28	0,13	—0,53	—0,10	0,44
Titanium	0,07	0,05	0,51	—0,68	—0,21	0,09	0,28	0,38

Table IX. Principal components analysis of trace-elements in magnetite: the till samples.

Latent roots:	2,34	1,63	1,48	0,98	0,77	0,51	0,19	0,10
% of variance:	29,22	20,39	18,47	12,24	9,67	6,32	2,38	1,31
Latent vectors:	I	II	III	IV	V	VI	VII	VIII
Variables								
Cobalt	—0,51	0,03	0,03	—0,10	—0,66	—0,07	0,22	—0,49
Nickel	—0,56	—0,17	0,07	—0,26	—0,01	—0,38	—0,39	0,53
Copper	0,18	—0,11	0,68	—0,08	0,16	—0,56	0,36	—0,10
Chromium	—0,36	—0,39	0,17	—0,28	0,55	0,42	—0,01	—0,37
Zinc	—0,08	—0,15	0,55	0,65	—0,20	0,28	—0,37	0,03
Manganese	0,31	—0,42	0,19	—0,44	—0,43	0,40	0,17	0,35
Vanadium	—0,19	—0,54	—0,32	0,47	0,07	—0,10	0,53	0,22
Titanium	0,34	—0,56	—0,25	—0,02	—0,12	—0,35	—0,47	—0,40

variable part of the system or, to put it in another way, a sort of a base for background values. Hitherto the properties of the smallest latent root and its vector has not been studied very much, at least not in the fields where PCA is generally used. But the value of the smallest latent vector should not be underestimated, as it in fact serves as a "fingerprint" for the data and its dispersion matrix. Two different sets of data yielding similar last latent vectors, provided their latent roots are small, therefore should represent sets with the same constant relationship between their variables. The potential of this relationship may probably be useful in, for instance, geochemical prospecting; by inserting the values from a sample of unknown origin into the linear equation representing the last latent vector of a set of data from a well-known geochemical population, it can be seen if the unknown sample is likely to belong to that population or not, and if so, it can then be possible to see which elements are enriched or depleted in the unknown sample by studying the significant loadings of the last vector. It could therefore probably be used as a complement to canonical variate analysis or discriminant analysis.

Turning back now to the different areas and their trace-element PC's it can be seen that titanium and manganese have high numerical loadings on the first component for both the Pite and Lule samples; this is also the case for zinc. The Kalix samples on the other hand show markedly low loadings for titanium on both the first and second component while zinc and manganese are strongly positive. Chromium shows up on the second component mainly in the Pite and Lule areas, while in the till samples it is negatively loaded on both the first two components, and in the Kalix samples it is mainly loaded on the first component. Vanadium has low loadings on the first two components among the Pite and the Lule samples but shows strong negative values on the third. In the till and the Kalix samples it is mainly loaded on the second component. Cobalt and nickel are usually positively correlated, and so is the case here except among the Kalix samples. They show very strong negative loadings in the first component of the till samples. Copper does not show up markedly in the first two components except in the Pite and Kalix areas where it is strongly loaded on the second component. In the Lule and the till samples it shows up on the third component.

The last component bears many resemblances between the Pite and Lule samples with strong positive loadings for manganese and strong negative ones for titanium. This means that titanium is depleted in the two areas and manganese is enriched, even if the absolute titanium values are higher than in the Kalix area and the area of till samples. The fact is, the northern areas are mainly granitic and, as such, are generally much poorer in titanium. The last vector of the Kalix area has strong positive loadings on vanadium and titanium and a strong negative on chromium and manganese. This means that chromium is depleted even if it is generally higher than in the Lule and Pite areas, and manganese is depleted, and is also lower than in the Lule or Pite areas. Vanadium and titanium are enriched and the mean of vanadium also lies over the mean for all areas together, but titanium lies under the grand mean but still seems to be enriched in the Kalix samples. However, the last latent root of the Kalix samples still shows 1,7 % of the total variance, and the scores corresponding to that root show rather large fluctuations. But the area is fairly large and geologically inhomogeneous. Finally the till samples do not show loadings on the last vector similar to those of the Kalix area as might perhaps have been expected. Cobalt is depleted and nickel enriched according to the last vector, and the means show the similar features in comparison with the other areas. Chromium is depleted but shows higher means for the till samples than for the rest. Manganese tends to be enriched but still has lower means than the river and beach sediments; titanium is depleted according to the loading as well as the mean.

Returning to the Pite area it can be noted that its smallest latent root contributes only about 0,07 % of the total variance in the system, hence there is a very stable constant relationship between manganese and titanium. This is also revealed in the correlation coefficient between the two elements, which is almost 0,98. — The till samples, taken to the west of the Kalix River, in an area stretching from north of Tärendö southwards towards a line straight to the west from Korpilombolo, are all from an area overwhelmingly dominated by Lina Granite, according to the geological map. As the till is probably transported for rather short distances (see p. 169 for discussion) the till data may be used as a crude approximation for the trace-element composition in the Lina Granite, and as an even cruder approximation for the granites in general. One problem when using the till samples is that they contain much more nickel than the other samples; whether this is a local phenomenon for the till (patches of gabbros in the area) or whether it is dependent on the dilution of the river sediments, is difficult to say. The first latent vector of the Kalix samples may then be interpreted as a Lina Granite vector with the granite on the negative loadings. The positive loadings probably denote metamorphic rocks and/or diorites. The first principal component of the Lule samples seems to denote diorites on the negative loadings and granites on those near zero. The first component of the Pite samples seems to separate magnetites originating from rocks of pelitic and mafic origin, respectively, with the pelitic ones on the negative loadings. It is peculiar, as is the case everywhere among the samples in this investigation, that chromium seems to be relatively more abundant in the more acid rocks.

Principal components analysis of trace-elements in magnetite (till samples excluded). — The principal components are presented in Table X. The correlations among the different elements show generally low numerical values (Table XI). The first principal component, with 43 % of the total variance, shows high positive values for manganese and zinc and to some extent titanium, and high negative values for chromium and vanadium and to a lesser extent nickel. According to the previous chapter, this component's negative loadings should point to rocks of acidic composition and the positive loadings to the more basic rocks.

Table X. Principal components analysis of trace-elements in magnetite.

Latent roots:	3,44	1,39	1,01	0,91	0,48	0,41	0,26	0,09
% of variance:	43,00	17,43	12,60	11,33	6,00	5,16	3,30	1,19
Latent vectors:	I	II	III	IV	V	VI	VII	VIII
Variables								
Cobalt	—0,17	—0,60	0,49	0,15	0,43	0,26	—0,32	—0,01
Nickel	—0,29	—0,56	0,09	0,07	—0,64	—0,32	0,25	0,12
Copper	—0,04	0,37	0,78	—0,42	—0,26	0,11	0,06	0,03
Chromium	—0,44	0,05	—0,31	—0,34	—0,18	0,26	—0,54	0,44
Zinc	0,43	—0,17	—0,09	0,10	—0,45	0,72	—0,03	—0,20
Manganese	0,48	—0,21	0,01	—0,23	0,18	0,03	0,29	0,74
Vanadium	—0,42	—0,12	—0,19	—0,40	0,24	0,37	0,62	—0,20
Titanium	0,32	—0,32	—0,12	—0,68	0,02	—0,30	—0,27	—0,40

Table XI. Correlation matrix of magnetite data.

Cobalt	1	1,00							
Nickel	2	0,50	1,00						
Copper	3	—0,00	—0,13	1,00					
Chromium	4	0,05	0,34	0,01	1,00				
Zinc	5	—0,15	—0,26	—0,17	—0,54	1,00			
Manganese	6	—0,11	—0,36	—0,10	—0,69	0,69	1,00		
Vanadium	7	—0,24	0,39	0,00	0,73	—0,55	—0,52	1,00	
Titanium	8	—0,07	—0,11	—0,06	—0,27	0,42	0,72	—0,23	1,00
		1	2	3	4	5	6	7	8

But these are not the only facts found in this component; it also discriminates very well between the three different areas as can be seen in Fig. 9.

The second component, with over 17 % of the total variance, has high negative loadings on cobalt and nickel, a fairly high negative loading on titanium and a high positive loading on copper. This might imply results from crystalline fractionation with the negative loadings connected with the earlier stages and the positive with the

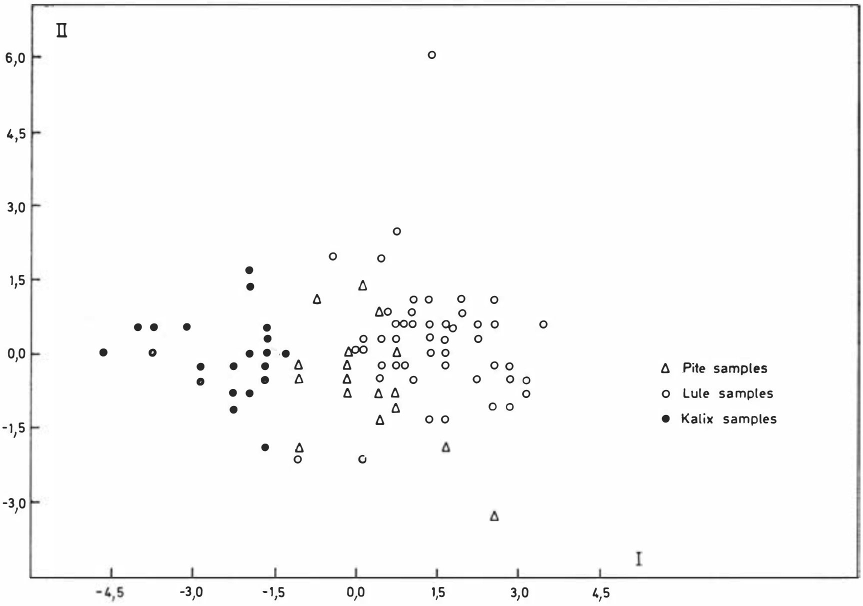


Fig. 9. Plot of the first two components scores derived from PCA of trace-element data in magnetite.

later stages (Wager & Mitchell 1950). This is, of course, relevant only for "true" magmatic rocks, but Theobald et al. (1967) report that intense regional metamorphism should reduce the amount of titanium in magnetite — quite in contradiction to that reported by Abdullah (1965). Manganese should also be reduced, according to the former authors, under the same circumstances. Nothing has been found in the literature about the behaviour of cobalt and nickel in connection with metamorphism. But as the scores are scanned in relation to the second component it seems obvious that it is also closely related to metamorphism. The very high score for sample 10101 in this component is solely due to lack of cobalt and nickel and should not be taken too seriously. The rest of the components are, at least at this stage, difficult to interpret.

Adjustment of PCA. — As in fact the physical factor is irrelevant in this investigation, but the "true" and not the "apparent" representation of each mineral at each locality is of considerable interest, the following analysis was made: the first latent root was calculated together with its scores. Then, by regressing the scores onto the original variables, one at a time, a matrix of fitted values and another of residuals were obtained. In our case, it is, of course, the latter matrix which is of interest. This can now be treated as a new data matrix from which a new set of principal components can be calculated.

The smallest latent root in this analysis will now be zero as the dispersion matrix is no longer of full rank. The new set of components appears to be rotated with respect to the original set. The new components and the matrices **R** and $\hat{\mathbf{R}}$ are presented in Tables XII—XIV. The first adjusted component shows a strong division between metamorphic and igneous minerals. The second separates basic and acid rocks while minerals which do

Table XII. Correlation matrix of heavy mineral data (**R**).

Opaques	1	1,00												
Amphiboles	2	—0,67	1,00											
Garnet	3	0,05	—0,60	1,00										
Epidote	4	—0,64	0,57	—0,39	1,00									
Diopside	5	—0,41	0,36	—0,28	0,32	1,00								
Enstatite-Hypersthene	6	—0,42	0,45	—0,46	0,38	0,47	1,00							
Kyanite	7	—0,33	0,32	—0,34	0,19	0,14	0,23	1,00						
Brookite-Rutile	8	—0,20	0,20	—0,18	0,16	0,02	0,16	0,04	1,00					
Apatite	9	—0,20	0,24	—0,18	0,24	0,04	0,22	0,21	—0,06	1,00				
Zircon	10	0,16	—0,11	—0,13	0,05	—0,17	—0,33	0,10	—0,08	0,14	1,00			
Monazite	11	—0,53	0,53	—0,41	0,33	0,26	0,33	0,45	—0,03	0,09	0,05	1,00		
Zoisite	12	—0,29	0,21	—0,09	0,24	0,13	0,12	0,09	0,03	0,29	0,06	0,04	1,00	
Magnetite	13	0,58	—0,39	0,03	—0,35	—0,32	—0,23	—0,31	—0,00	0,05	0,27	—0,34	—0,23	1,00
		1	2	3	4	5	6	7	8	9	10	11	12	13

Table XIII. Adjusted correlation matrix of heavy mineral data ($\hat{\mathbf{R}}$).

Opaques	1	1,00												
Amphiboles	2	0,02	1,00											
Garnet	3	—0,85	—0,28	1,00										
Epidote	4	—0,14	—0,08	0,04	1,00									
Diopside	5	0,11	—0,25	0,06	—0,15	1,00								
Enstatite-Hypersthene	6	0,27	—0,27	—0,13	—0,19	0,16	1,00							
Kyanite	7	0,17	—0,24	—0,07	—0,29	—0,21	—0,17	1,00						
Brookite-Rutile	8	—0,06	0,06	—0,08	0,02	—0,11	0,03	—0,08	1,00					
Apatite	9	0,09	—0,03	—0,00	0,03	—0,18	0,02	0,06	—0,14	1,00				
Zircon	10	0,08	0,02	—0,26	0,22	—0,12	—0,32	0,20	—0,06	0,20	1,00			
Monazite	11	0,01	—0,06	—0,05	—0,28	—0,19	—0,20	0,18	—0,23	—0,17	0,19	1,00		
Zoisite	12	—0,05	—0,14	0,13	0,00	—0,07	—0,14	—0,10	—0,05	0,21	0,11	—0,25	1,00	
Magnetite	13	0,24	0,22	—0,43	0,12	0,02	0,25	—0,02	0,15	0,30	0,24	0,07	—0,05	1,00
		1	2	3	4	5	6	7	8	9	10	11	12	13

Table XIV. Adjusted principal components analysis of heavy mineral data.

Latent roots:	2,34	1,84	1,69	1,45	1,12	1,03	1,01	0,83	0,73	0,47	0,42	0,08	0,00
% of variance:	17,99	14,14	12,99	11,18	8,58	7,94	7,79	6,35	5,59	3,59	3,26	0,59	0,00
Latent vectors:	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII
Variables													
Opaques	—0,54	0,19	0,10	0,13	0,04	0,10	—0,32	—0,23	0,05	0,22	0,14	0,56	0,32
Amphiboles	—0,19	—0,15	—0,20	—0,56	—0,18	0,50	0,05	0,05	—0,23	—0,19	—0,13	0,33	—0,30
Garnet	0,60	—0,05	0,02	0,11	—0,06	—0,06	0,27	0,12	—0,09	—0,06	—0,01	0,65	0,31
Epidote	0,07	—0,17	—0,48	—0,02	0,47	—0,32	—0,03	—0,43	0,03	—0,09	0,25	0,20	—0,33
Diopside	0,06	0,43	0,07	0,15	0,47	0,13	0,15	0,51	—0,38	0,06	0,13	0,08	—0,31
Enstatite-Hypersthene	—0,15	0,56	—0,00	0,17	—0,11	—0,16	0,34	—0,15	0,24	—0,21	—0,47	0,17	—0,33
Kyanite	—0,13	—0,26	0,43	0,24	—0,29	—0,33	—0,15	—0,07	—0,40	—0,41	0,14	0,12	—0,29
Brookite-Rutile	—0,03	0,11	—0,25	—0,30	—0,39	—0,57	—0,22	0,38	0,06	0,34	0,05	0,13	—0,13
Apatite	—0,14	—0,18	—0,26	0,47	—0,25	0,16	0,40	—0,04	—0,30	0,52	0,07	—0,01	—0,20
Zircon	—0,23	—0,47	—0,08	0,17	0,32	—0,16	—0,10	0,29	—0,02	0,01	—0,67	0,10	0,09
Monazite	—0,09	—0,27	0,50	—0,14	0,19	0,00	0,33	0,17	0,47	0,25	0,22	0,18	—0,33
Zoisite	0,11	—0,12	—0,27	0,43	—0,23	0,30	—0,36	0,25	0,50	—0,24	0,14	0,08	—0,21
Magnetite	—0,42	0,00	—0,25	0,01	0,05	—0,13	0,44	0,37	0,02	—0,42	0,35	—0,04	0,31

not affect such phenomena have low loadings. The third component discriminates between mafic and pelitic metamorphic minerals while the fourth is difficult to interpret.

Further adjustments of PCA. — To increase the possibility of reification of the heavy mineral principal components, some of the minerals were deleted. Chosing which minerals to delete was decided by the variance accounted for when the different heavy minerals were regressed against the first principal component. Thus brookite-rutile, apatite, zircon, and zoisite were deleted in this reduced-adjusted PCA. The first principal component with 25,1 % of the explained variance again shows the division between metamorphic and magmatic minerals. The second component with 18,3 % variance gives an impression of the relations between mafic and pelitic metamorphic rocks. The third component is related to metamorphic grade with the higher grades on the negative loadings (Table XV).

Table XV. Adjusted and reduced principal components analysis of heavy mineral data. First three components.

Latent roots:	2,26	1,65	1,54
% of variance:	25,11	18,30	17,07
Latent vectors:	I	II	III
Variables			
Opaques	—0,58	—0,01	—0,12
Amphiboles	—0,16	0,03	0,59
Garnet	0,61	—0,02	—0,15
Epidote	0,14	—0,35	0,42
Diopside	—0,00	—0,40	—0,42
Enstatite-Hypersthene	—0,23	—0,38	—0,40
Kyanite	—0,10	0,52	—0,24
Monazite	—0,08	0,52	—0,14
Magnetite	—0,41	—0,16	0,17

Results of combinations of different types of data

Regression and canonical correlation. — The size data were regressed onto the principal components of the heavy mineral data. It was only the regression onto the first ("physical") component that showed any significant results, much as expected; it accounts for 39,4 % of the variance, the other regressions account for percentages near zero. The regressions of the different minerals onto the size components did not give any meaningful results, as was also expected. When the trace-element values of magnetite were regressed onto the second, third and fourth heavy mineral components, a variance of 26,4 % was accounted for in the last case. When the analysis is made "the other way around", i.e. the heavy mineral data regressed onto the trace-element components, we find that the first case with the first component accounts for 42,6 % variance, and that "acid" minerals have high negative coefficients and "basic" minerals have high positive coefficients.

Canonical correlation was carried out between heavy mineral data, size data and trace-element data, respectively. The results are shown in Tables XVI and XVII, but reification seems difficult.

Procrustes rotation. — A procrustes rotation was carried out of the factor scores of the magnetite trace-element data onto the factor scores — with the first component excluded — of the heavy mineral data. Here the results clearly show the differences between the areas, especially in the graph showing the third rotated component versus the second (Fig. 10).

Table XVI. Vector loadings for the first canonical correlation between the reduced and adjusted heavy mineral data and size data.

Heavy mineral data Variable		Size data Variable	
Opaques	—0,01	1,0—1,5 Φ	0,06
Amphiboles	0,07	1,5—2,0 Φ	0,01
Garnet	—0,08	2,0—2,5 Φ	0,01
Epidote	0,06	2,5—3,0 Φ	0,03
Diopside	0,01	3,0—3,5 Φ	—0,06
Enstatite-Hypersthene	0,06	3,5—4,0 Φ	0,07
Kyanite	0,07	> 4,0 Φ	0,38
Monazite	0,12	Amount of heavy minerals	—0,06
Magnetite	—0,05		

Canonical correlation = 0,67

Table XVII. Vector loadings for the first canonical correlation between the adjusted heavy mineral data and trace-element data from magnetite.

Heavy mineral data Variable		Trace-element data Variable	
Opaques	0,04	Cobalt	—0,04
Amphiboles	—0,04	Nickel	0,01
Garnet	—0,07	Copper	—0,01
Epidote	—0,01	Chromium	—0,18
Diopside	—0,00	Zinc	0,09
Enstatite-Hypersthene	0,00	Manganese	—0,15
Kyanite	0,00	Vanadium	—0,32
Brookite-Rutile	0,01	Titanium	0,05
Apatite	—0,05		
Zircon	0,03		
Monazite	—0,01		
Zoisite	—0,01		
Magnetite	0,02		

Canonical correlation = 0,70

Results of canonical variates analysis

CVA of heavy mineral data. — The canonical variates analysis was carried out via the PCO (principal coordinates) directive in the GENSTAT language. Using this instead of the CVA directive was due to the fact that the groups were of different sizes: 17, 48 and 21 observations for the Pite, Lule and Kalix areas, respectively. The within sums of squares and products matrix (WSSP) and the standardized group means are presented in Table XVIII. The results of the analysis appear in Table XIX. The first canonical variate with high loadings, negative and positive, respectively, for garnet and magnetite, and 76 % of the total variance, discriminates between Kalix and Pite samples. The second canonical variate discriminates between Kalix and Pite samples on one hand, and Lule samples on the other. Here we have a high positive loading for monazite and high negative loadings for amphiboles, garnet, brookite-rutile, and opaques. The coordinates for the canonical variate means and the sample scores are shown in Fig. 11. The Pite samples fall out quite well but there is some overlapping between the Lule and Kalix samples. The physical factor was found to have virtually no influence on this analysis.

CVA of trace-element data from magnetite. — The WSSP matrix for this analysis and the standardized group means are presented in Table XX. The results appear in Table XXI. From this we see that the first canonical variate, with a high positive loading on vanadium, a high negative

Table XVIII. Pooled correlation (WSSP) matrix and standardized group means for heavy mineral data.

Pooled correlation matrix

Opaques	1	1,00												
Amphiboles	2	—0,72	1,00											
Garnet		0,10	—0,58	1,00										
Epidote	4	—0,67	0,56	—0,37	1,00									
Diopside	5	—0,39	0,37	—0,34	0,33	1,00								
Enstatite-Hypersthene	6	—0,44	0,41	—0,40	0,38	0,49	1,00							
Kyanite		—0,30	0,29	—0,32	0,17	0,09	0,16	1,00						
Brookite-Rutile	8	—0,33	0,21	0,15	0,19	0,11	0,18	0,15	1,00					
Apatite	9	—0,26	0,26	—0,22	0,27	0,08	0,27	0,27	—0,13	1,00				
Zircon	10	0,07	—0,17	0,04	0,04	—0,13	—0,34	0,11	—0,12	0,16	1,00			
Monazite	11	—0,61	0,55	—0,30	0,33	0,25	0,31	0,36	0,17	0,20	—0,02	1,00		
Zoisite	12	—0,29	0,27	—0,28	0,29	0,14	0,19	0,12	0,09	0,33	0,18	0,15	1,00	
Magnetite	13	0,59	—0,55	0,31	—0,48	—0,31	—0,27	—0,28	—0,27	—0,05	0,07	—0,46	—0,19	1,00
		1	2	3	4	5	6	7	8	9	10	11	12	13

Group means

	1	2	3	4	5	6	7	8	9	10	11	12	13	N
Pite	—0,41	—0,25	0,72	—0,11	0,27	—0,06	0,28	—0,75	—0,25	—0,56	0,17	0,37	—1,12	17
Lule	0,15	—0,10	0,16	—0,07	—0,14	—0,17	—0,29	0,32	0,13	0,02	—0,45	0,01	0,29	48
Kalix	—0,01	0,42	—0,96	0,26	0,11	0,44	0,44	—0,12	—0,10	0,42	0,89	—0,32	0,24	21

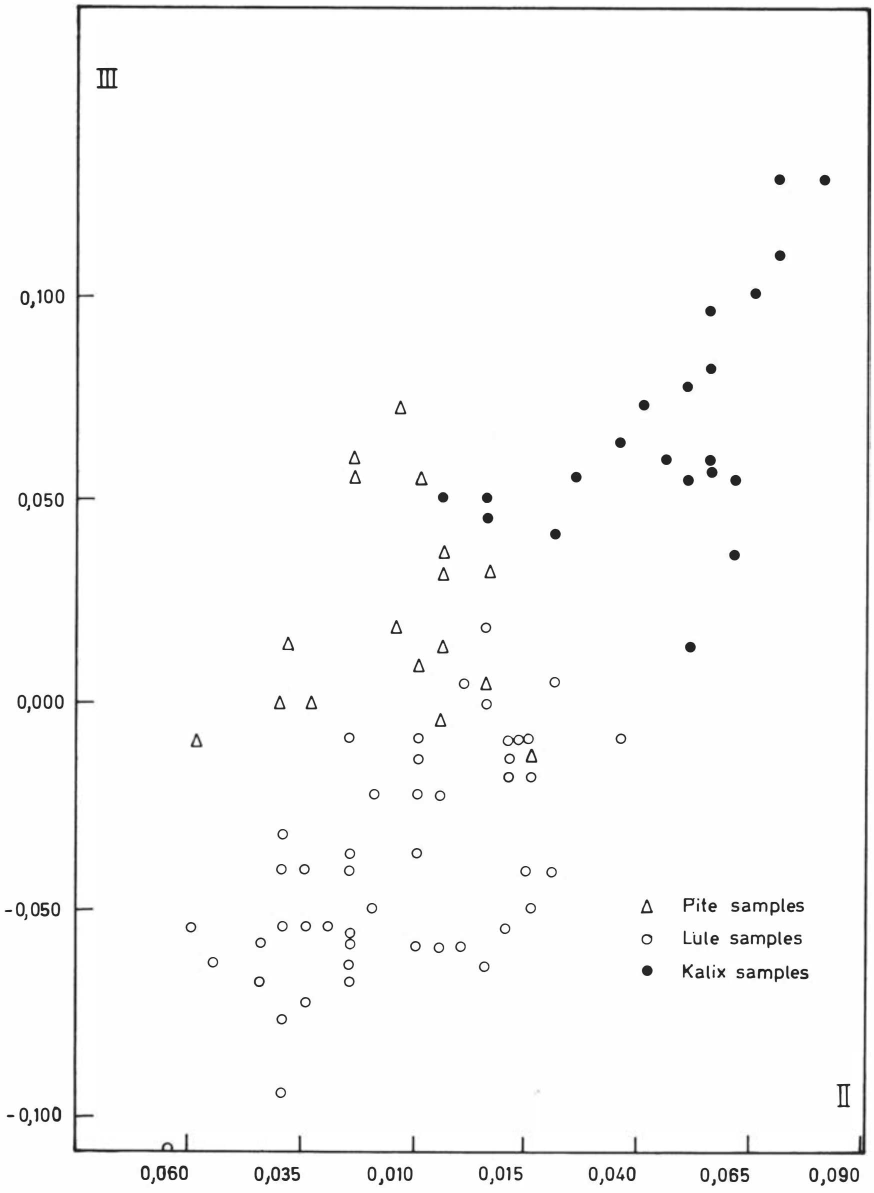


Fig. 10. Procrustes rotation of trace-element data onto the factor scores of heavy mineral data. Third rotated component versus the second.

one on zinc, and a total explained variance of 77 %, discriminates between the Kalix and the Lule samples. The second canonical variate has very high positive loadings on chromium and zinc, and high negative ones on manganese and vanadium, and it discriminated between the Pite samples on one hand and the Lule, and to some extent the Kalix samples on the other. A plot over the canonical variate means and the sample scores is found in Fig. 12. Here the Kalix samples fall out nicely but the Lule and Pite samples are not so clearly separated; however, this CVA discriminates slightly better than the previous one.

CVA on a combination of heavy mineral and trace-element data. — A combined analysis was made to improve the canonical variates results. The pooled WSSP matrix is rather meaningless to show here but the CVA results appear in Table XXII. The same minerals and elements are highly loaded

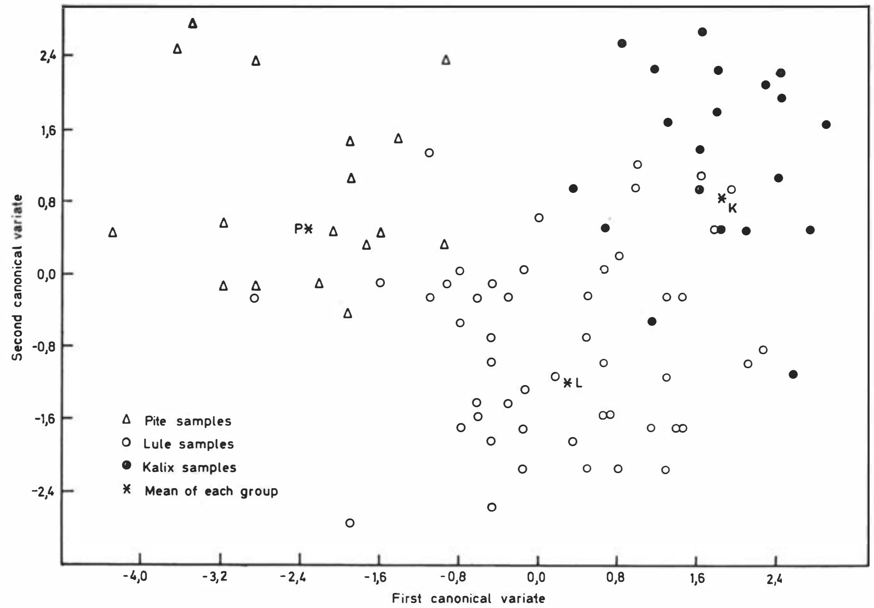


Fig. 11. Coordinates for CVA means and sample scores for heavy mineral data

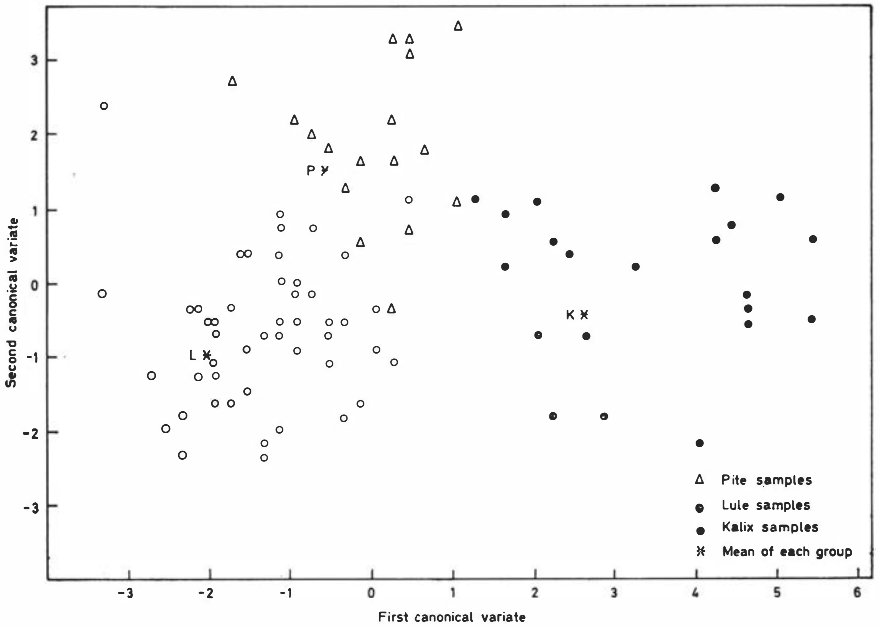


Fig. 12. Coordinates for CVA means and sample scores for trace-element data.

on the first canonical variate as in the two separate CVA's. It discriminates between the Kalix samples on one hand and the Pite and Lule ones on the other. The second variate with a high positive loading on chromium and high negative loadings on amphiboles, opaques, and manganese, discriminates between the Lule samples and the Pite samples, and to some extent between the Lule samples and the Kalix samples. The plot of the canonical variates means and the sample scores

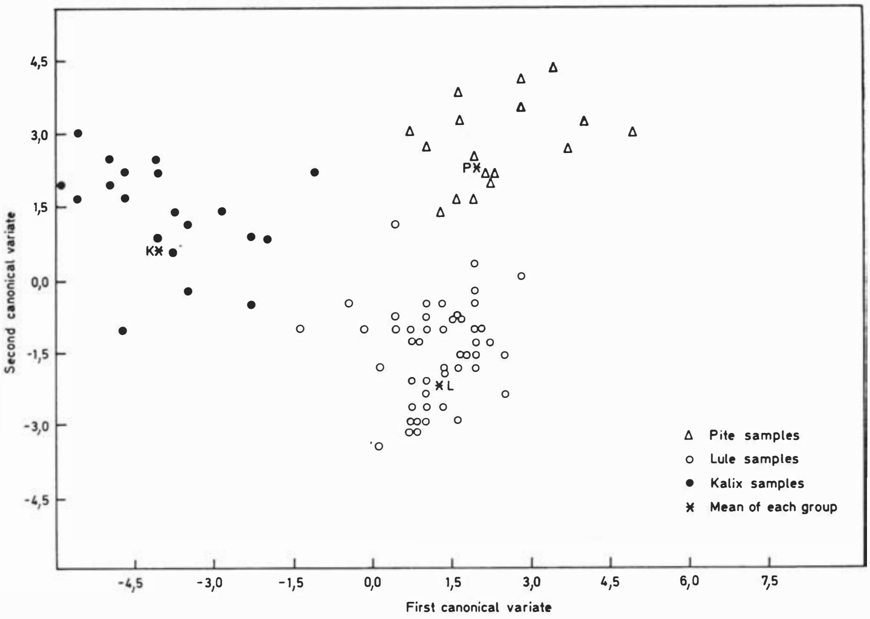


Fig. 13. Coordinates for CVA means and sample scores for a combination of heavy mineral and trace-element data.

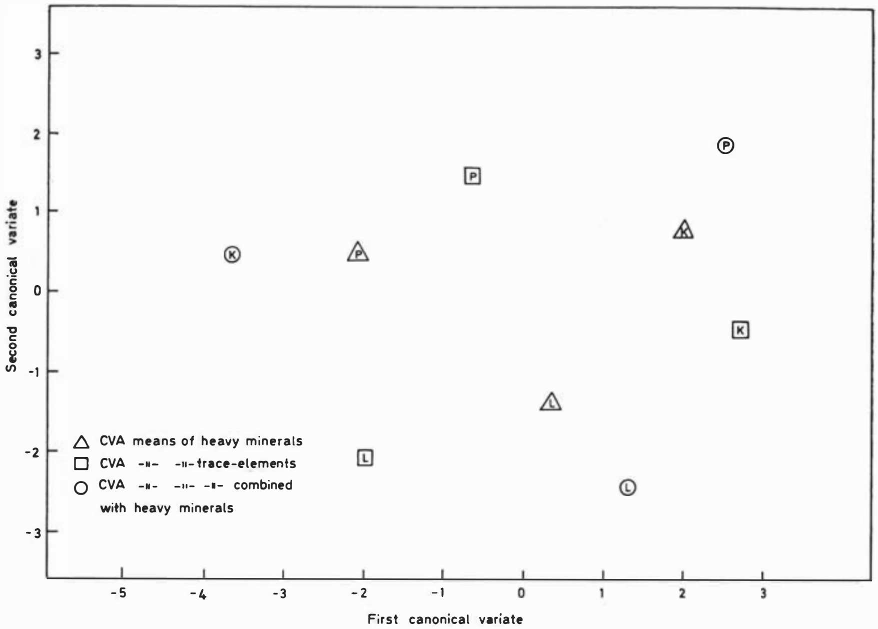


Fig. 14. A comparison of the different CVA means calculated.

shows an excellent discrimination between all groups and also a very dense concentration of the Lule samples (Fig. 13). A plot of canonical means evaluated by different methods is shown in Fig. 14.

CVA of trace-elements in magnetite with till samples included. — Magnetite samples from till, taken in an area around the Kalix River, roughly between Överkalix and Tärendö, were at last included in a canonical variates analysis. The WSSP matrix and the standardized means are presented in Table XXIII, and the results of the CVA in Table XXIV. The first canonical variate discriminates between the till and the Kalix samples on one hand and the Lule and Pite samples on the other. It has a variance of 88 % and the elements with the most discriminatory power are vanadium (—) and zinc (+), respectively. The second variate has 9 % of the total variance and discriminates between the Lule and Pite samples. The third variate, with only about 2,5 % of the explained variance, has thus a very small discriminatory power, and it separates the

Table XIX. Results of CVA for heavy mineral data.

Distance matrix

Pite	1	0,00		
Lule	2	3,14	0,00	
Kalix	3	4,13	2,66	0,00
		1	2	3

Latent roots

I	II
8,63	2,70

Coordinates of means

	I	II
Pite	—2,22	0,51
Lule	0,33	—1,33
Kalix	1,90	0,82

Canonical variate loadings

	I	II
Opaques	—0,38	—0,62
Amphiboles	0,01	—0,85
Garnet	—1,04	—0,84
Epidote	0,00	—0,16
Diopside	—0,22	—0,12
Enstatite-Hypersthene	0,09	0,11
Kyanite	—0,23	0,17
Brookite-Rutile	0,28	—0,76
Apatite	—0,08	—0,46
Zircon	0,42	—0,03
Monazite	0,26	0,74
Zoisite	—0,42	—0,06
Magnetite	1,04	—0,23

Table XXI. Results of CVA for trace-element data.

Distance matrix

Pite	1	0,00		
Lule	2	2,89	0,00	
Kalix	3	3,88	4,76	0,00
		1	2	3

Latent roots

I	II
11,80	3,53

Coordinates of means

Pite	—0,68	1,49
Lule	—2,02	—1,06
Kalix	2,70	—0,42

Canonical variate loadings

Cobalt	0,09	0,49
Nickel	0,36	0,35
Copper	0,09	0,18
Chromium	—0,46	1,18
Zinc	—0,78	1,15
Manganese	0,43	—0,93
Vanadium	0,79	—0,78
Titanium	0,27	0,61

Table XX. Pooled correlation (WSSP) matrix and standardized group means for trace-element data.

Pooled correlation matrix

Cobalt	1	1,00							
Nickel	2	0,41	1,00						
Copper	3	—0,03	—0,20	1,00					
Chromium	4	—0,33	—0,18	—0,09	1,00				
Zinc	5	—0,02	0,05	—0,16	—0,15	1,00			
Manganese	6	0,12	—0,00	—0,06	—0,35	0,47	1,00		
Vanadium	7	0,08	0,05	—0,10	0,42	0,04	—0,01	1,00	
Titanium	8	—0,02	—0,00	—0,04	—0,13	0.28	0,77	0,00	1,00
		1	2	3	4	5	6	7	8

Group means

	1	2	3	4	5	6	7	8	N
Pite	0,34	0,50	—0,02	0,41	0,58	—0,11	—0,18	0.28	17
Lule	—0,28	—0,49	—0,06	—0,66	0,38	0,53	—0,52	0,14	48
Kalix	0,37	0,72	0,15	1,17	—1,33	—1,12	1,33	—0,55	21

Table XXII. Results of CVA for a combination of heavy mineral and trace-element data.

Distance matrix

Pite	1	0,00		
Lule	2	4,51	0,00	
Kalix	3	6,35	5,75	0,00
		1	2	3

Latent roots

I	II
21,45	9,81

Coordinates of means

	I	II
Pite	2,45	1,95
Lule	1,27	—2,41
Kalix	—3,72	0,46

Canonical variate loadings

	I	II
Opaques	0,69	—1,09
Amphiboles	0,40	—1,14
Garnet	0,98	—0,69
Epidote	0,18	—0,28
Diopside	—0,01	—0,02
Enstatite-Hypersthene	0,01	—0,13
Kyanite	0,31	0,07
Brookite-Rutile	—0,21	—0,55
Apatite	0,08	—0,47
Zircon	—0,12	—0,33
Monazite	—0,27	—0,30
Zoisite	0,08	0,26
Magnetite	—0,96	—0,43
Cobalt	—0,00	0,52
Nickel	—0,29	0,25
Copper	—0,19	0,02
Chromium	—0,24	1,09
Zinc	1,01	0,52
Manganese	—0,13	—0,98
Vanadium	—0,85	—0,16
Titanium	0,06	0,26

Table XXIV. Results of CVA for trace-element data with the till samples included.

Distance matrix

Pite	1	0,00			
Lule	2	2,71	0,00		
Kalix	3	3,81	4,87	0,00	
Till	4	5,94	6,94	2,59	0,00
		1	2	3	4

Latent roots

I	II	III
29,96	3,11	0,86

Coordinates of means

	I	II	III
Pite	2,01	—1,32	—0,22
Lule	3,17	1,13	—0,06
Kalix	—1,47	—0,10	0,76
Till	—3,71	0,29	—0,48
	I	II	III

Canonical variate loadings

	I	II	III
Cobalt	0,19	—0,55	0,92
Nickel	—0,63	—0,31	—1,15
Copper	—0,25	—0,03	—0,35
Chromium	—0,29	—1,20	0,09
Zinc	0,93	—0,99	—0,28
Manganese	0,37	1,25	—0,32
Vanadium	—1,25	0,90	0,38
Titanium	—0,11	—0,80	—0,05

Kalix samples from those of the till. The coordinates of the canonical variate means together with a plot of the sample scores are found in Fig. 15. As can be seen, the samples are fairly well concentrated around the respective means and some overlapping occurs, as expected, between the Kalix and the till samples.

Table XXIII. Pooled correlation (WSSP) matrix and standardized group means for trace-element data with the till samples included.

Pooled correlation matrix

Cobalt	1	1,00							
Nickel	2	0,42	1,00						
Copper	3	—0,06	—0,19	1,00					
Chromium	4	—0.21	—0,10	—0,06	1,00				
Zinc	5	0,02	0,04	—0,03	—0,07	1,00			
Manganese	6	0,08	—0,09	—0,01	—0,27	0,35	1,00		
Vanadium	7	0,08	0,06	—0,12	0,39	0,06	—0,01	1,00	
Titanium	8	—0,08	—0,02	—0,03	—0,12	0,17	0,73	0,05	1,00
		1	2	3	4	5	6	7	8

Group means

	1	2	3	4	5	6	7	8	N
Pite	0,44	0,17	—0,17	0,05	0,77	0,19	—0.49	0,41	17
Lule	—0,19	—0,74	—0,21	—0,86	0.62	0,76	—0,77	0,27	48
Kalix	0,47	0,38	0,00	0,70	—0,66	—0,71	0,75	—0,43	21
Till	—0,36	1,08	0,55	1,12	—1,27	—1,08	1,29	—0,48	23

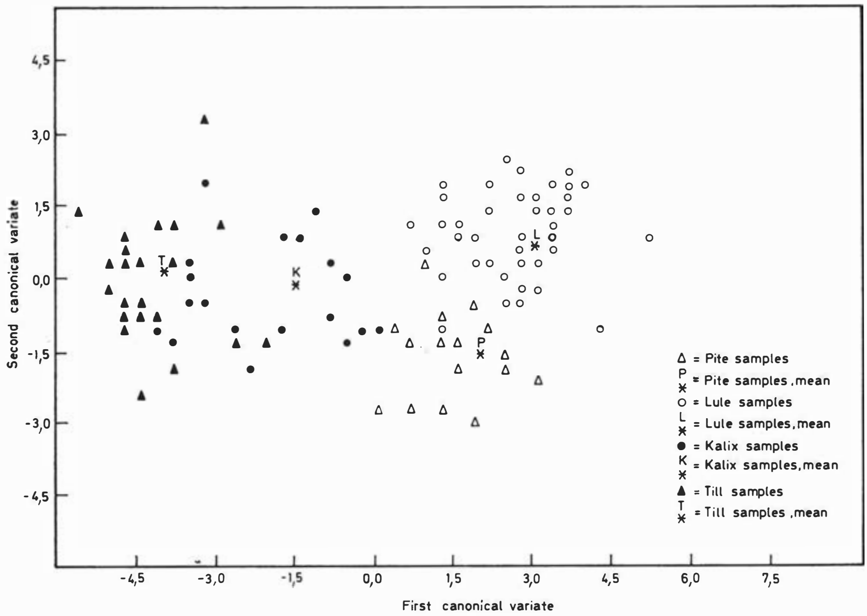


Fig. 15. Coordinates for CVA means and sample scores with the till samples included.

Discussions

Different trends between the respective areas

Generally it could be stated that the minerals in the sediments of one area also originate from the same river basin. Exceptions may, however, occur, for instance the two samples taken SW of Råneå (10601—10602), which by no means belong to the catchment area of the Kalix River; the same holds for the two samples (10701—10702) taken SW of Kalix (Nederkalix). The reason for alloting these samples to the Kalix area is simply practical and, furthermore, they show many likenesses with the rest of the Kalix samples. The sample taken at Trundön (10101) is still more critical as it could have a chance, at least theoretically, of receiving minerals from both the Lule and the Pite River basins.

The trends are best exposed by the combined CVA of heavy minerals and trace-elements in magnetite. As can be seen from Table XXII, the variables that best discriminate between the areas are zinc, vanadium, chromium, garnet, manganese, magnetite, and monazite, respectively. In general the trace-elements are better discriminators than the heavy minerals themselves, but unfortunately the trace-elements in magnetite are more difficult to interpret geologically.

The Kalix area stands out from the other two by its low amounts of zinc and garnet and by its high values for vanadium. The area of possible provenance for the Kalix samples has few metamorphic rocks compared to the other two which explains the low garnet values. On the other hand, the kyanite values are remarkably high which either must be explained by unlikely long distances of transportation or hitherto undiscovered pelitic gneisses, poor in garnets, in the area. The generally high monazite content could perhaps support the theory. The low zinc values might be related to the extensive areas covered by granites, as magnetites from granites are reported to contain fairly little zinc (Theobald et al. 1962, 1967). The high vanadium value is difficult to explain, but vanadium seems, according to regression analyses, to be less frequent in metamorphic rocks than in magmatic ones. Theobald et al. (1967) report that the vanadium content should decrease with increasing metamorphic grade as well. The contrary is the case for titanium (Abdullah 1965). Regressions of the trace-elements onto the component of metamorphic grade also suggest this fact. Zircon and enstatite-hypersthene contents are also fairly high in the Kalix area.

The Pite area is distinguished from the others by its unusually high garnet values and low values of zircon, brookite-rutile and especially magnetite. The magnetite, however, contains a little more titanium than the average. These facts lead to the conclusion that the area should be extensively covered by metamorphic rocks and that they are

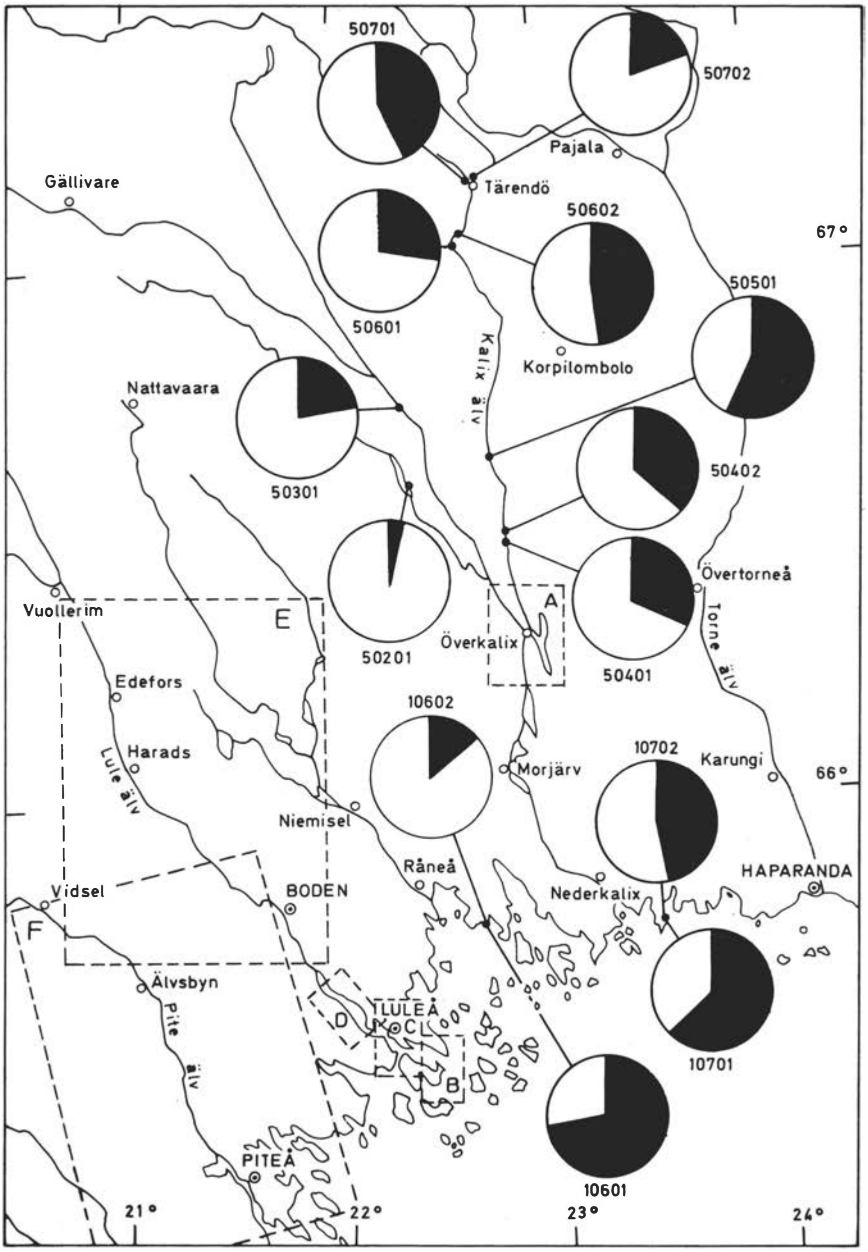


Fig. 16 A. Map showing the percentage of magnetite (black) in the heavy fraction in the Kalix area samples. This map also shows the location of other local maps. A = the Överkalix area, B = the eastern part of Sandön, C = the Luleå area, D = the Gammelstad area, E = the upper part of the Lule area, F = the Pite area. Scale 1:1585000.

generally of medium to high grade. There are both pelitic and mafic metamorphic rocks in the area as can be seen from the geological map. The very low magnetite content is difficult to explain.

The Lule area is, in many respects, a mixture of the two others, but it has some special features. The content of chromium, nickel, cobalt, vanadium, monazite, and kyanite is lower than in the other two areas and manganese, brookite-rutile, opaques, and apatite are higher, even if the differences are not so marked as in the other two areas, and the fluctuations of most variables in the area are fairly high.

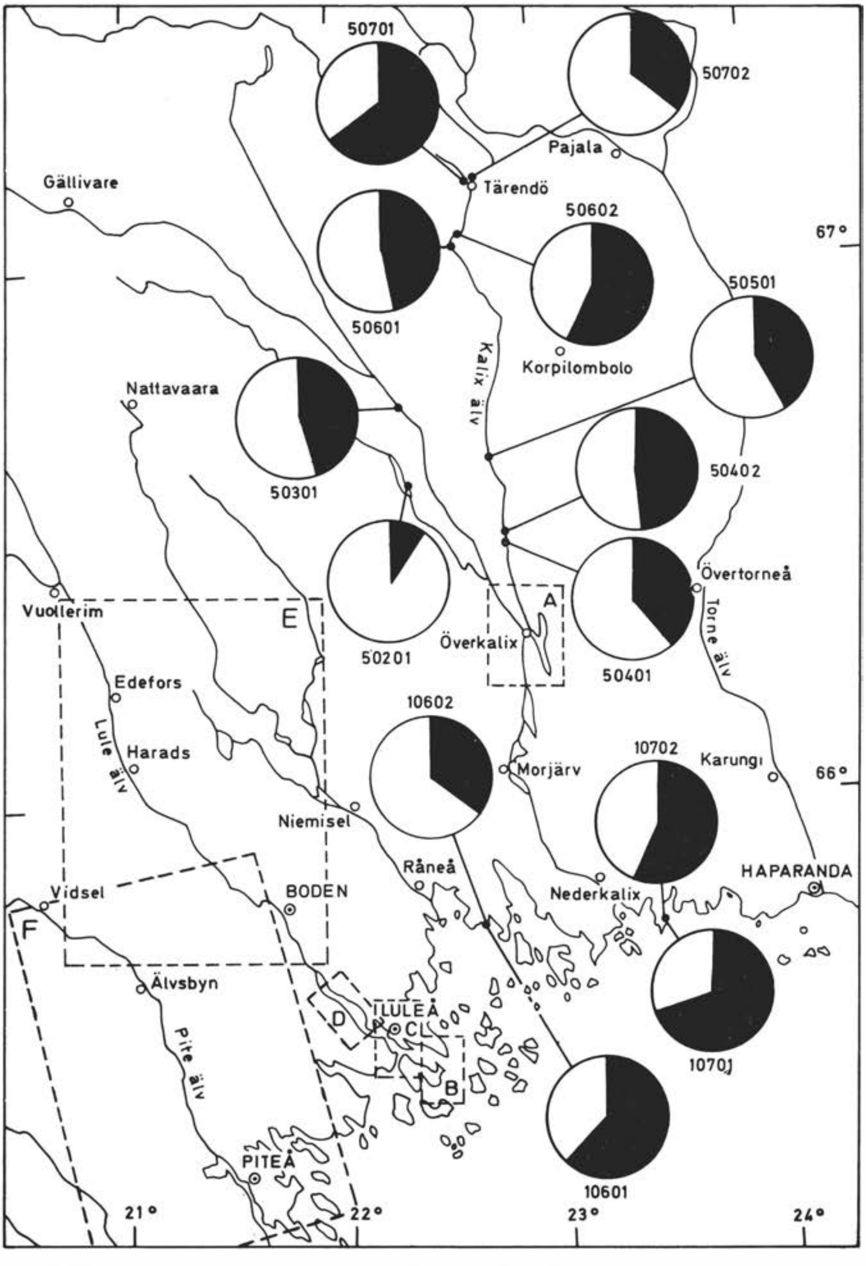


Fig. 16 B. Same as the former map but showing the adjusted magnetite percentages.

Trends within individual areas

These trends are most easily seen by studying the adjusted raw and principal component data together with available maps of bedrock and Quaternary geology. At first the term "adjusted raw data" has to be explained. These data are obtained when the variables of the heavy mineral data are, one at a time, regressed against the "physical factor". The residual matrix so obtained is thereafter "de-standardized" and retransformed back to percentage values. The means of the new values are of course the same, but the standard deviations are smaller because we have removed fluctuations caused by physical phenomena. The data becomes more homogeneous and hence the geological interpretation is made easier. In Figs. 16 B—24 B the adjusted percentages of magnetite are shown and

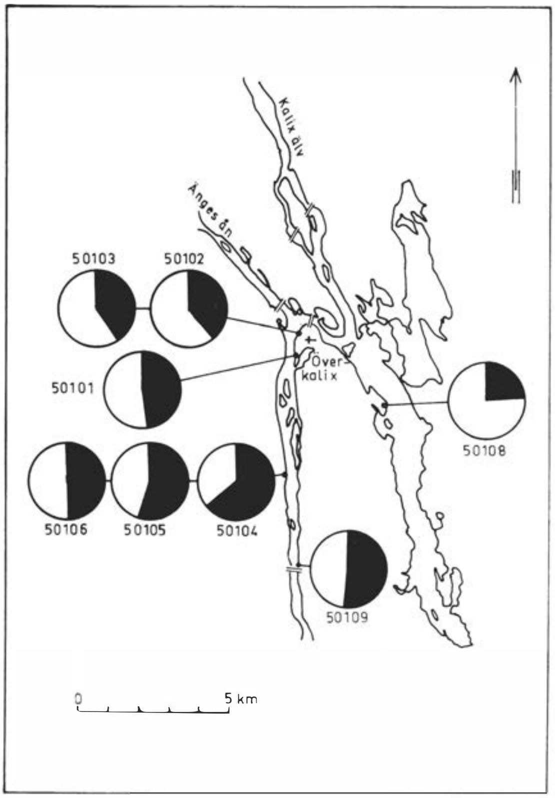


Fig. 17 A. Magnetite percentages in the Överkalix area. — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

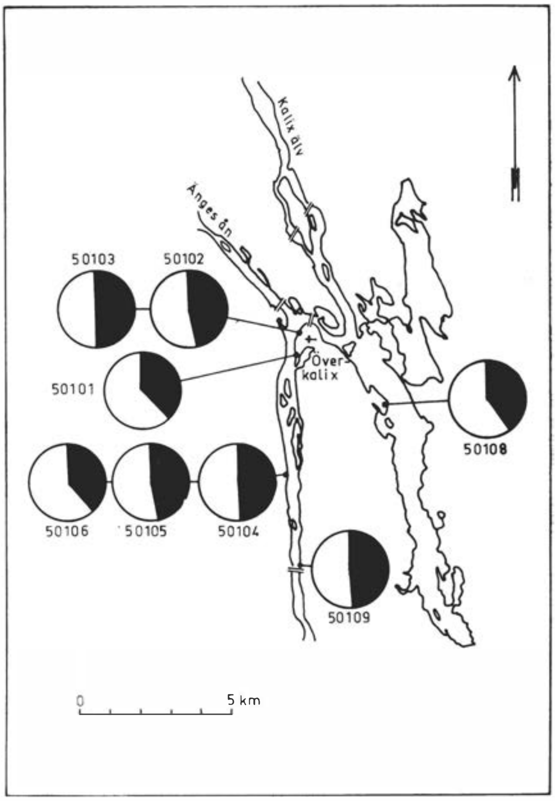


Fig. 17 B. Adjusted percentages (see Fig. 17 A). — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

these should be compared to Figs. 16 A—24 A, which display the raw data. One drawback with the method is that the regressions are calculated over all samples which can sometimes cause false high or low values; for example in sample 20101, there are very low values for magnetite and garnet; diopside and enstatite-hypersthene are very high but opaques are just over the grand mean. This leads to the following situation: as the loadings of diopside and enstatite-hypersthene have high negative values and those for magnetite and garnet have high positive values on the first (the "physical") component, the resulting score will be a strong negative one, and when the loading for opaques is multiplied with the score, the fitted value will be strongly negative which results in a marked positive residual value. The results for opaques in this sample becomes 53,9 % which is a value well over that expected. As a whole, the opaques seem to be slightly overrepresented in the Pite samples. Another drawback, alas not so great, is that many minerals when reported absent still show up, with small values though, in the residuals. Bearing these circumstances in mind when scrutinizing the table of adjusted data and also keeping an eye on the raw data, it should be possible to get out some meaningful results anyway.

The scores for the three largest principal components of adjusted, reduced heavy mineral data were transformed to proportions of the range and row-normalized to produce the pie-diagrams in Figs. 25—33. These transformations should be taken into account when studying the figures; so, for example, a zero-value on the first component does not mean that the sample in question has no metamorphic minerals, but rather that it has the largest negative score on the first component and should therefore be fairly poor in minerals of metamorphic origin. Also worth mentioning is that the communalities across the three components vary from sample to sample, so they are only roughly on the same scale in the maps. Perhaps the circles ought to have been drawn in slightly different sizes.

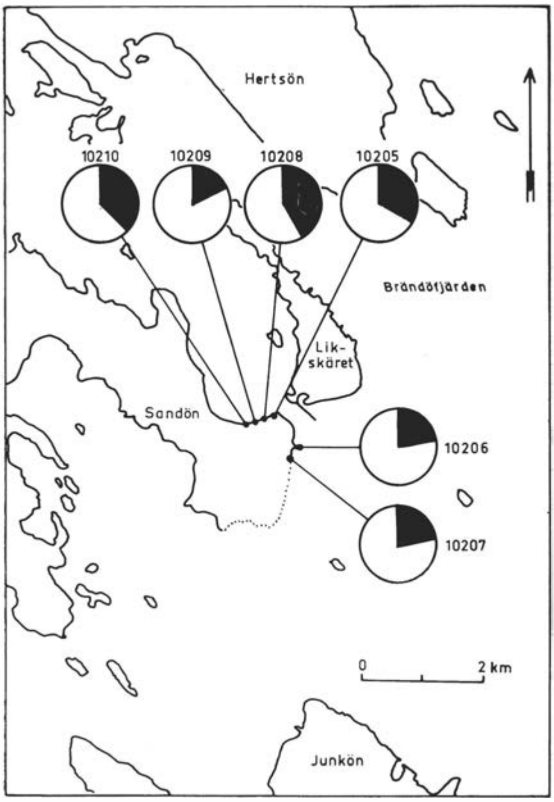


Fig. 18 A. Magnetite percentages in the eastern part of Sandön. — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

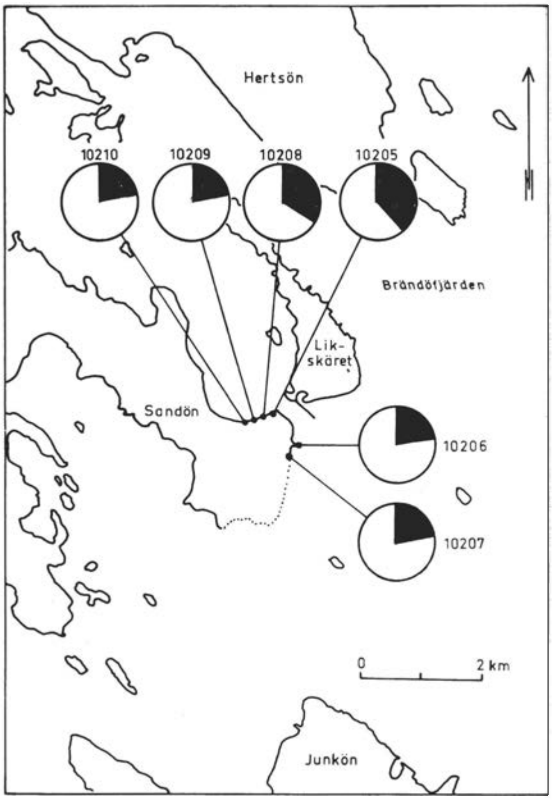


Fig. 18 B. Adjusted percentages (see Fig. 18 A). — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

The Kalix area. — This area is considered first, as it is the largest and many of its samples have for practical reasons been plotted on the key-map. The area consists of samples 10601—10702 and 50101—50702 (Fig. 25). The samples 10601 and 10602 are taken from esker material just where the esker plunges into the sea. The esker runs in a NW direction as far as Niemisel with some breaks in between. The samples are both low on the first PC for heavy minerals and low on the first PC for trace-elements as well. This suggests a comparatively small area of metamorphic rocks traversed by the esker, and a fairly high content of basic rocks. According to the geological map there are diorites and gabbro in the area and also migmatized sedimentary gneisses. The other two heavy mineral "metamorphic" components show differences between the samples, which are rather difficult to explain. Perhaps it reflects differences in the grade of migmatization in the gneisses. A further possibility might be that it is caused by an earlier enrichment which occurred during the formation of the esker.

The other two coastal samples (10701—10702) were also taken from an esker which runs in a NW direction to Morjärv and beyond. The PCA of heavy minerals suggests some more metamorphic rocks than in the former two cases, and the PCA of trace-elements also suggests the presence of basic rocks. This is also the case according to the geological map. The fluctuations in the other two heavy mineral components are difficult to explain here as well, but the same explanations as above may hold. On the whole, samples taken from esker material are more difficult to interpret because of the presumably larger distances travelled by the minerals. The samples from Överkalix and vicinity (Fig. 26) mostly show low values on the first and third heavy mineral PC's and high values on the second PC. This suggests few metamorphic rocks in the area, but the metamorphic rocks should be pelitic in origin, magmatic rocks should

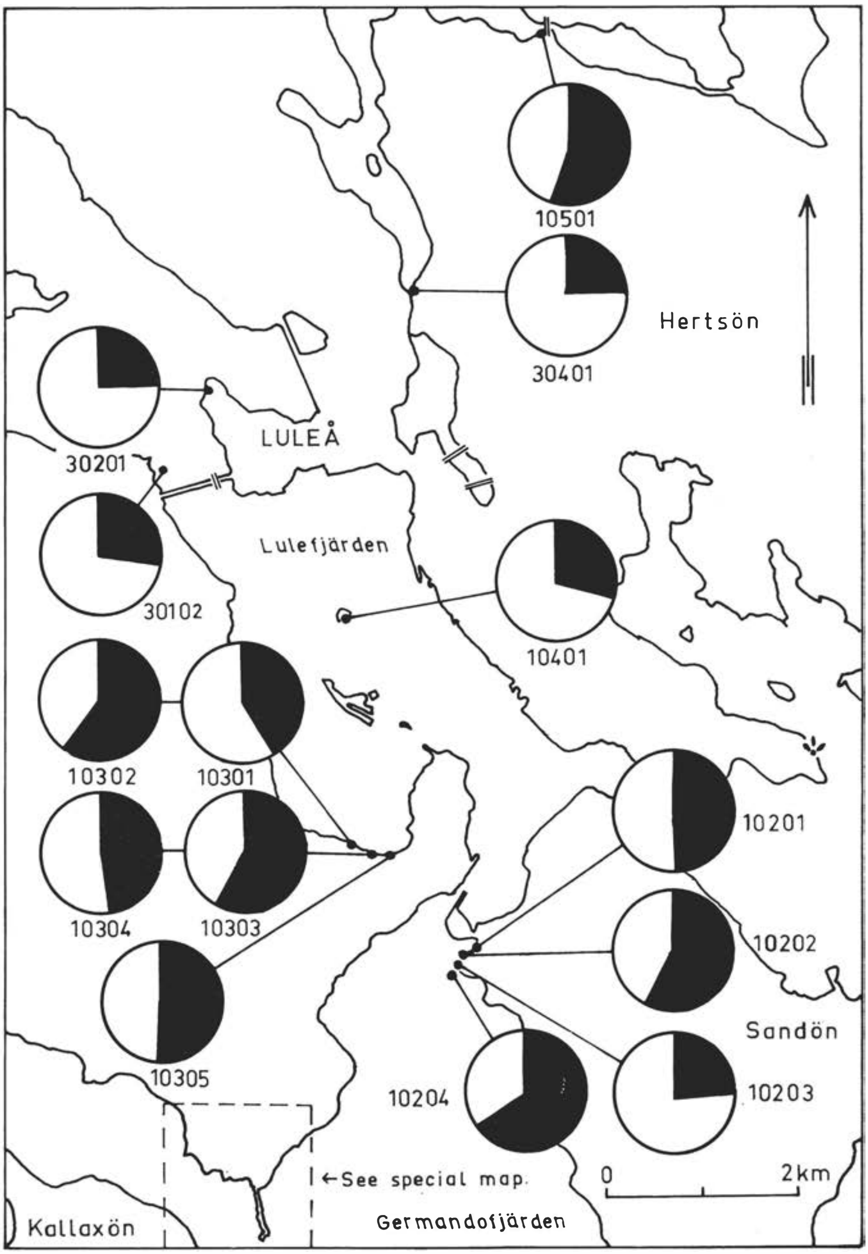


Fig. 19 A. Magnetite percentages in the area around Luleå. — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

be more of the acidic type and the grade of metamorphism where it occurs should be of medium or high grade. The first PC of trace-elements also suggests acidic rocks. From the geological map over the bedrock, it can be seen that the area N and NW of Överkalix is mainly underlain by Lina Granite, and diorites and granites from the Haparanda "Series". But there are also gabbroic massifs and migmatized gneisses of unknown origin together with smaller patches of acid and basic lavas. Comparing the different samples in the area in detail, however, is difficult. One of the samples (50104) stands out from the others by having the lowest scores on the first and third heavy mineral PC's. It should, therefore, be very "igneous" and the metamorphic grade of the metamorphic mine-

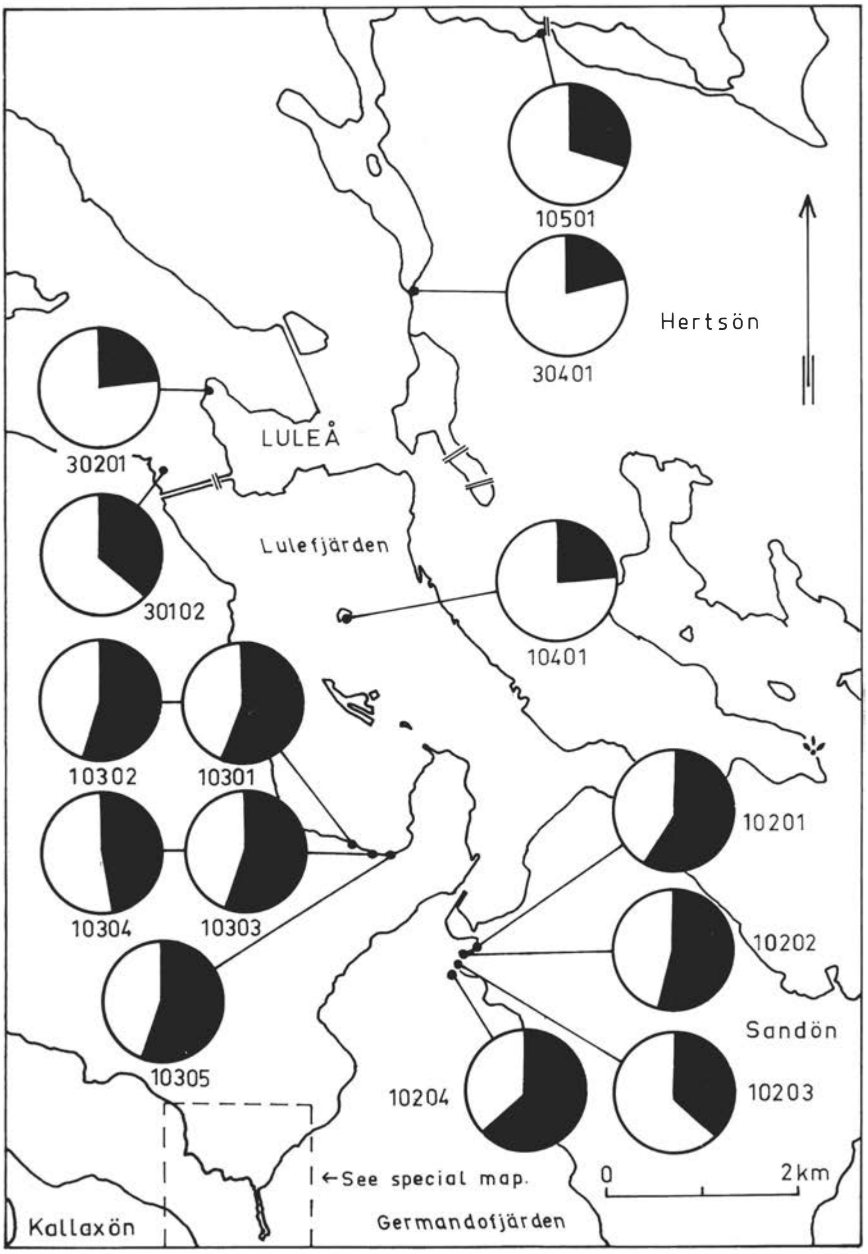


Fig. 19 B. Adjusted percentages (see Fig. 19 A). — Permission for distribution proved by the Security Officer. The National Land Survey (of Sweden) 1978 03 10.

rals should be high. In fact, the sample is taken near the summer water-level in glacio-fluvial material, so the minerals probably originated from the esker and are not swept in by the spring floods. In the area that the esker traverses, there are diorites, acid and basic lavas, and a gabbroic massif in the possible extension of the esker to the NW. Unfortunately the exposures of bedrock are scarce and the bedrock geology is perhaps much more complicated than it appears on the geological map.

The sample taken at Sanningslandet (50201) is taken from a lacustrine sand, according to the map over Quaternary deposits. The sample is low on the first heavy mineral PC but high on the second and third, suggesting few metamorphic rocks

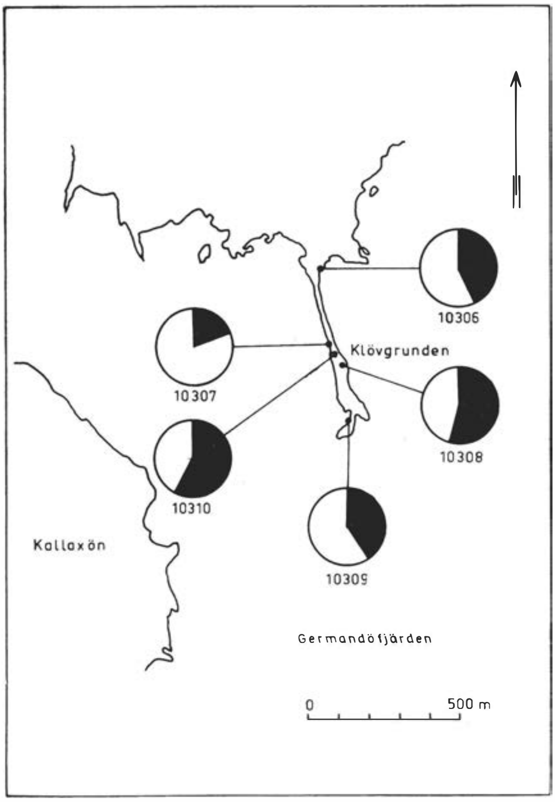


Fig. 20 A. Special map, marked on the former map, of magnetite percentages. — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

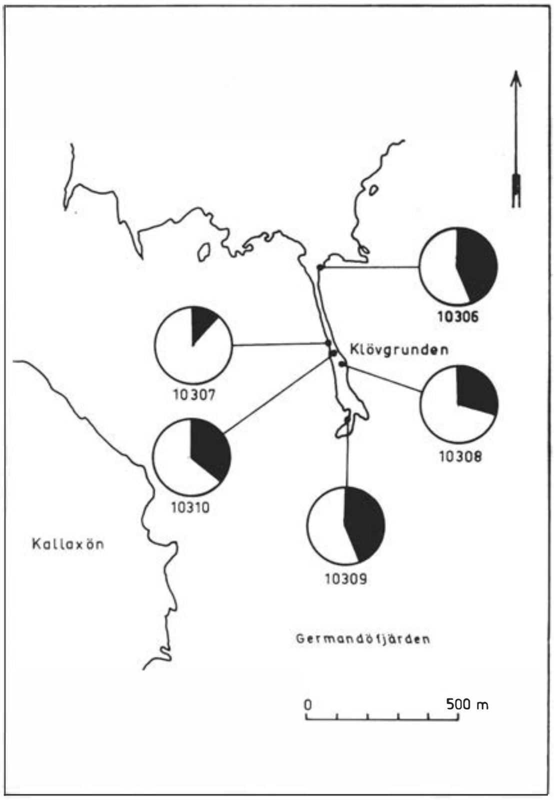


Fig. 20 B. Adjusted percentages (see Fig. 20 A). — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden). 1978 03 10.

in the area; metamorphic rocks present should be pelitic in nature and not of too high grade. The sample is also very poor in magnetite. According to the geological map the area is underlain by Lina Granite and to the west, in the general direction from where the ice moved, there are partly migmatized diorites. According to Fromm (1965), the till in the area contains up to 60 % of Lina Granite, about 20 % of gabbro and diorite, and 20 % of pegmatite and traces of basic volcanics, amphibolite, leptite, porphyry, and gneiss.

An extreme sample is the one taken at Ängeså (50301), which has the lowest score on the second heavy mineral PC. It suggests basic gneisses in the area. By studying the geological maps of the area one finds the spot underlain by Lina Granite, but an extensive esker reaches to the NW towards Gällivare, which traverses several gneisses of which some are of basic, and some of unknown nature. Otherwise the rocks in the path of the esker are Lina Granite and some small gabbroic massifs. The first PC suggests a slight majority of metamorphic rocks in the area of origin and the third shows a low to medium grade metamorphism. In fact, the sample has the highest content of all of epidote and diopside. Fromm (1965) reports about 80 % of Lina Granite in the till of the area, which means that most of the material in the sample has been transported via the esker from the gneissic areas lying to the NW.

Along the main tributary of Kalix River, north of Överkalix, there are two samples from Rödupp and a sample from Jokk (50401—50402; 50501). These are rather alike with high negative scores on the first heavy mineral PC and high positive ones on the second. This implies an abundance of magmatic rocks, and a pelitic origin of the metamorphic minerals. The sediments sampled are from river deposits which first were transported, probably from the west, by the ice, and deposited as till, and then transported southwards by the river. On the map of bedrock geology it can be

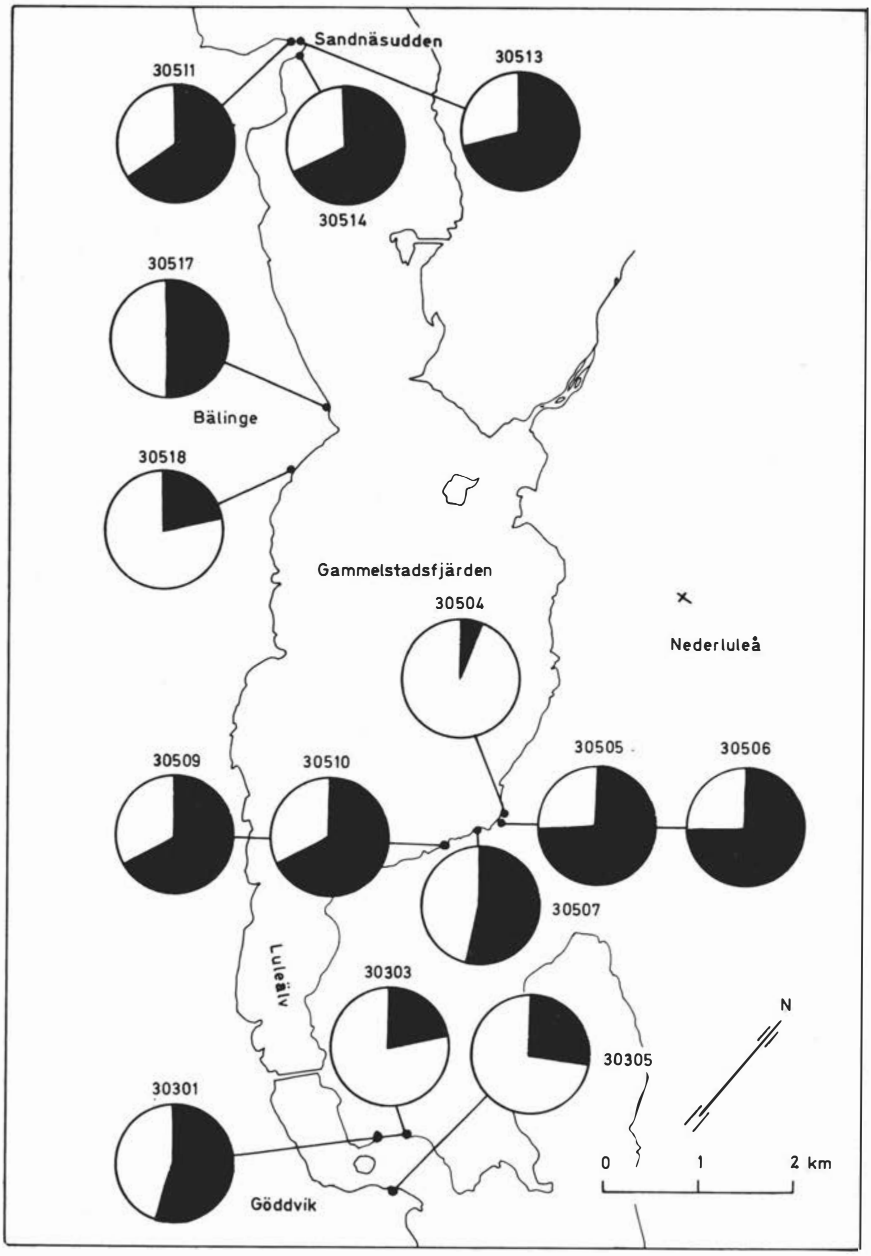


Fig. 21 A. Magnetite percentages in the Gammelstad area, just upstream from Luleå. — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

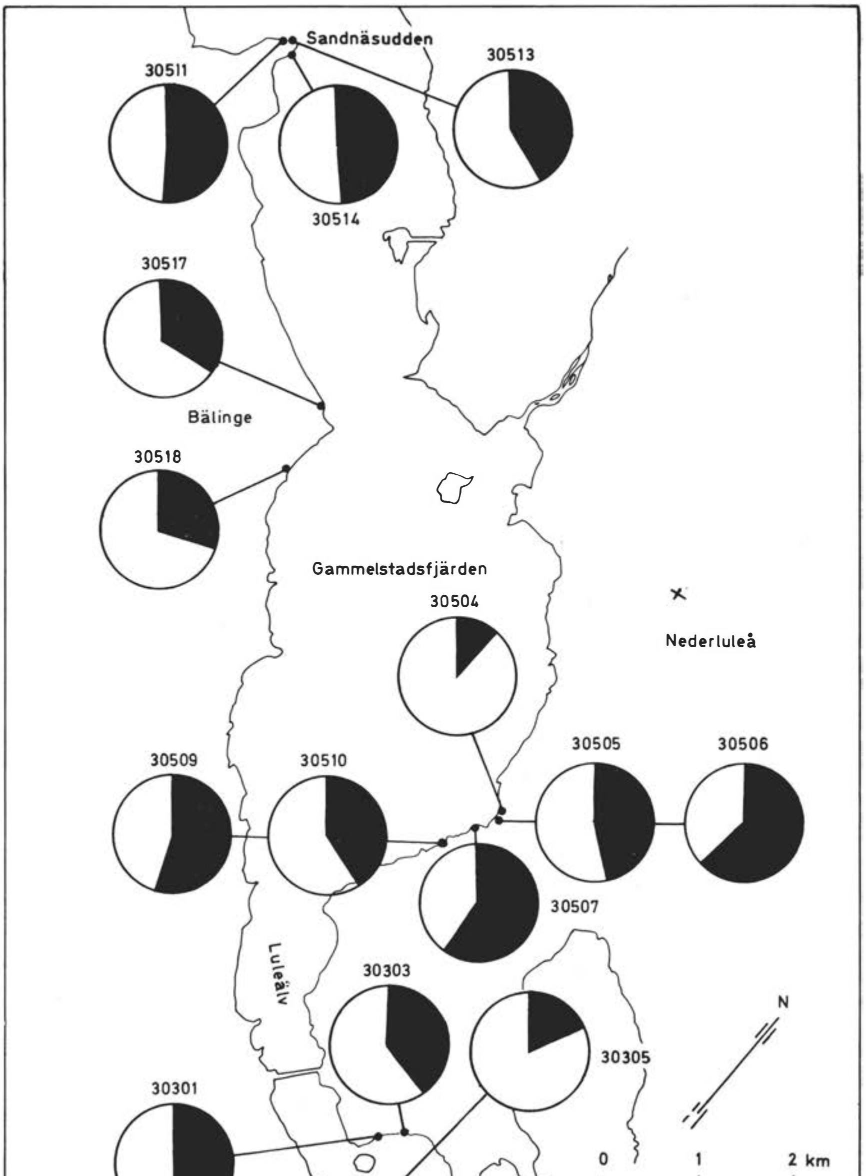


Fig. 21 B. Adjusted percentages (see Fig. 21 A). — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

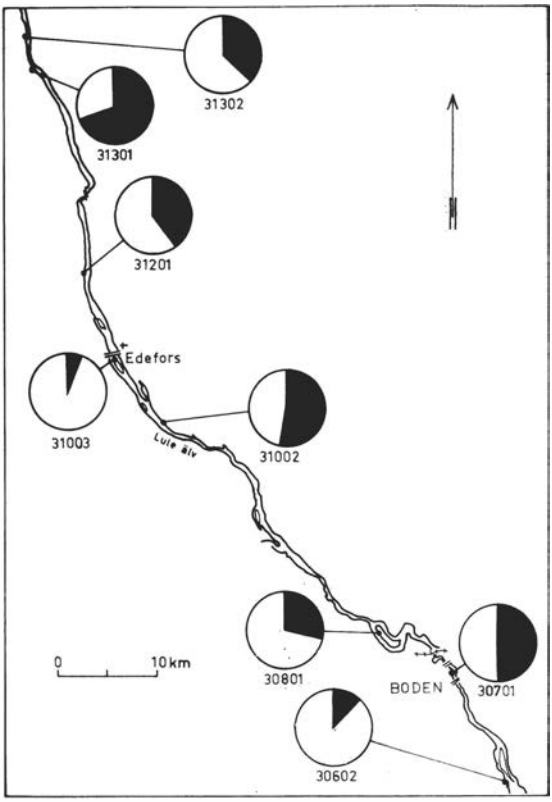


Fig. 22 A. Magnetite percentages in the upper part of the Lule area. — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

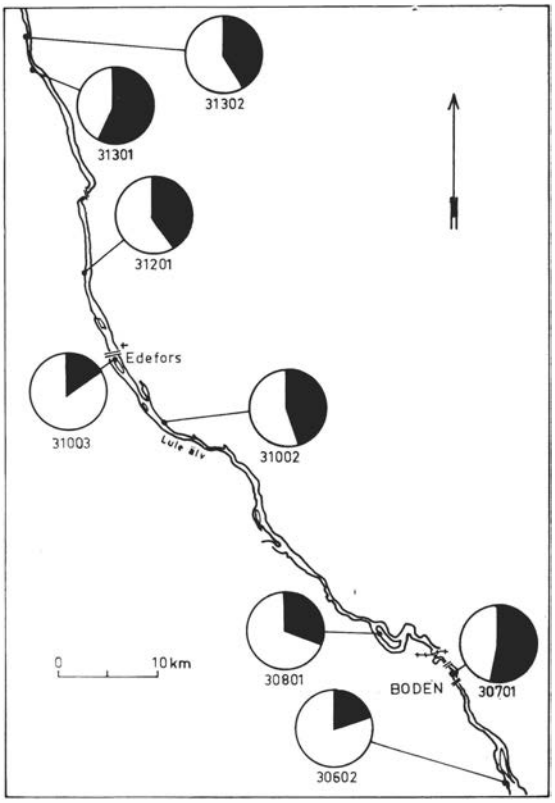


Fig. 22 B. Adjusted percentages (see Fig. 22 A). — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

seen that the area west of the river, and for a considerable distance to the north, consists of Lina Granite with a little gneiss of unknown origin in it. However, the area around Narken (at the river bend NW of Korpilombolo) has quite recently been described by Frietsch (1972). This gives a much more detailed view of the geology in this particular area than can be found in Ödman (1957). Frietsch reports, apart from the Lina Granite, gneisses, and the gabbro at Narken, extensive areas of syenite and deposits of metasediments, which, in places, are metasomatically altered. The syenite contains epidote and hornblende and the metasediments are quite rich in epidote. Also the Lina Granite is often epidotized. This implies that the extensive areas of Lina Granite west of the Kalix River might also bear more complicated features. As the river sediments are quite rich in monazite and kyanite, one might presume that there are, for instance, pelitic gneisses to the NW of Rödupp and Jokk. As monazite is also a "fairly bad traveller", monazite bearing rocks should occur quite nearby. North of these three samples there are two samples taken at the river-bank of a large glaciofluvial delta, Mestoskangas. These samples are quite different to each other as one (50601) seems to be intermediate on the first heavy mineral PC and the second (50602) seems to be rather igneous in nature. Furthermore, the second has a low score on the second and a high on the third PC. These differences are mainly due to a high content of enstatite-hypersthene in 50602 and a high content of monazite in 50601. The area is underlain by perthite-granite with smaller gabbros, and further up the river, which is surrounded by glaciofluvial deposits to Tärendö and beyond, there is another fairly extensive gabbro. Due to natural reasons there are few outcrops of bedrock in the area. Also here, there is a secondary sorting and enrichment of the minerals which make conclusions about the provenance difficult. Further upstream, at the village

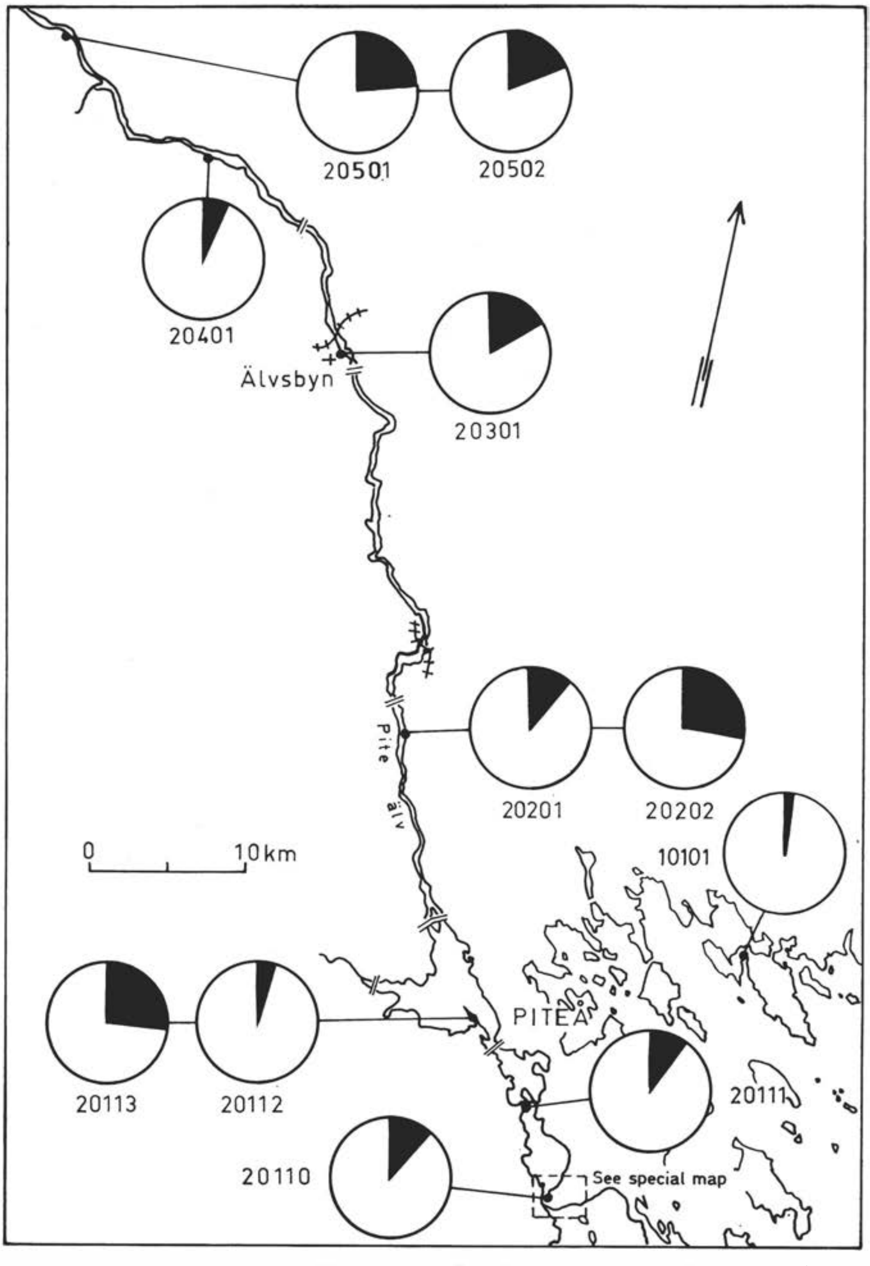


Fig. 23 A. Magnetite percentages in the Pite area. — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

of Tärendö, two samples are taken, whereof one was taken in the Kalix River (50701) above the junction of the Tärendö River, in which the other (50702) was taken. The first sample is from glaciofluvial deposits which stretch along the Kalix River upstream, and the other is taken from river sediments, even if glaciofluvial deposits upstream are not far away. The reason for taking these two samples was to see whether any marked differences existed. The differences in the heavy mineral composition are characterized by a low PC score on the first component in 50701 and a low score on the third in 50702. This means, that samples from the Kalix River area should be more igneous than

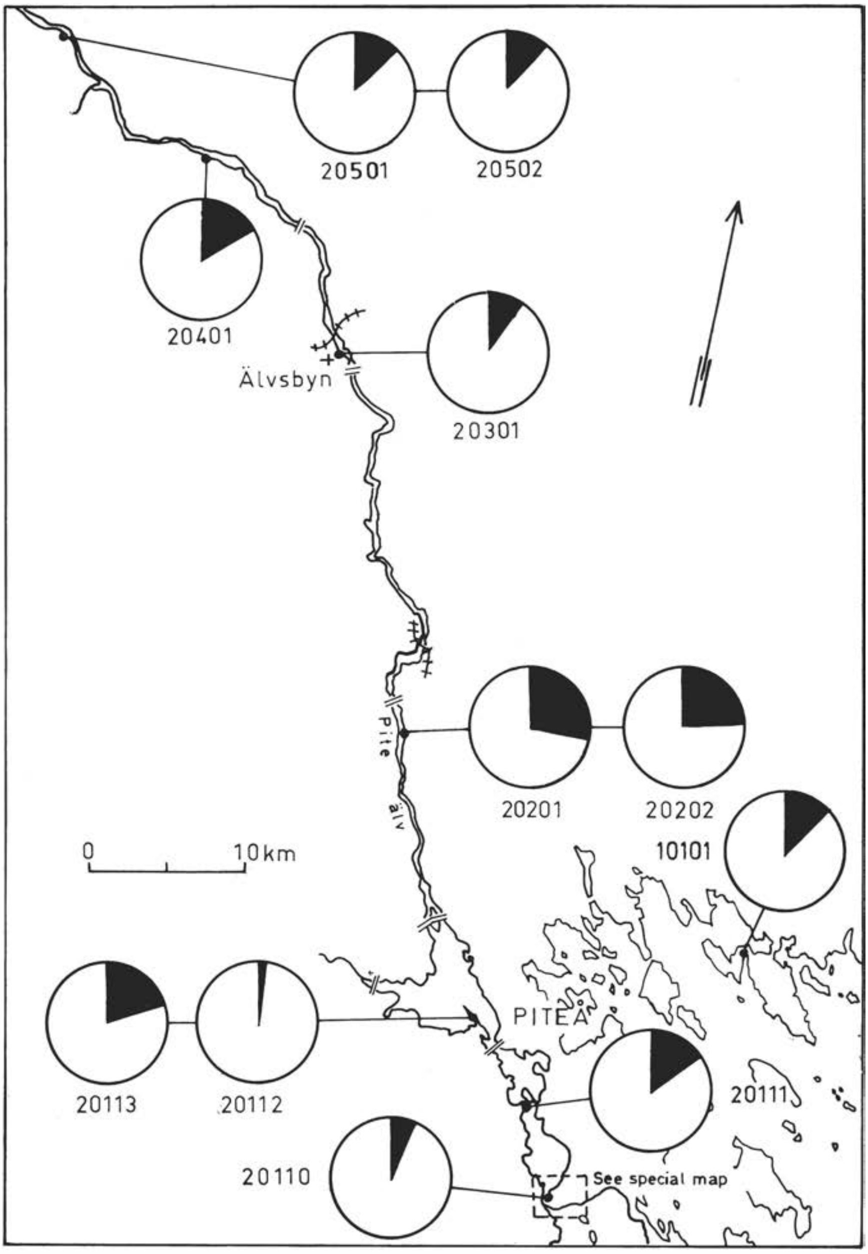


Fig. 23 B. Adjusted percentages (see Fig. 23 A). — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

those from the Tärendö River. On the other hand, this is partly due to the fact that the former sample contains much more magnetite than the latter. It is difficult to draw any conclusions from the heavy mineral data from these two samples as both the bedrock and the Quaternary geology are complex in this area. The areas Mestoskangas and Tärendö have also recently been sampled for heavy minerals in a larger mineral investigation of the Pajala area (Svensson (ed.) 1977). These samples were taken from glaciofluvial material through drilling; no placer investigations were made. The results are, therefore, difficult to compare.

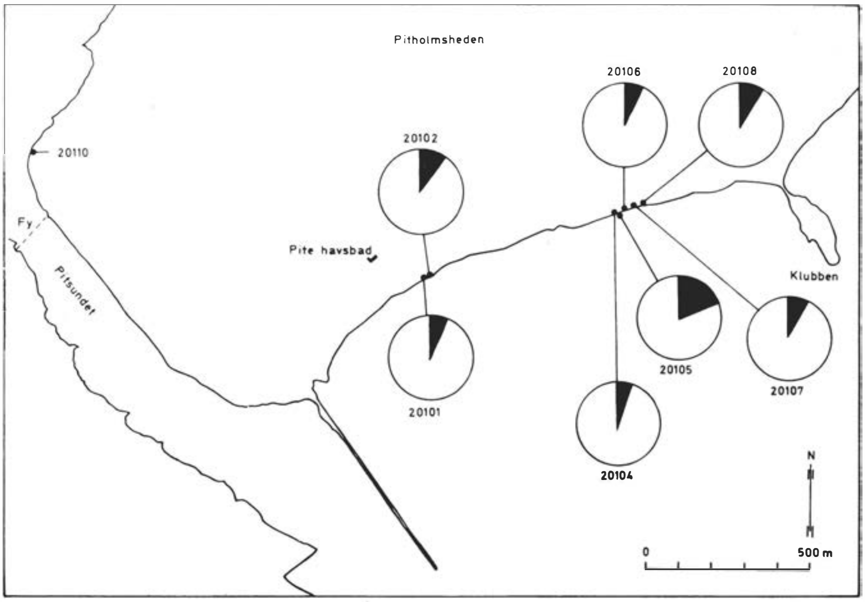


Fig. 24 A. Magnetite percentages on the Pite Beach (special map marked on the former map) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

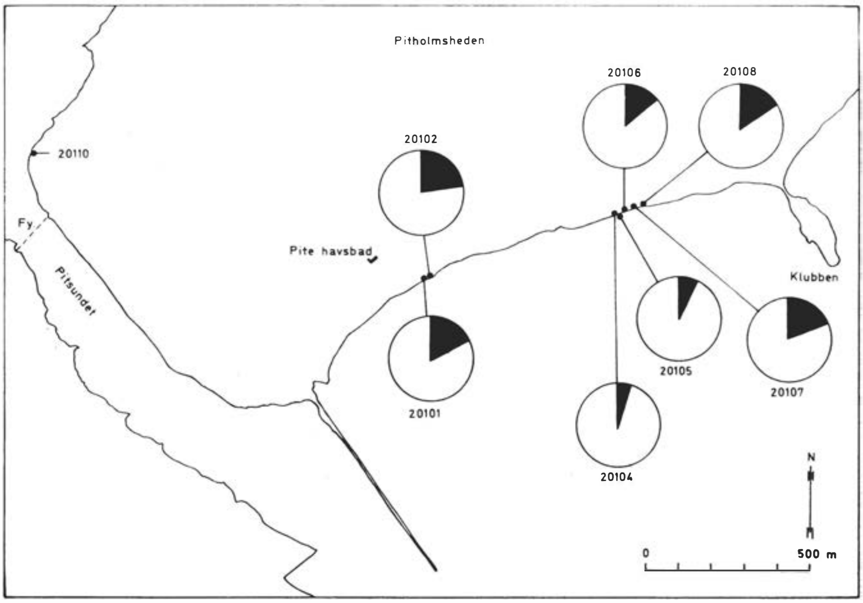


Fig. 24 B. Adjusted percentages (see Fig. 24 A). — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

The Lule area. — On the coast, between Luleå and Piteå on the island of Trundön, a sample (10101) was taken (Fig. 32). This sample is in fact neither a Lule or a Pite sample as mentioned earlier. The sample was taken in sandy sediments, the origin of which is probably from local till. This implies a primary transport from NNW by the ice and then secondary longshore transport

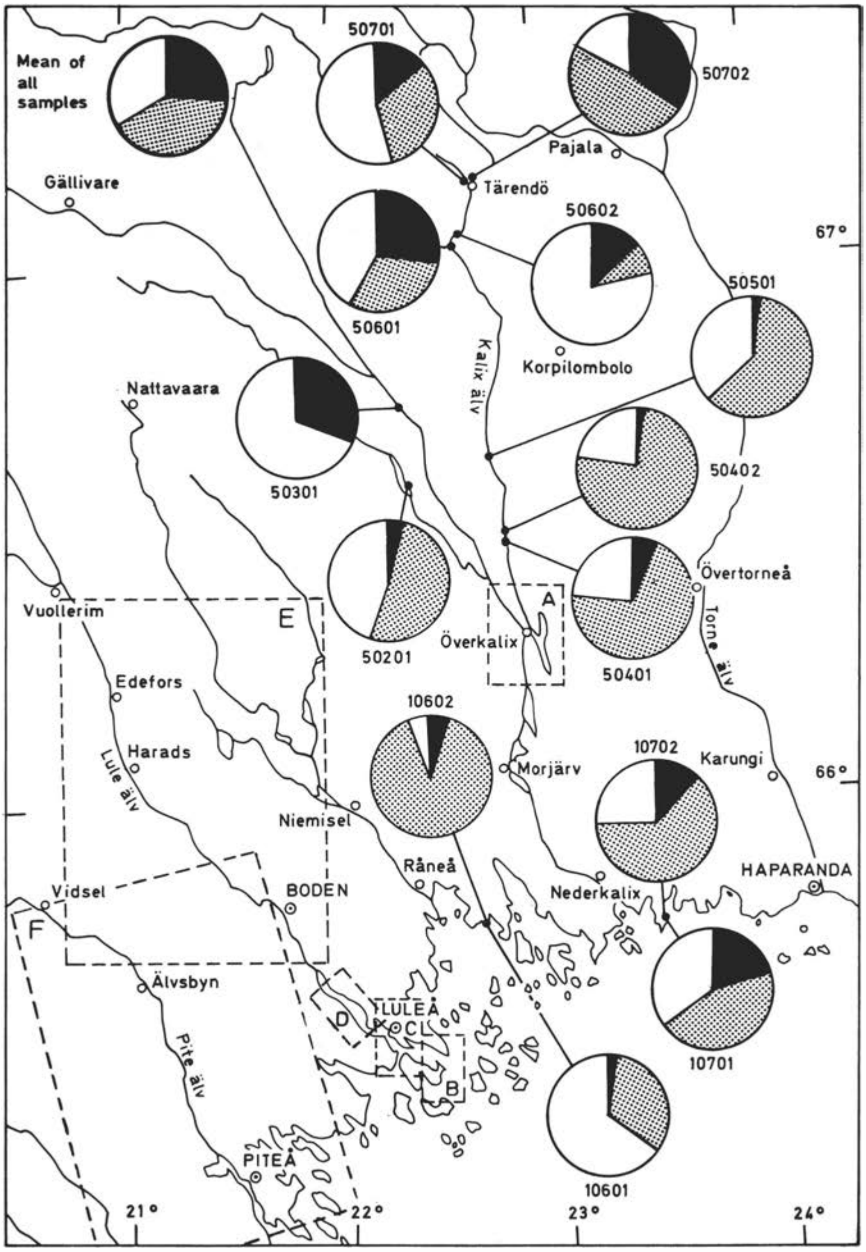


Fig. 25. Proportions of the three largest, adjusted and reduced heavy mineral components in the Kalix area. First component black, second component stippled, and third component white. Scale 1:1585000.

which, in this case, ought to be quite small as the sample was taken from a very sheltered position. The sample has a high value on its first heavy mineral PC and low to very low values on the second and third PC's. This implies a dominance of metamorphic rocks of mafic nature and high grade. According to the geological map the locality itself is underlain by granite of Lina-Arjeplog type but immediately to the NNW there is a small area of migmatized granite of the Haparanda "Series" followed by basic volcanics and some gneissic phyllites, both migmatized. So, in this case, the PCA seems to give a clue about the provenance. Another remarkable feature is that

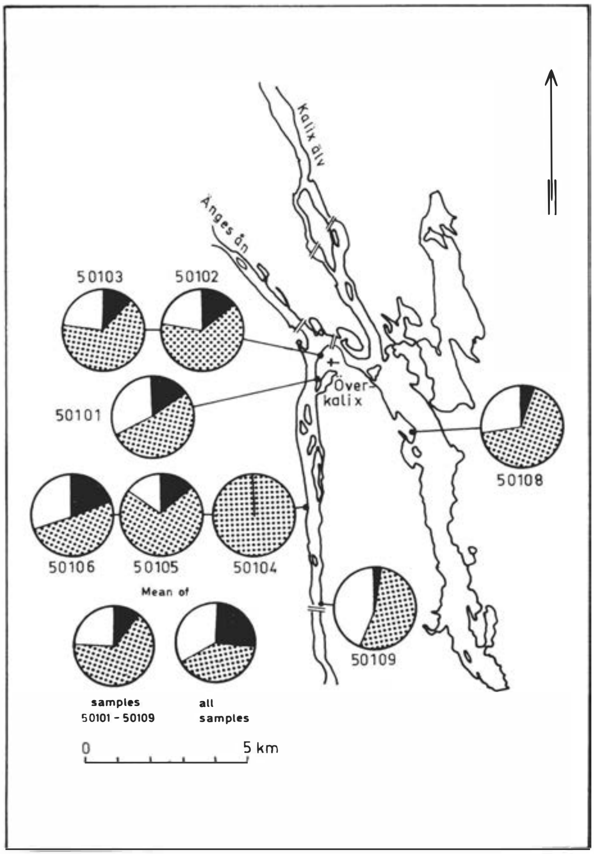


Fig. 26. Proportions of the three largest, adjusted and reduced heavy mineral components in the Överkalix area. (Same symbols as in Fig. 25.) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

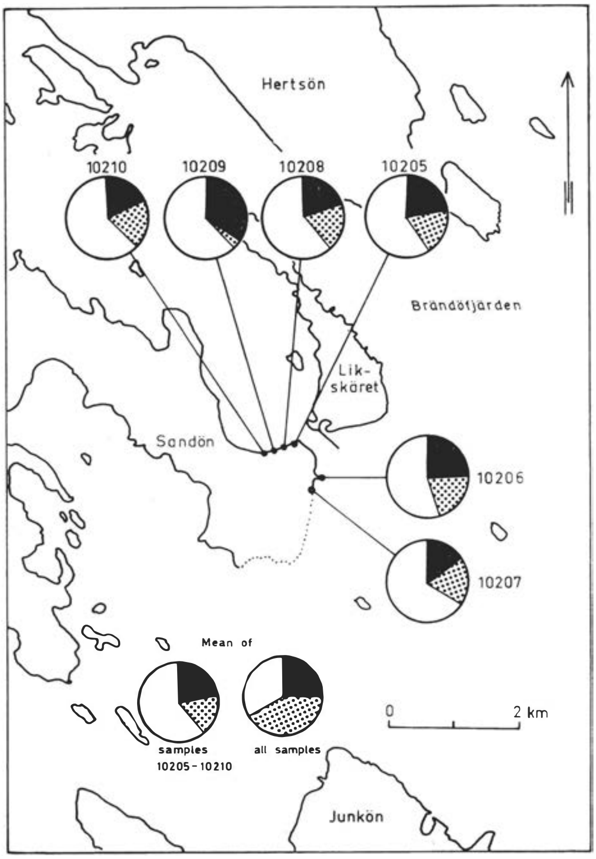


Fig. 27. Proportions of the three largest, adjusted and reduced heavy mineral components in the eastern part of Sandön. (Same symbols as in Fig. 25.) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

this sample is the only one where no cobalt or nickel could be detected. It is also very poor in magnetite.

The samples taken at Sandön (10201—10210) are all from extensive glaciofluvial delta deposits, the direction of which has been that of the Lule River. The samples 10201—05 are located at the strait of Tjuvholmssundet. They are all quite near the mean of the first heavy mineral PC, low to very low on the second and high to very high on the third. It implies that the samples are of both igneous and metamorphic origin and the metamorphic minerals ought to be of the more mafic part and of low to medium grade. The geological map shows Lina-Arjeplog Granites and gneissic intermediate to basic volcanics. To compare the samples among themselves would probably be hazardous owing to their glaciofluvial origin.

Six similar samples were collected at the eastern part of the island of Sandön (10205—10210) (Fig. 27). They all cluster around the mean on the first heavy mineral PC, have low values on the second and high values on the third PC, as was the case for the first four samples. The same provenance seems likely for all ten. The only difference is that the latter samples are poorer in magnetite. The magnetite trace-element PC suggests an intermediate to acid origin which seems reasonable as there are both granites and intermediate to basic metamorphic rocks in the possible source area.

On the mainland opposite Sandön, on a large glaciofluvial delta called Kallaxheden, ten samples were taken (Fig. 28). The first five (10301—10305) were taken in the bight of Lulefjärden. They all have negative scores on their first heavy mineral PC's even if 10304 does not appear to have so. This is due to the high

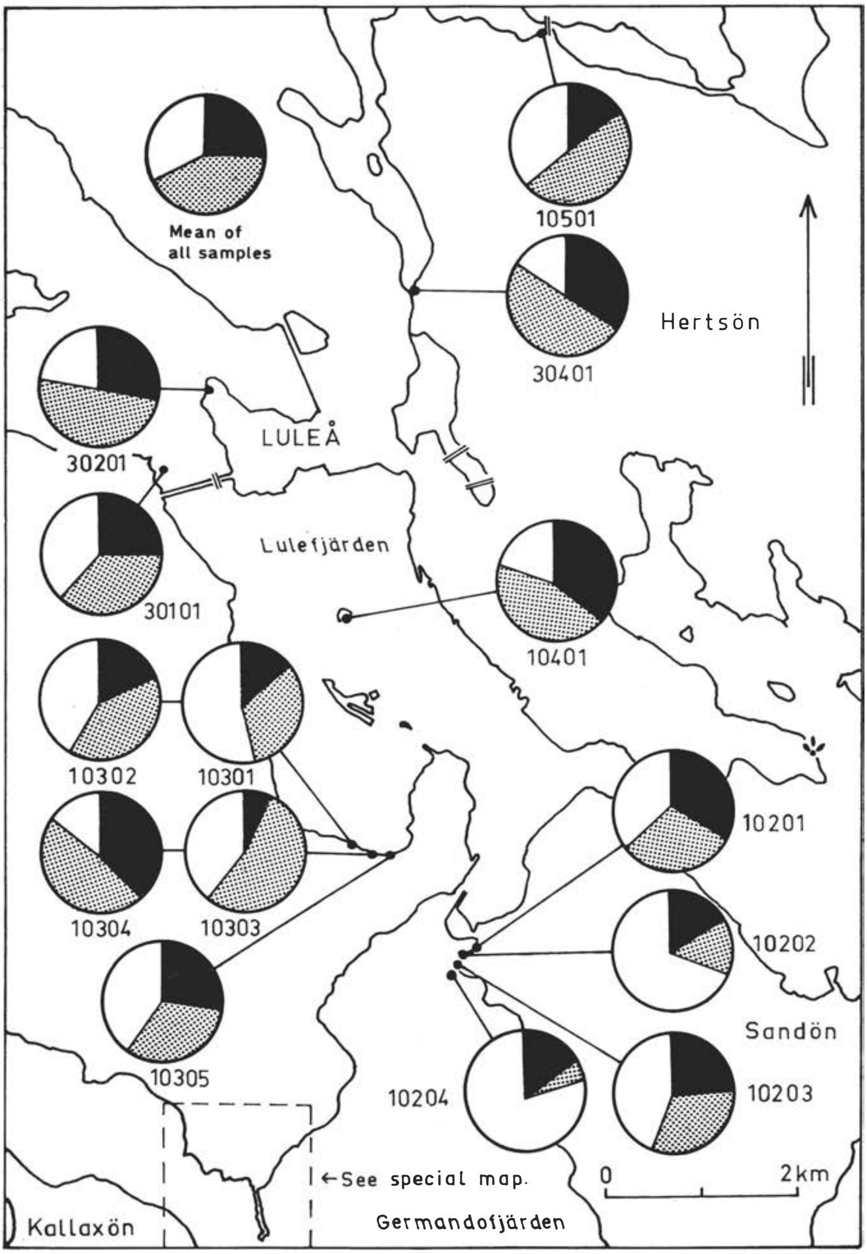


Fig. 28. Proportions of the three largest, adjusted and reduced heavy mineral components in the area around Luleå. (Same symbols as in Fig. 25.) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

negative loadings on the other two; an example of the hazards of closure! The other two PC's fluctuate somewhat, but are quite well centered around the mean or a little above for the third PC. According to the geological map, these samples could also be derived, to some extent, from till with reworked sediments about one to two km to the NW. The area is underlain by Lina-Arjeplog Granite, but there is a small area about two km to the NW with migmatized acid volcanic rocks. This might cause some of the fluctuations in the compositions, as the samples are taken quite near each other but at different levels and might be contributed to differentially

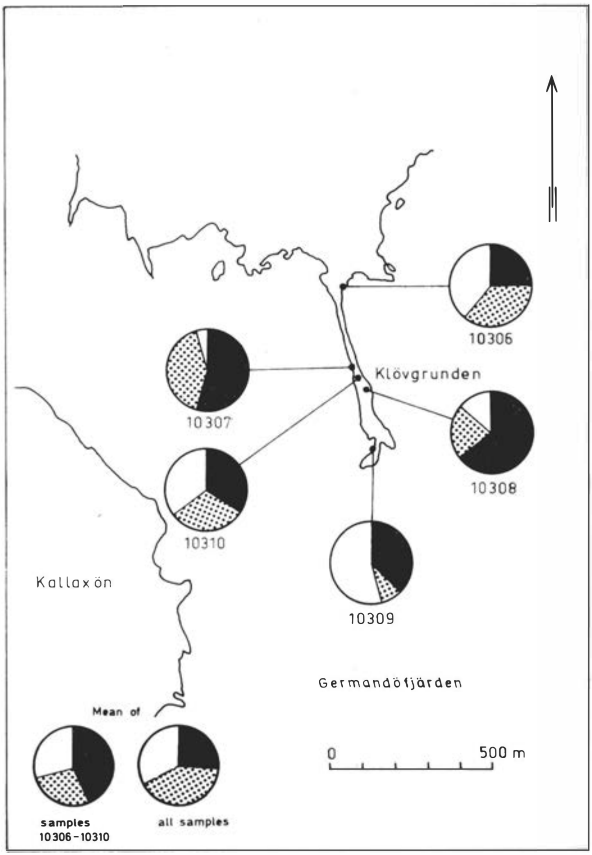


Fig. 29. Proportions of the three largest, adjusted and reduced heavy mineral components in the special area south of Luleå. (Same symbols as in Fig. 25.) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

by material brought in by longshore drift from the above mentioned area. The negative scores on the first PC probably reflects the added amount of granitic material brought in.

At the southern tip of Kallaxheden, there is a locality called Klövgrunden, from where five samples (10306—10310) were obtained (Fig. 29). Here the samples show rather large fluctuations in all heavy mineral PC's. Here is another case where the closure effect is seen, namely in sample 10308, which has a score close to zero in the first heavy mineral PC, but as the other two have very high negative values the first component score will be greatly exaggerated. The first PC scores are close to the mean except in 10307, where it is strongly positive, and in 10306 where it is a little below zero. The second component is strongly negative throughout except in 10307 where it is slightly positive and the third PC varies from about zero to a strong negative value. The mean of the scores on the first component becomes 0,33 which points to a slight dominance of a metamorphic origin. However, as this value is already affected by sample 10308 it could be presumed that this part has been influenced by currents of unknown origin. Otherwise, the samples are pelitic and medium to high metamorphic and there is a slight dominance of granitic minerals. But this spot seems to have been subject to many different physical agents besides those occurring during glaciofluvial transport and deposition, and that a comparison between the samples would need a detailed hydraulic investigation on the site, with a dense sampling grid, probably over several years, which is outside the scope of this work.

The samples in and around the city of Luleå (10401, 10501, 30101, 30201, 30401) (Fig. 28) are all from sands derived from till except 30201, which is from the river bottom. They are all slightly metamorphic in composition according to the first heavy mineral PC except 10501, which is dominantly igneous. The scores of the second PC do not fluctuate very much, keeping near the mean, and indicate that both pelitic and mafic metamorphic rocks should be present. The samples seem to be medium- to high-grade metamorphic in their mineral composition except for 30101, which is more of a medium- to low-grade composition. It is quite natural that the latter sample stands out from the others as it probably has been transported over a considerable distance as bedload. According to the geological map, the bedrock in the area consists of gneissic volcanics of intermediate to basic composition, gneisses of sedimentary origin and migmatized granodiorites and a little granite of the Lina-Arjeplog type.

Where the Lule River flows out from the bay of Gammelstadsfjärden, at Gäddvik, three samples were taken (30301, 30303, 30305), two on the northern side and one on the southern side, all in glaciofluvial material (Fig. 30). According to the heavy mineral PCA, they are all metamorphic in composition, especally 30301, and the two from the northern side of the river are intermediate to mafic in their composition of metamorphic minerals. The sample from the southern side of the river is more pelitic on the other hand, but this is due to its high monazite content; the kyanite content is almost zero. The metamorphic grade should be lower in the two northern samples than in the southern, but this is mainly due to the much lower epidote content in the latter sample. This again shows the hazards of taking samples in

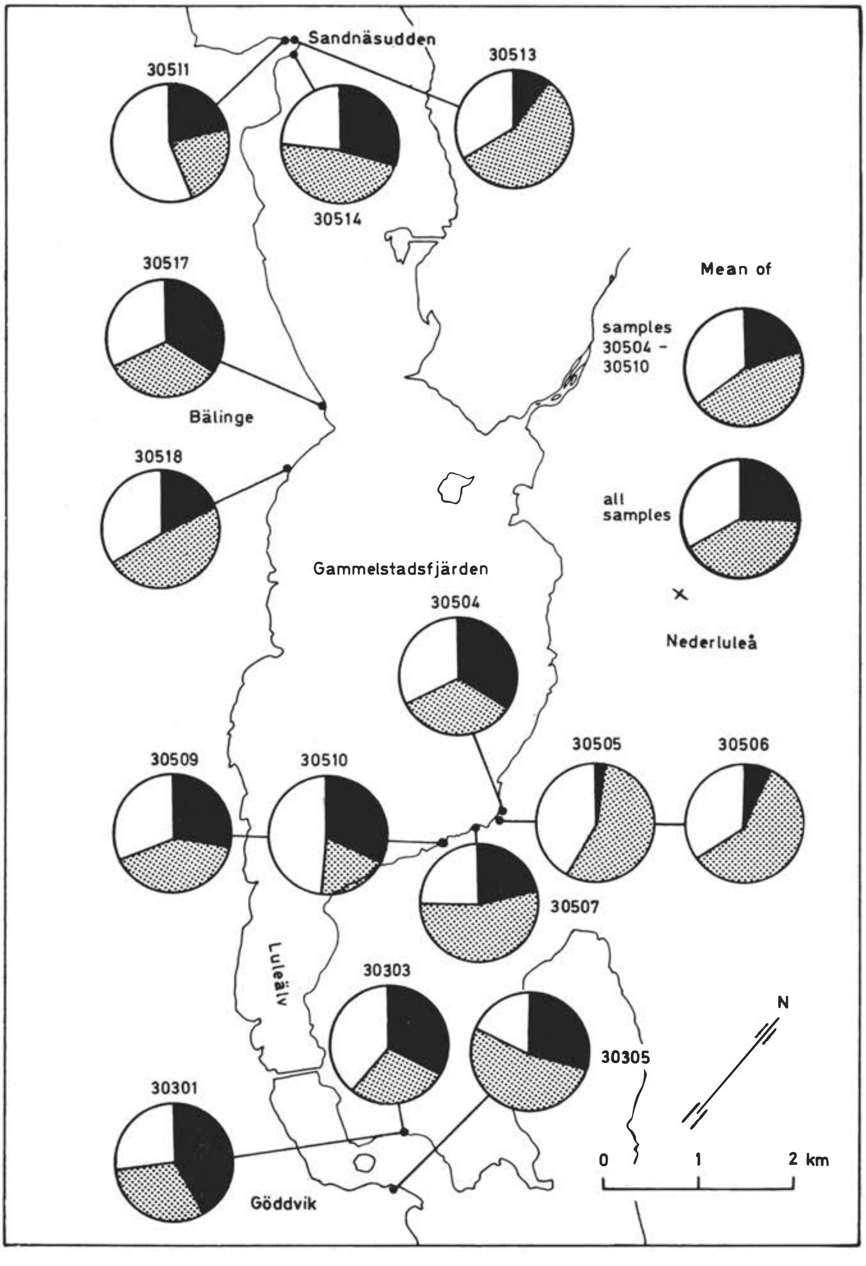


Fig. 30. Proportions of the three largest, adjusted and reduced heavy mineral components in the Gammelstad area. (Same symbols as in Fig. 25.) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

glaciofluvial material without taking due notice of probable erroneous highs or lows of certain minerals caused by enrichment or dilution during the glaciofluvial processes. According to the geological map, the promontory where the northern samples are taken, consists mainly of gneissic intermediate and basic volcanics and a little Lina-Arjeplog Granite as on the southern side of the river. Northwards on both sides of the river there are granodiorites and on the western side, at Bälinge, there is the Bälinge Conglomerate, and further to the north on the same side of the river, Lina-Arjeplog Granite.

On the northern side of the same promontory

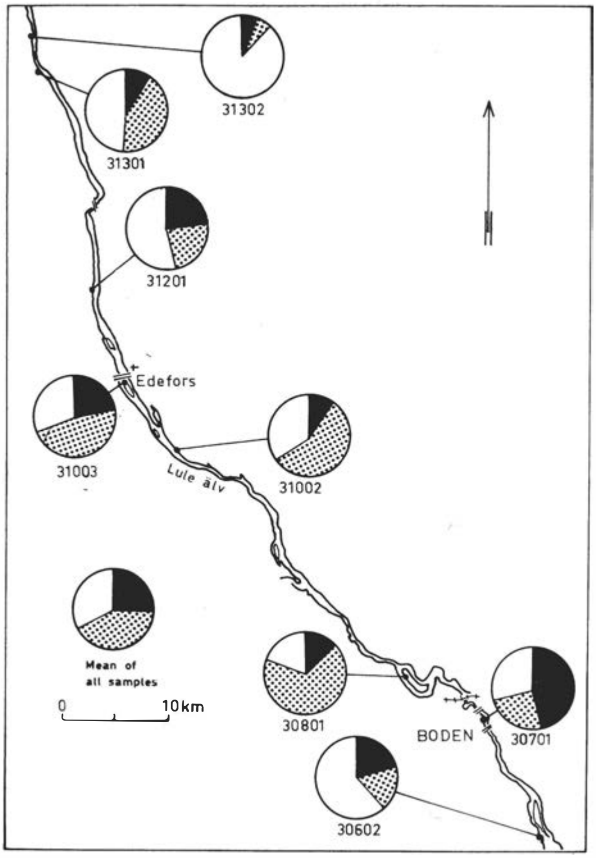


Fig. 31. Proportions of the three largest, adjusted and reduced heavy mineral components in the upper part of the Lule area. (Same symbols as in Fig. 25.) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

as from where 30301 and 30303 were taken, six samples were collected (30504—30507, 30509—30510), all in glaciofluvial material. These samples shaw fluctuations similar to those at Klövgrunden (10306—10310). If the mean is taken for the scores of the first principal component, however, a mean score of −0,82 is found which denotes a dominance of magmatic rocks. The same operation on the second PC gives −0,30 and on the third −0,20. This implies that an "ideal" sample is, as already stated, dominantly magmatic; the metamorphic minerals are mainly of mafic origin and of a medium to high grade. The first PC of the trace-elements of magnetite also shows a marked trend towards basic rocks. As the rocks on the NE side of the river are dominantly granodiorites and the metamorphics, occurring further up, are migmatized gneissic intermediate to basic volcanics, the "ideal" sample seems to adequately describe the situation. Further north, and on the opposite side of Gammelstadsfjärden, two samples were collected at Bälinge, in glaciofluvial material (30517—30518), and further north, on the promontory of Sandnäsudden, three more were collected (30511, 30513, 30514), also in a glaciofluvial deposit. The latter three samples have a mean score on the first heavy mineral PC of −0,85, −0,55 on the second and −0,37 on the third. This implies a dominance of igneous derivatives, with the metamorphic rocks of mainly mafic origin with a medium to high grade. If the geological map is studied, the results seem plausible since the granites are nearby and the migmatized basic rock lie beyond. The other two samples, those at Bälinge, are more difficult to interpret. They have positive scores on all three PC's considered which should mean a dominance of metamorphics of pelitic nature and low to medium grade. As they occur further downstream they ought to be more igneous than the former three samples. Furthermore, pelitic metamorphic rocks, which are of low grade are some distance away. Of course, the "pelitic" trend may reflect the Lina-Arjeplog Granites but the samples are very difficult to interpret. The geology of the bottom of Gammelstadsfjärden is not known but it should not bear too many surprises. Where the Lule River "proper" flows into Gammelstadsfjärden, at Unbyn, one sample (30602) was taken from river sediments (Fig. 31). This has a fairly high score on its first heavy mineral PC, a slightly negative on the second and a very high on the third one. This suggests a dominance of igneous rocks in the source area and the metamorphic rocks should be of low to medium grade, and intermediate to mafic in composition. This sample contains a large amount of epidote which causes the third PC score to have such a high value. The first PC score is fairly straightforward as there is a dominance of igneous rocks. It might get its metamorphic part from two areas, either from nearby where there is a gneissic intermediate to migmatized basic volcanic rock, which may have been carried as glacial drift towards the river valley, or from an area north of Boden with acid gneisses. Furthermore, the Edefors Syenite, which the river runs through all the way from Boden, also carries epidote as an accessory mineral.

The sample at Boden (30701) is from river sediments and has rather high a positive score on its first heavy mineral PC, rather high a negative on the second and a low negative on the third. A majority of metamorphic rocks might be expected, which are predominantly mafic and mostly of medium to high grade. The locality is situated on Edefors Syenite, which soon changes upstream into a partly migmatized granodiorite and further up there are basic gneissic volcanic rocks. The influence of the acid gneisses north of Boden is probably not so great since they have most probably been transported by the ice, as drift in a path which does not cross the river until further south of Boden. So this sample could give a clue about the composition of the rocks upstream.

Further upstream, on the island of Kusön, comes the next sampling site from where 30801 was taken. It was taken from sandy river sediments which originate in the till upstream. This sample is somewhat different from the former as it, according to the PCA of heavy minerals, should be fairly igneous, but its metamorphic minerals are pelitic and of medium to high grade. The PCA of trace-elements in magnetite points to an acid composition. Furthermore, the sample is quite rich in monazite. Igneous rocks are abundant, granodiorites, partly migmatized, and Lina-Arjeplog Granites and basic volcanics are found if we follow the river upstream. Pelitic gneisses, however, are not reported, and monazite usually originates from these (Overstreet 1967). This mineral can also occur, however, in granites and pegmatites but seldom in granodiorites (ibid.). Because monazite does not survive transport well, its origin still remains problematical.

The next sample (31002) was taken from a sandy river sediment south of Edefors. The heavy mineral PCA points to a mainly magmatic origin, but its metamorphic minerals show an intermediate composition of medium to high grade. The sample locality is underlain by quartzite, and on the opposite side of the river there are extensive areas consisting of Edefors Granite. Upstream, there are patches of diorite and gabbro and an area of migmatized volcanics; the Edefors Granite then stretches for some 30 km further north. After that, in the Palja Granite, there are patches of migmatized acid gneisses. The PCA does not contradict the geological map.

The following sample (31003) was collected on an island close to Edefors church and was taken from sandy river sediments. It has a high score on its first heavy mineral PC, even if it does not appear so on the pie-diagram. It suggests a metamorphic dominance in the source areas. It is very high on its second component and high on its third. Accordingly the minerals should be of mainly pelitic origin and of fairly low grade. This does not agree closely with the geological map. The "pelitic high" is mainly caused by an unusually high amount of monazite in the sample. The sample is, furthermore, poor in magnetite and opaque minerals, which together with the facts above, point to some hitherto unknown pelitic gneiss nearby.

Sample 31201 was taken at the mouth of a young ravine, cut into fluvial valley deposits, where the older sediments are redeposited. According to the heavy mineral PCA, the sediments are of both magmatic and metamorphic origin with an excess of mafic metamorphic minerals, due to surprisingly little monazite in the sample. The metamorphic minerals are furthermore of low to medium grade. The locality is underlain by Edefors Granite, but this may contain unknown gneisses. Some of the mafic minerals, especially enstatite-hypersthene, may also originate from gabbroic massifs traversed by an esker which makes a junction with the river upstream.

Some 25 km further upstream, sample 31301 was collected in a sandy river sediment. The sample has a negative score on its first heavy mineral PC indicating dominance of igneous rocks in the source areas. The second component has a high positive value suggesting pelitic rocks as the dominant metamorphic rocks, even if epidote is quite abundant. The third component points to a low grade of metamorphism. The sample was taken at a point underlain by a gneiss of unknown origin, and around the gneiss on its northern side there is an extensive area consisting of Palja Granite.

About 4 km further upstream, the next sample (31302) was taken from sandy river sediments where a creek flows into the river. The heavy mineral PCA suggests a predominance of igneous rocks in the source areas and the metamorphic rocks present should be greatly dominated by mafic types of medium to low grade. The area is underlain by Palja Granite, but not too far upstream the river divides with one tributary, the Stora Lule älv, coming from an area with, except for Palja Granite, Arvidsjaur Granite and acid gneissic volcanics. The other tributary, the Lilla Lule älv, comes from an area of gabbros, acid volcanics and Palja Granite. The sample is very rich in amphiboles, but the Arvidsjaur Granite contains much hornblende, which may give the high negative score on the second component. The sample is also very poor in monazite and lacks kyanite, so the acid gneisses do not seem to contribute very much to this sample.

The Pite area. — Seven samples (20101—20102, 20104—20108) were collected on a beach, consisting of glaciofluvial deltaic material, south of Piteå

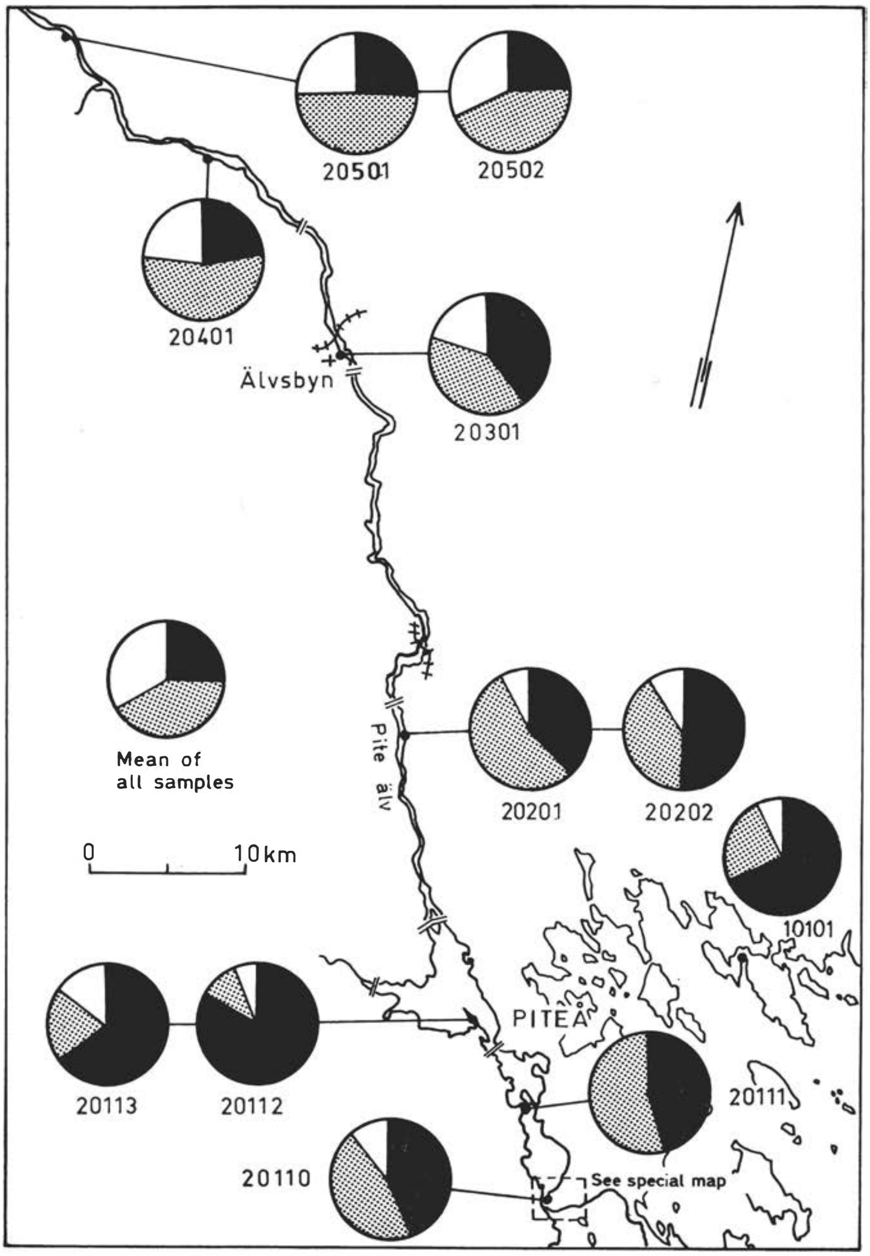


Fig. 32. Proportions of the three largest, adjusted and reduced heavy mineral components in the Pite area. (Same symbols as in Fig. 25.) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

(Figs. 32 and 33). This material was transported to its present site mainly from NNW, where an esker stretches along the Pite River, although today it remains only in certain places. Some material was probably also transported to this site along the valley of the Lillpite älv, which runs from NW into the bay north of Piteå. The scores of the PCA of heavy minerals for these seven samples fluctuate a great deal, at least for the two first components, which is common in glaciofluvial samples. The mean score for the first PC, which is 0,67, points at a dominantly metamorphic origin. The second com-

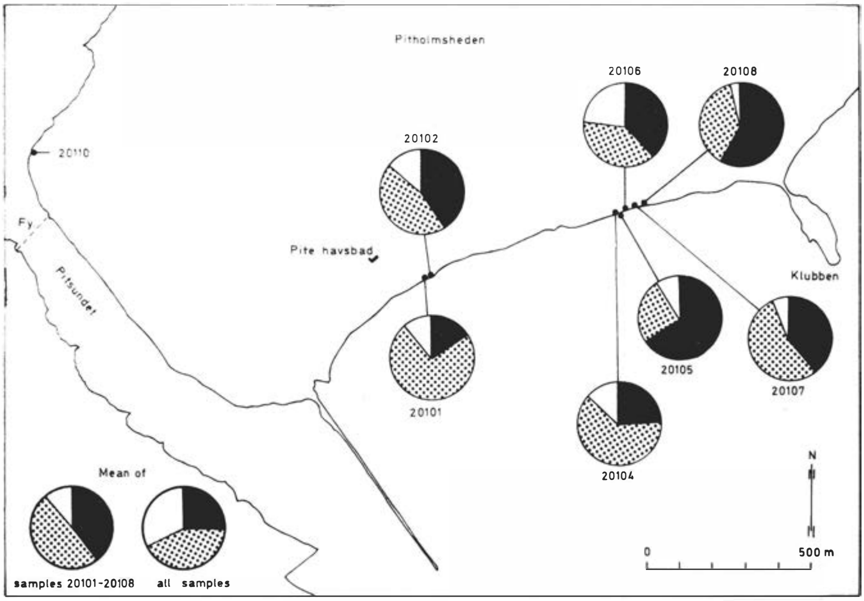


Fig. 33. Proportions of the three largest, adjusted and reduced heavy mineral components on the Pite Beach. (Same symbols as in Fig. 25.) — Permission for distribution proved by the Security Officer. The National Land Survey Office (of Sweden) 1978 03 10.

ponent's mean score is —0,14 and suggests both pelitic and mafic metamorphic rocks in the source areas and the third, which is constantly highly negative, with a mean score of —1,42, suggests a high grade of metamorphism. The probable source rocks consist to an overwhelming extent of gneissic phyllites, which are interlayered with mafic zones and are highly migmatized. There are also areas with Lina-Arjeplog Granite within the gneiss. The PCA of heavy mineral data gives a fairly good description of the provenance of the minerals.

On the same glaciofluvial delta, but close to the northern mouth of Pitsundet, the sample 20110 was collected. It is very similar to the former seven samples and should have the same area of origin.

The samples 20111—20113 were taken from the esker "feeding" the delta of Pitholmsheden. Also these show the same features as the former samples. To discuss the differences between the samples is rather meaningless at this point, since it would demand a more detailed study of the glaciofluvial deposits themselves.

The samples at Arnemark, 20201—20202, were collected in sandy river sediments. According to the PCA of heavy minerals their source areas should consist of mainly metamorphic rocks of mostly pelitic nature and high grade. The gabbroic massif, a little further upstream from this locality does not seem to have much influence on the composition of these two samples; nor the syenite at Älvsbyn appears to have contributed very much, as it is reported to be fairly rich in hornblende and exceptionally rich in zircon; amphiboles are rather sparse in these samples and zircons are almost completely absent.

The sample site at Älvsbyn is located at an esker, the same esker as the one at Piteå. About 10 km north of Älvsbyn this esker divides into two equal parts, one following the path of the river and one coming almost from the north. The part of the esker running along the Pite River is more or less redeposited by the river. The score of the first heavy mineral PC has the highest value of all, 4,49, which indicates a great dominance of metamorphic rocks in the source areas. The second component's score is also the highest of them all pointing to a great dominance of pelitic rocks. In fact, diopside and enstatite-hypersthene are completely lacking. The third component's score suggests low- to medium-grade metamorphism. The source rocks of this sample are probably, to a great extent, the acid gneissic volcanic rocks north of Älvsbyn. Neither the syenite at Älvsbyn nor the gneissic basic volcanic rocks further upstream seem to have contributed very much to this sample.

Some 15 km further upstream a sample, 20401, was taken from a river sediment. According to the PCA of heavy minerals the original rocks producing this sample should be mainly of metamorphic type, pelitic composition and of medium to low grade. If this is correct, the minerals should originate from acid low to medium grade gneissic rocks 60—70 km to the NNW; at least a great deal of the garnets should have come from this area. The high monazite content in this sample is difficult to explain.

The two samples at Vidsel, 20501—20502, were also collected from river sediments. They show a composition very similar to that of sample 20401, and their provenance is probably more or less the same. A feature supporting the theory of the gneissic acid volcanics being source rocks of a great deal of the minerals, is that a rather magnificent esker leads from this area down towards the Pite River. The Arvidsjaur Granite in the area has certainly also contributed to these samples but it is difficult to distinguish its role from the data.

The trace-element data of the magnetite has not been of much help among the Pite samples, because very little is known of the trace-element content of magnetite in these rocks.

Final remarks and conclusions

The main difficulty in an investigation of this sort lies in the fact that the grains have been transported in several steps. First the ice removes from the bedrock the material which is then transported as glacial drift during the progression. Then, during the period of retreat, a glacial stream transports the debris again and deposits it as an esker. Finally, in postglacial time the present river again transported and deposited the material. Of course, not all of the above processes have always occurred. For instance, the glacial stream could very well have eroded the bedrock directly (Gillberg 1968) as could the present stream have eroded either the till or the bedrock. In the case of the coastal sediments the effects of currents are added, but those are probably not too strong in this area.

The question then rises, how far the material can be transported by the different agents. The frequency of a rock or mineral type in, for instance, a till diminishes with increasing distance "downstream" from the outcrop. Krumbein (1937) and Gillberg (1968) showed that the decrease obeys a negative exponential function of the form

$$Y = Y_0 e^{-ax}$$

where Y = frequency of rock type at distance x from the starting point, Y_0 = frequency of rock type at the starting point, e = base of natural logarithms and a = constant of lithological nature.

The half distance value $x_{1/2}$ is the distance at which the frequency of a given rock type Y has been halved from what the frequency Y_0 was at the starting point x_0. Perttunen (1977) found from till in southern Finland the following values of $x_{1/2}$: 5,6 km for granitoids (granodiorite and microcline granite) of size range 0,6—2 mm, and 5,2 km for basic volcanics (porphyrites and tuffites) of the same size range. In addition to this, Virkkala (1971), also investigating the till in southern Finland, reported an $x_{1/2}$ of 16,4 km for gabbro in the same size class. The maximum distance is, of course, infinite in theory, but in practice it is only about two to four times the above distances.

Most authors (Gillberg 1968) are of the opinion that esker material must be of extremely local origin (cf. Stone 1899; Alden 1918; Hellaakoski 1930; Trefethen & Trefethen 1945; Flint 1957). The above mentioned authors though, have only studied coarser material as pebbles and cobbles which of course have a much shorter distance of transport than sand and fine sand in running water. In fact, the important point is the length of the esker stream, i.e. the glacial stream feeding the developing esker. It is believed that subglacial tunnels extend themselves headward as the ice front recedes, so the length of the esker per se is no quide to the problem (Shilts & McDonald 1975). The latter authors made an investigation in Quebec, Canada, where an esker traverses outcrops of different rocks and these outcrops were of different width. They found, by comparison of peaks of the different pebble lithologies, the following possibilities:

a) Esker stream longer than outcrop width: a broad peak with its maximum at the downstream edge of the outcrop belt, which maintains its maximum for some distance downstream;

b) Esker stream same length as outcrop width: a sharp peak at the downstream end of the outcrop belt;

c) Esker stream shorter than outcrop width: a broad peak over the downstream portion of the outcrop belt.

Thus they managed to estimate their esker stream to a length of 3 to 4 km. They also separated out the magnetite of the fine sand fraction, but the amount of magnetite did not show any marked peaks along the esker which indicates that the fine fractions probably can not be used to estimate the esker-stream length. The fine fractions, like fine sand, are most likely to be washed straight through by the rapid current to the tunnel mouth while the coarser fractions, like pebbles and cobbles, lag behind.

In the case of fluvial transport in recent rivers, it must be stated that during the millenia the present rivers have existed, the sediments could have travelled for considerable distances. Garnet, in particular, with its high abrasion resistance, could also be expected far from the source. In this investigation, where there is garnet present in all samples mostly in fairly large amounts, it may be suspected that some of them in the river samples are derived from the Caledonian mountains. In any case, there must be a dispersion of the material; as a constant erosion occurs, the nearby sources will be much better represented than the more remote ones. But of course, a background value of garnet certainly exists, which though, is difficult to estimate.

The above mentioned problems show that the methods presented in this investigation are not very well suited for prospecting, at least not in any detail. But as was stated in the introduction, the aim was to study the placers and if possible find out their provenance. In most cases the placers reflect the composition of the bedrock quite well on a larger scale. The trace-elements in magnetite did not prove to be as useful as was hoped, but as very little is known about these, even on a global scale, it is not so astonishing that in this case the results are fairly meagre. Anyhow, as they seemed to show the differences between the three areas quite well, they are able to reflect, to some extent, the difference between an area with overwhelmingly metamorphic rocks and one with mainly igneous rocks.

In fact, a larger investigation of trace-elements in magnetite should be done on all types of rocks in Norrbotten, and then several samples from several localities should be analysed. The method of using the trace-elements of magnetite is not unsatisfactory in itself, if only there is something to get hold on.

Placers are probably not very suitable for prospecting in general, at least not in a glaciated terrain, but could perhaps be of value in, for instance, such cases as wadis in the desert or in smaller creeks in glaciated terrains.

But placers themselves are of interest as they often can be mined for valuable minerals, even if this does not occur in Scandinavia (except for some gold-panning in Finland on a minor scale). The most interesting feature of the placers in Norrbotten is the high monazite content. The values may appear too high and perhaps sometimes are, but as this mineral belongs to the easier to detect under the microscope, the error should not be too great. The mineral is sparse in nature and it is only in certain pegmatites that it occurs in larger crystals or in carbonatites in any great concentrations. In other rocks it occurs as very small crystals and in small concentrations. It is brittle, so it cannot sustain long transportation, although it is easily enriched in placers. But it is the above mentioned rocks which make monazite especially interesting, as both monazite in itself and carbonatites can be very valuable sources for rare-earth metals. Monazite from syenite-pegmatites has also drawn early interest for its high thorium content. In the case of Norrbotten, however, it is most probable that the monazite originates from pelitic gneisses, and granites. An interesting task would be to make chemical analyses of the mineral as the composition varies with the host rock. There is, as mentioned earlier, always a possibility of confusion, but the only mineral with which it could possibly be confused is sphene (not included in this investigation but always present in fairly large amounts) but even if 50 % of the monazites were misclassified high values still occur in many samples.

Finally it should be stressed that multivariate statistical methods are extremely useful in the study of placers, but care must always be taken to see if the results are meaningful and do not contradict common sense.

Acknowledgements. — I should like to thank Professor Bengt Collini, of the Department of Mineralogy and Petrology, Uppsala, who directed this work. Professor J. O. Norrman and Professor Å. Sundborg, of the Department of Physical Geography, Uppsala, gave me valuable advice and suggestions during the initial part of the investigation. Professor R. A. Reyment, of the Palaeontological Institute, read and criticized the manuscript and gave me very valuable advice. Mr. C. F. Banfield and Mr. J. C. Gower, of Rothamsted Experimental Station, Harpenden, Herts., England, introduced me to the GENSTAT language and gave very valuable suggestions about the statistical part of the work. Dr. D. Sörbom, of the Department of Statistics, Uppsala, also gave much valuable advice on statistical matters.

Dr. B. Lindqvist was very helpful with the X-ray analysis and on mineralogical questions. Mr. S. Eriksson helped to introduce to the technicalities of running computers.

Miss Margareta Lindell assisted with mineral separations, and Mr. O. Wallner prepared the slides for microscopy. Miss Anne-Marie Karlson carried out the atomic-adsorption spectroscopy and Mr. H. Filing and Mr. H. Holmström drew the illustrations. The manuscript was typed by Miss Kersti Gløersen and Miss

Anita Holtéus. The manuscript was linguistically corrected by Dr. N. Mateer.

Mr. T. Kiiver accompanied and assisted me during the field work and Professor G. Bylund, of the University of Umeå, gave me information about placer deposits in the areas around Luleå.

To all these persons and to Dr. H. Brundin, Dr. U. Qvarfort, Mr. S. Bååth, Dr. C. A. Nilsson, Dr. J. Bergström, Dr. J. O. Larsson and all my other collegues I tender my sincere thanks.

REFERENCES

Abdullah, M. L., 1965: The iron-titanium oxide phases in metamorphism. *In* Pitcher, W. S. & Flinn, G. W. (eds.): *Controls in metamorphism.* Oliver & Boyd Ltd., Edinburgh.

Åhman, E. & Ödman, O. H., 1952: Konglomeratet på Bälingsberget i Nederluleå s:n. *Sver. Geol. Unders. C 523.* Stockholm.

Ahrens, L. H., 1954: The log-normal distribution of elements. I, II. *Geochim. Cosmochim. Acta 5, 6.* London.

Alden, W. C., 1918: Quaternary geology of southeastern Wisconsin. *U. S. Geol. Surv. Prof. Paper 196.* Washington.

van Andel, Tj. H., 1950: *Provenance, transport and deposition of Rhine sediments.* 129 pp. H. Veenman & Zonen, Wageningen.

Angino, E. E. & Billings, G. K, 1967: *Atomic adsorption spectrometry in geology.* 144 pp. Elsevier, Amsterdam.

Banfield, C. F. & Harries, J. M., 1975: A technique for comparing judges' performance in sensory tests. *J. Food Technol. 10.* Oxford.

Beskow, G.: 1935: Praktiska och kvartärgeologiska resultat av grusinventeringen i Norrbottens län. *Geol. Fören. Stockh. Förh. 57.* Stockholm.

Blackith, R. E. & Reyment, R. A., 1971: *Multivariate morphometrics.* 412 pp. Academic Press, London, New York.

Briggs, L. I., 1965: Heavy mineral correlations and provenances. *J. Sediment. Petrol. 35.* Tulsa.

Brower, J. C. & Veinius, J., 1974: The statistical zap versus the shotgun approach, *J. Math. Geol. 6.* New York.

Burnaby, T. P., 1966: Growth invariant discriminant functions and generalized distances. *Biometrics 22,* Washington.

Carver, R. E. (ed.), 1971: *Procedures in sedimentary petrology.* 653 pp. Wiley, New York.

Chayes, F., 1956: *Petrographic modal analysis — An elementary statistical appraisal.* Wiley, New York and London.

Chayes, F., 1960: On correlation between variables of constant sum. *J. Geophys. Res. 65.* Washington.

Chayes, F., 1970: Effect of a single nonzero open variance on the simple closure test. *In:* Merriam, D. F. (ed.): *Geostatistics.* Plenum Press, New York.

Chayes, F. & Kruskal, W., 1966: An approximate statistical test for correlations between proportions. *J. Geol. 69.* Chicago.

Cooley, W. W. & Lohnes, P. R., 1971: *Multivariate data analysis.* 364 pp. Wiley, New York.

Daniel, E., 1975: Glacialgeologi inom kartbladet Moskosel i mellersta Lappland. *Sver. Geol. Unders. Ba 25.* Stockholm.

Darroch, J. N., 1969: Null correlation for proportions. *J. Math. Geol. 1.* New York.

Davis, J. C., 1973: *Statistics and data analysis in geology.* 550 pp. Wiley, New York.

Dryden, A. L., 1931: Accuracy in percentage representation of heavy mineral frequencies. *Proc. N. A. S., U. S. 17.* Washington.

Fagerlind, T., 1975: Kvartärgeologiska undersökningar av främst materialtransportriktningar i Pajala kommun 1973—1975. Sver. Geol. Unders. Unpublished report, Stockholm.

Fleischer, M., 1965: Composition of magnetite as related to type of occurrence. *U. S. Geol. Surv. Prof. Paper 525-D.* Washington.

Flint, R. F., 1957: *Glacial and Pleistocene geology.* 553 pp. Wiley, New York and London.

Freise, F. W., 1931: Untersuchungen von Mineralen auf Abnutzbarkeit bei Verfrachtung im Wasser. *Mineral. Petrogr. Mitt., N. F. 41.* Leipzig.

Frietsch, R., 1970: Trace elements in magnetite and hematite mainly from northern Sweden. *Sver. Geol. Unders. C 646.* Stockholm.

Frietsch, R., 1972: A late-metasomatic iron mineralization in the Narken area and its occurrence as glacial boulders at Kihlanki, both in northern Sweden. *Sver. Geol. Unders. C 672.* Stockholm.

Fromm, E., 1960: An interglacial peat at Ale near Luleå, northern Sweden. *Sver. Geol. Unders. C 574.* Stockholm.

Fromm, E., 1965: Jordartskarta över Norrbottens län nedanför lappmarksgränsen. *Sver. Geol. Unders. Ca 39.* Stockholm.

Geijer, P., 1931: Berggrunden inom malmtrakten Kiruna-Gällivare-Pajala. *Sver. Geol. Unders. C 366.* Stockholm.

Gillberg, G., 1968: Lithological distribution and homogeneity of glaciofluvial material. *Geol. Fören. Stockh. Förh. 90.* Stockholm.

Gower, J. C., 1971: Statistical methods of comparing different multivariate analyses of the same data. *In: Mathematics in the archaelogical and historical sciences.* Edinburgh Univ. Press, Edinburgh.

Hand, B. M., 1967: Differentiation of beach and dune sands, using settling velocities of light and heavy minerals. *J. Sediment. Petrol. 37.* Tulsa.

Hellaakoski, A., 1930: On the transportation of materials in the esker of Laitila. *Fennia 52.* Helsinki.

Hjorth, S., 1971: Torne och Kalix älvar. *UNGI Rapp. 12.* Uppsala.

Hoppe, G., 1948: Isrecessionen från Norrbottens kustland. *Geographica 20.* Uppsala.

Hoppe, G., 1969: Yttrande rörande Vindelälvens, Piteälvens, Kalixälvens och Torne älvs betydelse ur naturvårdssynpunkt. *Statens naturvårdsverks publ. 1969: 13.* Stockholm.

Imbrie, J. & van Andel, Tj. H., 1964: Vector analysis of heavy mineral data. *Bull Geol. Soc. Am. 75.* New York.

Jolicoeur, P., 1963: The multivariate generalization of the allometry equation. *Biometrics 19,* Washington.

Jones, M. P., 1965: A continuous, laboratory-size density separator for granular materials. *Mineral. Mag. 35.* London.

Jöreskog, K. G., Klovan, J. E. & Reyment, R. A. 1976: *Geological factor analysis.* 178 pp. Elsevier, Amsterdam.

Kelley, J. C. & Whetten, J. T. 1969: Quantitative statistical analyses of Columbia River sediment samples. *J. Sediment. Petrol 39.* Tulsa.

Kneuper, G. 1957: Ein Taschen-Magnetscheider. *Glückauf 93.* Essen.

Krumbein, W. C., 1937: Sediments and exponential curves. *J. Geol. 45.* Chicago.

Krumbein, W. C. & Pettijohn, F. J., 1938: *Manual of sedimentary petrography.* 549 pp. Appleton-Century-Crofts, New York.

Lindh, A., 1972: A hydrothermal investigation of the system FeO, Fe_2O_3, TiO_2. *Lithos 5.* Oslo.

Linnaeus, C., 1732: *Iter Laponicum.* (Unpublished report.) Swedish translation 1957, Wahlström & Widstrand, Stockholm

Ljunggren, P. & Sundborg, Å., 1968: Some aspects on fluvial sediments and fluvial morphology. II. A study of some heavy mineral deposits in the valley of the river Lule älv. *Geogr. Ann. 38, Ser. A.* Stockholm.

Marriot, F. H. C. 1974: *The interpretation of multiple observations.* 117 pp. Academic Press, London, New York, San Francisco.

Möller, H., 1962 a: Annuella och interannuella ändmoräner. *Geol. Fören. Stockh. Förh. 84.* Stockholm.

Möller, H., 1962 b: Om periodiska växlingar i isälvarnas intensitet och solfläcksperioder. *Geol. Fören. Stockh. Förh. 84.* Stockholm.

Morrison, D. F., 1967: *Multivariate statistical methods.* 338 pp. McGraw-Hill, New York.

Müller, G., 1967: *Methods in sedimentary petrology* (Engelhardt, W. v., Füchtbauer, H. & Müller, G.: Sedimentary petrology. Part 1). 283 pp. E. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart.

Nelder, J. A. and members of the Rothamsted Statistics Department, 1977: GENSTAT. A general statistics program. The Statistics Department. Rothamsted Experimental Station, Harpenden, Herts.

Nilsson, B., 1972: Sedimenttransport i svenska vattendrag, ett IHD-projekt. *UNGI Rapp. 16.* Uppsala.

Ödman, O. H., 1957: Beskrivning till berggrundskarta över urberget i Norrbottens län. *Sver. Geol. Unders. Ca 40.* Stockholm.

Overstreet, W. C., 1967: The geologic occurrence of monazite. *U. S. Geol. Surv. Prof. Paper 530.* Washington.

Parfenoff, A., Pomerol, C. & Tourenq, J., 1970: *Les minéraux en grain.* 578 pp. Masson et Cie, Paris.

Perttunen, M., 1977: The lithologic relation between till and bedrock in the region of Hämeenlinna, southern Finland. *Geol. Surv. of Finl. Bull. 291.* Esbo.

Pryor, W. A. & Hester, N. C., 1969: X-ray diffraction analysis of heavy minerals. *J. Sediment. Petrol. 39.* Tulsa.

Rankama, K. & Sahama, Th. G., 1950: *Geochemistry.* 912 pp. The Univ. of Chicago Press, Chicago.

Reyment, R. A., 1972: Application of multivariate morphometrics in paleontology. *Int. Geol. Congr. 24th Sess. sect. 7, Paleontology.* Montreal.

Reyment, R. A., 1974: The age of zap. *Syracuse Univ., Geol. Contr. 2.* Syracuse.

Reyment, R. A. & Banfield, C. F., 1976: Growth-free canonical variates applied to fossil foraminifers. *Bull. Geol. Inst. Univ. Upps. N. S. 7,* Uppsala.

Reyment, R. A. & Ramdén, H.-Å., 1970: FORTRAN IV program for canonical variates analysis for the CDC 3600 computer. *Computer Contribution 47.* Lawrence, Kans.

Rice, R. M., Gorsline, D. S. & Osborne, R. H., 1976: Relationship between sand input from rivers and the composition of sands from the beaches of southern California. *Sedimentology 23.* Oxford.

Rittenhouse, G., 1943: The transportation and deposition of heavy minerals. *Bull. Geol. Soc. Am. 54.* New York.

Russel, R. D., 1937: Mineral composition of Mississippi river sands. *Bull. Geol. Soc. Am. 48.* New York.

Shaikh, N. A., 1972: Geology of the Lauttakoski soapstone deposit, northern Sweden. *Sver. Geol. Unders. C 676.* Stockholm.

Shaw, D. M., 1964: *Interprétation géochimique des éléments en traces dans les roches cristallines.* Masson et Cie., Paris.

Shilts, W. W. & McDonald, B. C., 1975: Dispersal of clasts and trace elements in the Windsor Esker, southern Quebec. *Geol. Surv. Can. Paper 75-1, Part A.* Ottawa.

Stone, G., 1899: The glacial gravels of Maine. *U. S. Geol. Surv. Mon. 38.* Washington.

Svensson, N. B. (ed.), 1977: En mineralinventering i Pajala kommun. *Norrlandsfonden informerar 11.* Luleå.

Taylor, S. R., 1965: The application of trace element data to problems in petrology. *Physics and Chemistry of the Earth 6.* Pergamon Press, Oxford.

Theobald, P. K. & Thompson, C. E., 1962: Zinc in magnetite from alluvium and from igneous rocks associated with ore deposits. *U. S. Geol. Surv. Prof. Paper 450-C.* Washington.

Theobald, P. K., Overstreet, W. C. & Thompson, C. E., 1967: Minor elements in alluvial magnetite from the inner Piedmont Belt, North and South Carolina. *U. S. Geol. Surv. Prof. Paper 554-A.* Washington.

Trefethen, J. & Trefethen, H., 1945: Lithology of the Kennebec Valley Esker. *Amer. Journ. Sci. 242.* New Haven.

Virkkala, K., 1971: On the lithology and provenance of the till of a gabbro area in Finland *Etudes sur le Quaternaire dans le monde 2. VIII Int. Cong. INQUA, Paris 1969.*

Wager, L. R. & Mitchell, R. L., 1950: The distribution of Cr, V, Ni, Co and Cu during the fractional crystallization of a basic magma. *Int. Geol. Congr. Rep. 18 Sess. G. B. 1948, Part II,* London.

Welin, E., 1970: Den svekofenniska orogena zonen i norra Sverige — en preliminär diskussion. *Geol. Fören. Stockh. Förh. 92.* Stockholm.

Welin, E., 1971: Radiometriska dateringar och den svenska berggrundens ålder. *Geol. Fören. Stockh. Förh. 93.* Stockholm.

Zodrow, E. L., 1976: Empirical behavior of Chayes' null model. *J. Math. Geol. 8.* New York.

Zussman, J. (ed.) 1967: *Physical methods in determinative mineralogy.* 514 pp. Academic Press, London and New York.

APPENDIX

Description of the sample localities

The Pite area (201 01—205 02)

201	Pitholmsheden: the Pite Beach
201 01	300 m NE of the beach restaurant, on a small spit, just above water-level. Heavy minerals, on ripples, in layers about 1 mm thick.
201 02	10 m NE of previous locality. Same type of location as above.

201 04 600 m further along the beach, 40 cm above water-level, on a small crest, 2 mm thick layer of heavy minerals.

201 05 10 m further, on a spit, 30 cm above water-level, 2 mm thick layer.

201 06 20 m further along the beach, 30 cm above the water-level: several layers of which the uppermost one (sampled) was about 2 mm thick; the next one was about 5 mm.

201 07 30 m further along the beach, a layer 1 mm thick on the proximal side of a beach-ridge, about 10—30 cm above water-level.

201 08 20 m further along the beach, on the proximal side of a beach-ridge, 30 cm above water-level, thin layers (about 1 mm thick).

Pitholmsheden: the Pite River

201 10 200 m north of the eastern ferry berth at Pitsund, 1—2 mm thick layers at 0—5 cm above water-level.

201 11 Western side of the river, on the easternmost point of Sandholmen at water-level. No really marked layers, but heavy minerals abundant.

201 12 On the eastern side of Furunäset, protruding into Svensbyfjärden, a 1 mm thick layer about 5 cm above water-level.

201 13 On the western side of Furunäset, a layer 2—3 mm thick, 0—5 cm above water-level.

202 Arnemark

202 01 At the old ferry berth on the eastern side of the river, 30—40 cm above water-level, about 1 mm thick layers (not very distinctly marked).

202 02 12 m north from previous locality, 2 mm thick layer, 40—50 cm above water-level.

203 Älvsbyn

203 01 Southern end of the community bathing-beach, 2 mm thick layer, 30 cm above water-level (about 40 cm below high water-level).

204 Fällfors

204 01 Western (southern) side of the river, in a small cove just below the waterfalls of Fällforsen, sandy beach, 1 mm thick layers about 1 m above the water-level.

205 Vidsel

205 01 Western side of the river, 55 m downstream of the road-bridge, 3 mm thick layers about 1 m above water-level.

205 02 5 m NW of previous site, 1 mm thick layers at the water's edge.

The Lule area (101 01—105 01; 301 01—313 02)

101 Trundön

101 01 At a little bay on the northern side of Berkön, western side of the bay, 2 mm thick layer at 20 cm above water-level.

102 Sandön: Tjuvholmssundet

102 01 100 m south of the pedestrian bridge to Tjuvholmen, 10 m behind and 1 m above the water's edge, 3 mm thick layer.

102 02 60 m further south and 120 cm above water-level, 2—3 mm thick layers.

102 03 50 m further south, on a crest 70 cm above and 4 m behind the water's edge, 2 mm thick layer.

102 04 On the edge of the promontory, 40 cm above water-level: several layers, the highest of which 6—7 mm thick.

Sandön: Sandöklubb

102 05 20 m west of the breakwater, at the western end of the ship-canal, 3—4 mm thick layer about 0—5 cm above water-level.

102 06 On the edge of a spit, about 200 m south of the eastern end of the ship-canal, layers at the water's edge (difficult to estimate the exact thickness).

102 07 20 m further south, a layer about 1 mm thick, 0—5 cm above water-level.

102 08 200 m west of the landing-bridge at Klubbviken, thick layers (disturbed by human activity) about 15—20 cm above water-level.

102 09 400 m further west, 5 cm above the water-level, 2 mm thick layers.

102 10 100 m further west. Same type of location as above.

103 Kallaxheden: Lulvik bathing-place

103 01 At the western end of the bathing-place, 5—10 cm above water-level a 3—4 mm thick layer.

103 02 Landwards from the former site at 50 cm above water-level, several thin (1—2 mm) layers.

103 03 At about the midpoint of the beach, 4 mm thick layer just at the water's edge.

103 04 Landwards from the former site, formed against a turf, 30 cm above water-level, 1 mm thick.

103 05 At the eastern end of the beach, just at the water's edge, 2 mm thick layer.

Kallaxheden: Klövgrunden (a spit)

103 06 At the eastern side of the abutment of the spit, a thin layer (1—2 mm) just at the water's edge.

103 07 350 m south of previous sample site, on the western side of the spit, 40 cm above water-level, 2 mm thick layer.

103 08 50 m further south, on the eastern side, thick layers (4—5 mm) 100—150 cm above water-level.

103 09 On the spit-head, western side, 20 cm above water-level, 2 mm thick layers.

103 10 25 m south of sample 103 07 on the top of the spit, 150 cm above water-level, a thin layer (about 1 mm thick).

104 Gråsjälören

104 01 On the southern beach of the little island in Lulefjärden, 10 cm above water-level, 4—5 mm thick layer.

105 Sinksundet

105 01 Southern side of the strait, just west of the road-bridge, 20—30 cm above water-level, about 1 mm thick layer.

301 Bergnäset

301 02 200 m north of the Bergnäs Bridge, and 50 m out from the western shore, at the bottom of the Lule River, on a sandy bank. The depth was 15 cm, and the sample was taken from ripples.

302 Luleå: Gülzaudden

302 01 Just north of the bathing-place, 1—2 mm thick layer, 70 cm above water-level.

303 Gäddvik

303 01 Northern side of the river, east of the road-bridge, just where the "nipa" begins, 20 cm over water-level, many layers 2—3 mm thick.

303 03 100 m further NE, 1 mm thick layers just above water-level.

303 05 Southern side of the river, on the spit of Gäddviksudden near the saw-mill, 2 mm thick layers 0—5 cm above water-level.

304 Luleå: Björkskatafjärden

304 01 At the bathing-place, 10 cm over water-level, 2 mm thick layer.

305 Gammelstadsfjärden: northern side

305 04 About 2 km south of Nederluleå church, just north of a house called "Öhemmanet" at the northern end of the beach, 10 cm above water-level, 3—4 mm thick layer.

305 05 Above the former sample, 30 cm above water-level, 3—4 mm thick layer.

305 06 100 m south of the former locality, 10 cm above water-level, 10 mm thick layer.

305 07 On a spit outside locality 305 06, 4—5 mm thick layer just at the water's edge.

305 09 South of the bathing-place at the southern end of the beach, 20—30 cm above water-level, 3—4 mm thick layers.

305 10 Above the latter sample, 1 m above water-level, 5—6 mm thick layer.

Gammelstadsfjärden: Sandnäset (southern side of the Lule River)

305 11 Western side of the tip of the promontory of Sandnäset, 1 m above and 3 m behind the water's edge, a layer 1—2 mm thick.

305 13 At the tip of Sandnäset, 70 cm above water-level, 4—5 mm thick layer.

305 14 Eastern side of the tip of Sandnäset, thin layers (1—2 mm) about 1 m above water-level.

Gammelstadsfjärden: Bälinge

305 17 At the harbour of the village of Bälinge, northern end of the harbour, 50 cm above water-level, thick layers, the highest of which was about 20 mm thick.

305 18 100 m further south, flat beach with a crescent-shaped ridge on it, on the proximal side of the ridge, 20—30 cm above water-level, several layers 2—4 mm thick.

306 Unbyn (SW side of the river)

306 02 Just south of the landing-bridge, at the water's edge, on ripples, several layers 1—2 mm thick.

307 Boden: Bodforsen

307 01 Near the construction site of a dam, at the waterfalls of Bodforsen, at a whirlpool on the southern side of the river, a 30—40 mm thick layer of heavy minerals interlayered with very thin layers of quartz.

308 Kusön

308 01 On the island of Kusön, east of Boden, in the river, 1 km from its upstream end, on the SW shore 1—2 mm thick layers at the water's edge.

310 Harads (Edefors)

310 02 7,5 km SE from Edefors church on the NE side of the river, at the hamlet of Havsträsk, 50 cm above water-level, 4—5 mm thick layer.

310 03 Just south of the road-bridge in Harads on a sandy bank in the river, 0—5 cm above water-level a 2—3 mm thick layer.

312 Åbacken

312 01 At the village of Åbacken on the western side of the river, just at the mouth of a ravine, 5 cm above water-level, a layer 10 mm thick.

313 Vuollerim

313 01 13 km SSE of Vuollerim church, on the western side of the river just north of the farm of Linjeudden, steep sandy river-bank, 10—15 mm thick layer just at the water's edge.

313 02 At the recreation-area at Rimjokk, just where the creek of Lagnäsån falls into the river, 1—2 mm thick layer just at the water's edge.

The Kalix area (106 01—107 02; 501 01—508 01)

106 Råneå

Although not strictly belonging to the Kalix area it was for practical reasons grouped with it.

106 01 At the fishing-village of Rörbäck on the peninsula of Sandöskatan (16 km SE of Råneå church), eastern side of a small promontory, 40 cm above water-level, 2—3 mm thick layer.

106 02 At the abutment of the breakwater, 50 cm above water-level a 2 mm thick layer.

107 Sangis: Källnäset

107 01 On a glaciofluvial promontory just west of the village of Källnäset, southern side of the promontory, 20 cm above water-level a 2 mm thick layer.

107 02 50 m further west, just at the water's edge a 15—30 mm thick layer.

501 Överkalix

501 01 On the peninsula where the village of Överkalix is situated, eastern side of the river, 500 m SE of Överkalix church on a spit, a layer, 3 mm thick, 20 cm above water-level.

501 02 At the bathing-place, about 700 m north of locality 501 01, a layer, 15 cm above water-level, 2 mm thick.

501 03 At the same site, but 2 m landwards, and 40 cm above water-level a layer 1—3 mm thick (locally 10 mm).

501 04 On the eastern side of the river, 4 km downstream from locality 501 01, at the hamlet of Mjölan, just at the water's edge, thick layers, 3—10 mm.

501 05 On the same site, but 2,5 m landwards and 1 m above the water's edge a layer 3 mm thick.

501 06 On the same site, 6,5 m landward and 1,5 m above the water's edge a layer 2—5 mm thick. Some eolian influence.

501 08 At the ferry berth at Brändholm, 3 km SE of Överkalix church, on a small promontory just north of the berth a thin layer (1—2 mm) just at the water's edge.

501 09 Eastern side of the river, at Svartbyn, 7,2 km south of Överkalix church, 10 cm above water-level a 10 mm thick layer.

502 Lansjärv: Sanningslandet (River Lansån)

502 01 Eastern side of Lake Övre Lansjärv, at the bathing-place of the hamlet Sanningslandet, 10—15 cm over water-level, 1—2 mm thick layers.

503 Ängeså (River Ängesån)

503 01 At the village of Ängeså, just south of the road-bridge, near the old ferry berth, 1 mm thick layer at the water's edge.

504 Rödupp (Kalix River)

504 01 Western side of the river, about 1 km north of the ferry berth, a 1 mm thick layer at the water's edge.

504 02 Eastern side of the river, about 2 km north of the ferry berth, 50 cm above water-level, a 1—2 mm thick layer.

505 Jokk

505 01 About 1 km upstream from Jokk, western side of the river, at a place called Kvarnudden, a layer 10 mm thick, 1 m above water-level.

506 Mestoskangas

506 01 Western side of the river, just at the southern border of the glaciofluvial delta of Mestoskangas, a 10 mm thick layer about 1 m above water-level.

506 02 About 3 km upstream from locality 506 01, on the western side, on the glacial delta, a layer 2—3 mm thick 50—60 cm above water-level.

507 Tärendö

507 01 In the village of Tärendö, halfway between the two bridges traversing the Kalix River, western side, 75 cm above water-level, several layers 1—2 mm thick.

507 02 Southern shore of the Tärendö River, just beneath the forestry-school at Tärendö, layers 2—3 mm thick, 75 cm above water-level.

Printed by Ekenäs Tryckeri Ab, Ekenäs, Finland April, 1978.