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by Marjatta Perttunen and Heikki Vartiainen

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GLACIOFLUVIAL TRANSPORT OF CLASTS AND HEAVY MINERALS FROM THE SOKLI CARBONATITE COMPLEX, FINNISH LAPLAND

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with 10 figures and 6 tables

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The esker crossing the Sokli carbonatite complex in Finnish Lapland affords an ideal test site for the study of glaciofluvial transport in the area of the Pleistocene ice divide. The Devonian Sokli carbonatite complex is surrounded by Precambrian bedrock.

Samples were collected from 22 sites along the esker course over a distance of 16 km. The lithology of clasts and heavy minerals were studied using samples from the surficial parts of the esker.

The first appearance in the esker of clasts derived from the carbonatite complex occurs within one kilometre of its proximal contact whereas heavy minerals appear in the esker 2 to 3 kilometres from the proximal contact. Peak abundances in the esker are in the distal portion of the source area. The transport distance in the esker for the majority of carbonatite complex clasts and carbonatite heavy minerals is only 4—5 kilometres.

Indicator clasts and soft heavy minerals of surficial esker material are useful for mineral exploration in the areas of the last deglaciation during the Weichselian glaciation.

Key words (GeoRef Thesaurus, AGI): glacial transport, eskers, clasts, heavy minerals, garnet group, ilmenite, rutile, electron probe data, provenance, carbonatites, Sokli, Savukoski, Finland

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INTRODUCTION

Mineral exploration, as well as bedrock mapping, has been carried out by Rautaruukki Oy and Kemira Oy in the Sokli carbonatite complex, and its surroundings, since its discovery in 1967; most of the results of these investigations have been published (e.g. Vartiainen and Woolley 1976, Vartiainen and Paarma 1979 and Vartiainen 1980).

Abundant detailed petrological and mineralogical studies permit closer examination of the lithology of the esker system. The field work was done in 1988—1989. Marjatta Perttunen was responsible for planning the study, for carrying out the field and laboratory works as well as the glacial geology, Heikki Vartiainen carried out the stone counts and microscopic mineral analyses. Both authors are responsible for the results and conclusions of the study.

The esker system from the last deglaciation during the Weichselian glaciation trends from northwest to southeast and crosses the Caledonian (Devonian) Sokli carbonatite complex, which differs greatly in lithology from the Precambrian surroundings. Therefore the area is ideal for a study of glaciofluvial erosion, transport and deposition.

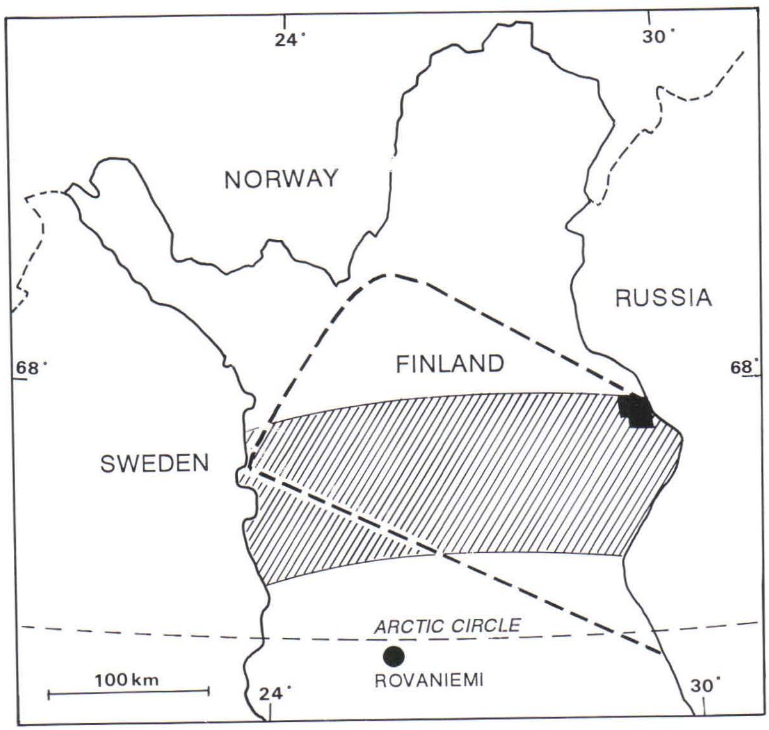

Fig. 1. Location of the study area in northern Finland (black area), ice divide zone (shaded area) during last deglaciation ca. 10,000 years B.P. (Ignatius, Korpela and Kujansuu 1980) and preglacially weathered bedrock zone (broken line) (Hirvas 1983) in Finnish Lapland.

The relative transport distances of clasts and heavy minerals in the Sokli esker were measured. Both the influence of the proximal increase in abundances of lithologies as well as distal decrease were studied. The objective was to assess the use of glaciofluvial sediments, in the deglaciated areas of the Weichselian glaciation, especially in the regions of ice divide (Fig. 1), applied to mineral exploration. In addition, the possible incidence of kimberlites in the area was investigated through the study of the heavy minerals.

GEOLOGICAL SETTING AND THE SOURCE ROCKS OF THE SOKLI ESKER

The geological setting of the Sokli esker is shown on the geology map (Fig. 2), compiled from previous work done on the Sokli carbonatite complex (Vartiainen and Woolley 1976, Var-

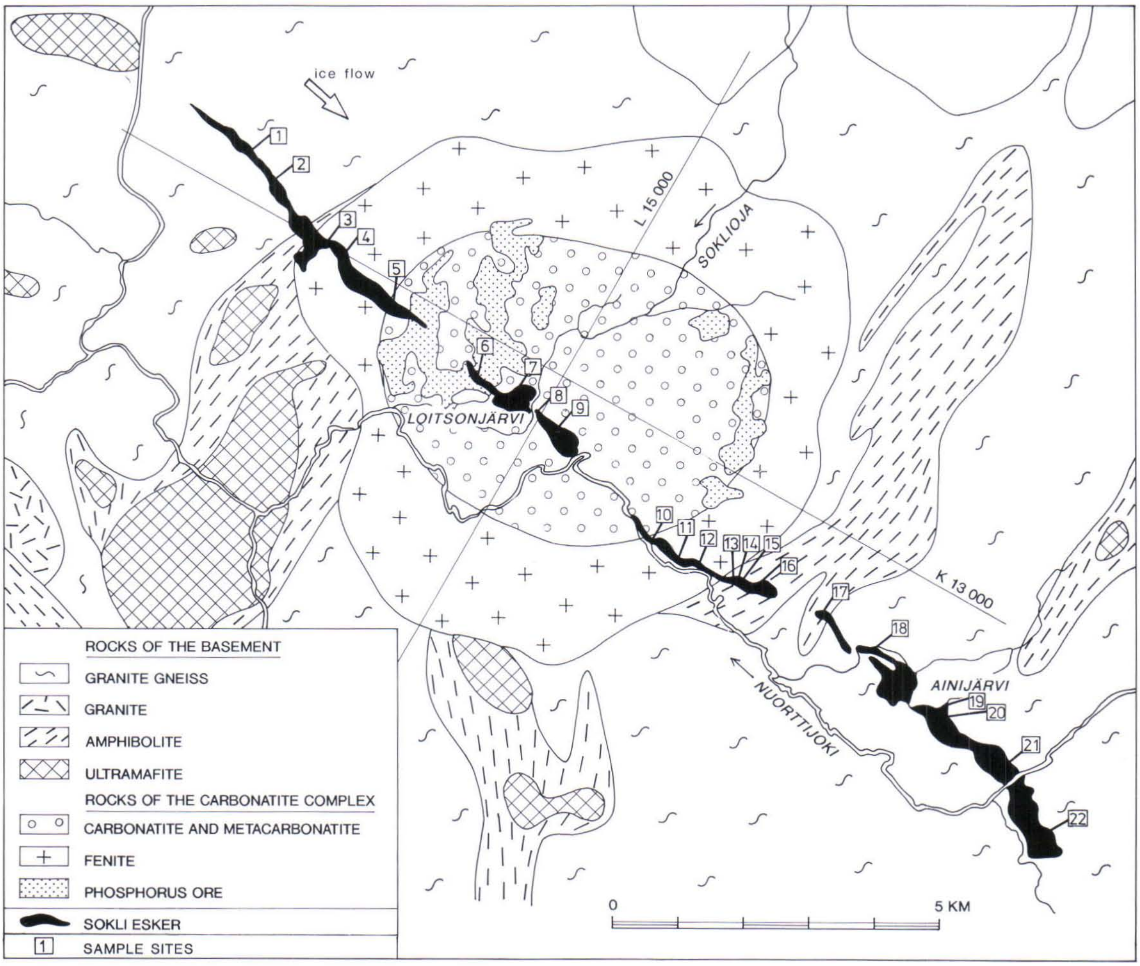

Fig. 2. Geological map of the Sokli carbonatite complex and surrounding bedrock with the sampling sites located on the Sokli esker.

Table 1. Average mineral contents of basement rocks, carbonatites and phosphorus ore (weathered crust), and heavy mineral fractions of the Sokli esker samples.

	Basement	Carbonatite massif	Esker Samples					
			Located over		Distance from SE-contact of carb. massif			
			basement	carbon.	**0.5—2.0**	**3.0—4.0**	**5.0—6.5**	**7.5**
Sample numbers (in Fig. 2)			1—4, 22	6—10	11—16	17—18	19—21	22
	%	%	%	%	%	%	%	%
Minerals from the basement rocks								
Garnet	+	—	28	17	11	3.5	12	30
Rutile	+	—	4	3	3	1	3	2
Quartz, feldspar	75	+	2.5	4	2	0.5	1	—
Minerals from the carbonatite massif								
Apatite	0.2	12.0	3.5	15	30	35	25	4
Francol.-goeth.	—	3.0	—	4	5	7	3	—
Pyrochlore	—	0.2	—	+	+	+	+	—
Carbonate	+	55	—	1	5	2.5	0.5	—
Common minerals								
Amphiboles	16	8	46	35	27	35	30	43
Opaques	3	11	12	17	12	12	17	15
Zircon	+	0.1	4	3	5	0.5	4	6
Micas	5	10	—	—	—	—	—	—

\+ observed
— not detected

tiainen 1980). The head of the Sokli esker lies on Precambrian basement rocks, traverses southeast over the fenite aureole, the carbonatites and their regolithic phosphorus ore, the fenite aureole and terminates on the basement again. The esker on the Sokli carbonatite complex is eight kilometres long.

The Archean basement rocks, in the vicinity of the esker on both sides of the carbonatite complex, comprise gneissose granites and granodioritic gneissose granites, as well as a variety of amphibolites. Serpentinized ultramafite bodies near the esker are over one kilometre in length. Pegmatites of variable width are common in the basement. The basement surface is unweathered. The generalized average mineral composition of the basement in the vicinity of Sokli is estimated in Table 1.

The 363 Ma carbonatite complex, consisting of the fenite aureole and the carbonatite massif, has a strong lithological contrast relative to the basement. The fenites are easily identifiable and originated through Na-metasomatism of the basement rocks. The fenite is composed principally of albite, sodium amphiboles and pyroxenes with the proportion of relict primary minerals diminishing with increasing degrees of fenitization. Because the fenite aureole is extensively tectonized, but not weathered, it readily yielded rock fragments during glaciation.

The upper part of the carbonatite massif is extensively weathered, particularly in a 1—2 kilometres wide zone in contact with the fenite aureole. This zone is composed of compositionally variable amphibole and mica rich metasomatites and metacarbonatites. Because of the strong weathering, no clasts of these rocks have been observed in the esker. The magnetic carbonatite core occupies 6 km^2 in the central part of these rocks. These carbonate rich magmatic carbonatites have been more resistant to weathering than the former rocks, and they form a blocky weathered surface (regolith) which has yielded some rock fragments.

The regolithic phosphorus ore was formed by the complex weathering and recrystallisation processes. Accordingly it contains relict carbonatite minerals such as apatite, and recrystallized minerals such as the phosphorus mineral francolite (Table 1). About 10 % of the volume of the phosphorus ore is composed of a hard ore type capable of yielding rock fragments.

The average mineral composition of the weathered crust of the carbonatite massif is estimated in Table 1. The mineralogical difference between the rocks of the basement and the carbonatite massif shown in Table 1 reflects the distinct lithological dissimilarity between these rocks.

Consequently, the Sokli area, at the site of the Sokli esker, offers two types of source rock. Because the basement and carbonatite complex lithologies differ so strikingly from each other, both petrographically and mineralogically, the Sokli esker is eminently suitable for the study and evaluation of the transport of clasts and heavy mineral grains.

QUATERNARY GEOLOGICAL SETTING

The Quaternary deposits in the area were mapped in 1966—1970 and described by Hirvas and Kujansuu (1972) at a scale of 1 : 400 000. The esker system within the study area was remapped at the scale of 1 : 20 000 by Marjatta Perttunen (Fig. 2). The Sokli esker is part of an approximately 35 km long esker system.

The deglaciation occurred in the area ca. 10,000 years B.P. (Ignatius, Korpela and Kujansuu 1980). According to till fabric analyses the upper till shows a northwest-southeast-trending ice flow direction, which correlates with stage II in Lapland (Hirvas 1977). The esker system trends from northwest to southeast and thus is parallel to the direction of the last ice flow. The earliest ice flow recorded in the area is from the west or southwest (Ilvonen 1973).

The esker system consists of sinous ridges with beads 200 m to 2 km in length. Proximal ridges mainly display a sharp crest and fairly steep sides. The distal parts consist of a broad esker complex partly with kames. The heights of the ridges range from 5 to 25 m and the widths from 40 to 400 m.

According to Ilvonen (1973) material in the Sokli esker shows great horizontal and vertical variation. In the proximal part of the esker ridges, layers of cobbles, pebbles and gravel alternate with sand. In the distal parts of the esker ridges sand is dominant.

There are two gravel pits in the Sokli esker. The one situated over the Sokli carbonatite massif shows sandy material with cross-bedding and layers with concentrates of garnets. The other pit at the Ainijärvi border station has coarser material such as cobbles and pebbles with gravel and sand. Garnet concentrations occur as well. Generally, the coarse fractions dominate in the sampled surficial portions.

The Sokli esker is subglacial in origin. In the supra-aquatic area it was, in places, formed by streams under high hydraulic pressure (Ilvonen 1973). The esker occurs in both supra-aquatic and subaquatic setting. In subaquatic areas the esker ridges are covered by glaciolacustrine sediments deposited by a previously unrecorded glacial lake. The glaciolacustrine sediments consist of homogeneous silt overlying silt with rhythmites.

In the surroundings of the esker system the dominant Quaternary deposit is ground moraine, which only occasionally attains a thickness of 15 m. The total thickness of Quaternary sediments, based on drilling, exceeds 38 m. Ilvonen (1973) described the Eemian Interglacial diatom deposit found at Sokli.

The study area is situated in the ice divide region, where the weathered crust is commonly preserved. The preglacial weathering profile over the Sokli carbonatite complex has been found to be on average 10—20 m thick. In the fenite aureole only the carbonatite dike rocks are weathered, in places down to 20 m.

METHODS

Sampling

Samples were collected from 22 sites along the esker course over a distance of 16 km. The pits were dug by shovel to one metre depth. The surficial parts of two existing gravel pits were used for sampling.

At each pit 100 clasts of the 2—10 cm fraction were collected for stone counts. Each sample, totaling 10 litres of < 4 mm fraction material was taken for heavy mineral analysis. These samples were panned in the field.

Laboratory work

Panned concentrates were sieved into subsamples: 2—4 mm, 1—2 mm, 0.5—1 mm, 0.250—0.5 mm, 0.125—0.250 mm, 0.07—0.125 mm and < 0.07 mm. Grain-size analyses were made on

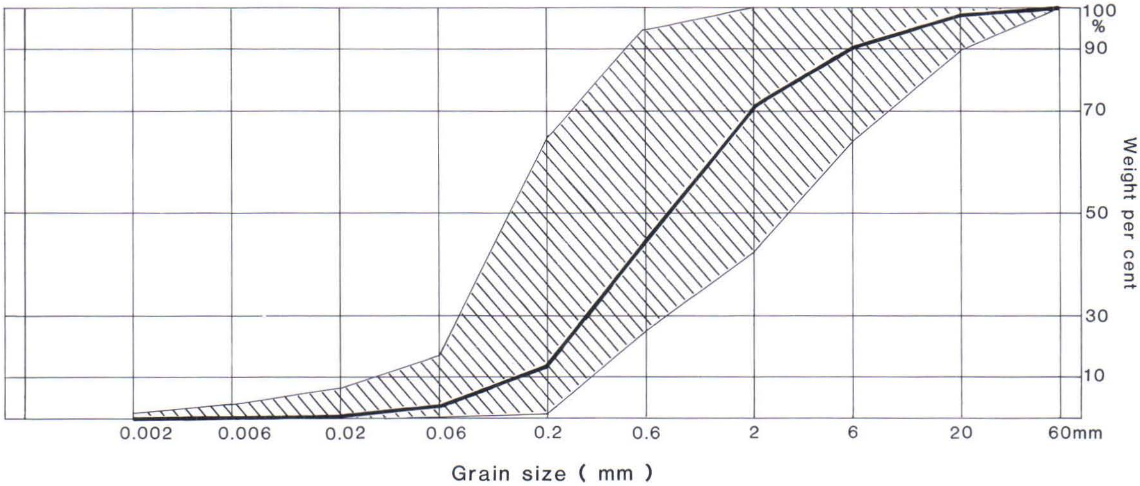

Fig. 3. Graph showing the grain-size analyses of 22 samples from the Sokli esker. The shaded area indicates the grain-size limits for the samples. The black line indicates the median curve.

samples (< 60 mm) representing the original material from the sampling sites of the 22 samples studied. The analyses show that the medium grain-size (Mz) was sand for 19 of the samples and gravel for 3 of the samples (Fig. 3). All samples, with the exception of number 6, contain cobbles and pebbles.

For the study in question the 0.07—0.125 mm fraction was treated in the laboratory with bromoform (SG 2.810—2.830) to separate the heavy minerals. The magnetic grains were then separated by hand magnet and the samples were prepared as polished thin sections.

Semiquantitative mineral contents of the heavy mineral fractions were determined optically from thin sections under the polarizing microscope using grain density charts and the chemical composition of the samples. The accuracy of this method is estimated to be about ± 5—10 %, which is acceptable for the purposes of this study. For each of the samples, mineral abundances of the heavy mineral fractions, from which the magnetic fraction was separated, were calculated for the 0.07—0.125 mm fraction.

Identification of the 2—10 cm clasts was made in the laboratory.

PROVENANCE OF CLASTS

Fenite

The mechanical properties of fenite, which forms an aureole surrounding the carbonatite massif (Figure 2), are comparable to those of granite. The fenite has, however, a tectonically disrupted, fragmentary and jointed nature, as a result of which it has contributed more material to the Sokli esker than have the other lithologies of the complex (Figure 4). Fenite clasts first ap-

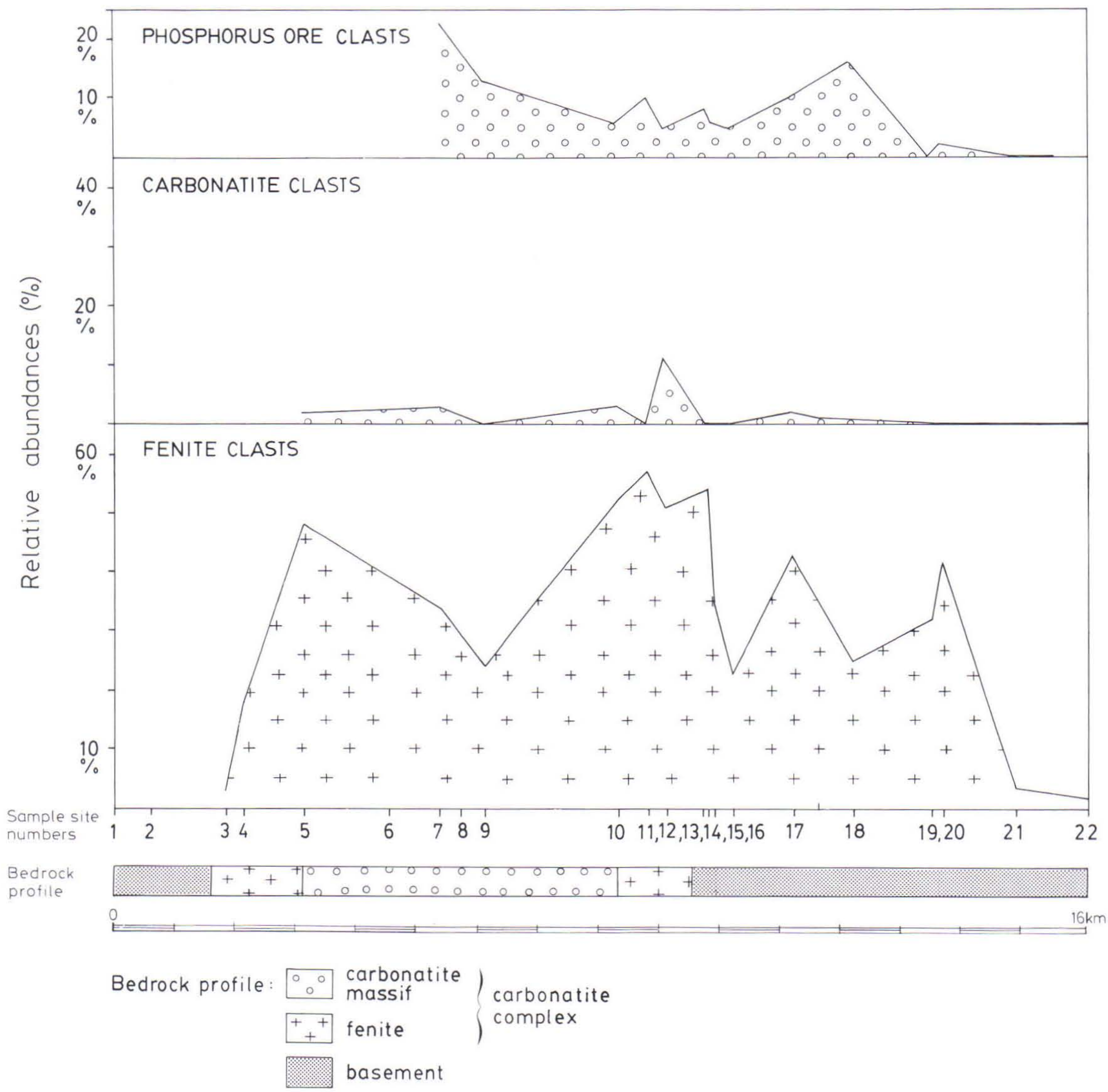

Fig. 4. Relative abundances of clasts derived from the carbonatite complex in the Sokli esker.

pear in the esker very close to the proximal contact, with abundances rapidly increasing and attaining maximum values of around 60 % within 5—6 km from the distal contact of fenite. Thus the fenites clearly indicate the location of the carbonatite complex. Figure 5 shows the dispersal of fenite clasts measured from both the inner (distal) contact of the aureole on the northwestern side of the complex (typically aegirine rock and light green fenites) and the outer (distal) contact of the aureole on the southeastern side (amphibole-rich dark green fenites). This indicates that fenite clasts still comprise 30—40 % of clast populations at a distance of 3—4 km from their source.

Phosphorus ore

Although the bulk of the phosphorus ore is soft and weathered, about 10 % by volume consists of more indurated material that is highly resistant to mechanical crushing. Thus, clasts of phosphorus ore are also present within the Sokli esker, showing the same kind of dispersal behavior as the fenite clasts. However, phosphorus ore clasts are only about half as abundant as those of fenite, in spite of the fact that the esker traverses both rock types over equal distances; this difference is therefore attributed to differences in mechanical properties, including fracturing and jointing. The occurrence of a distinct peak in phosphorus ore clast abundances within the esker southeast of the carbonatite massif may even indicate the presence of a previously undetected ore body (Figure 4).

Carbonatites

The surficial parts of the carbonatite massif are pervasively weathered, with only sporadic occurrences of fresh carbonatite having been exposed from beneath Quaternary overburden during the excavation of a total of 30 km of exploration trenches. This explains the dearth of carbonatite clasts in the esker, as is readily apparent from Figure 4. Although weaker, variations in distribution and abundance of clasts nevertheless follow the same trends as for the fenites and phosphorus ore.

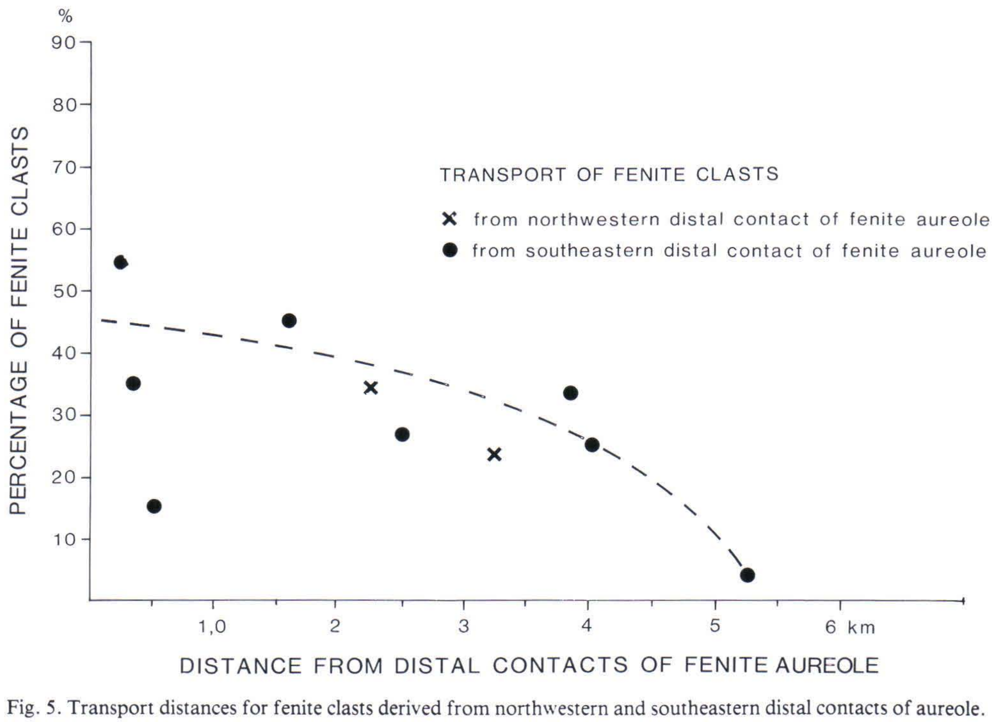

Fig. 5. Transport distances for fenite clasts derived from northwestern and southeastern distal contacts of aureole.

Other rock types

Mica-rich mafic lithologies (metasomatites, metaphosphorites and lamprophyres) are present throughout roughly two thirds of the carbonatite massif, but are so weathered that they have not contributed any coarse clastic material to the esker.

HEAVY MINERAL CONTENTS AND EVALUATION OF MINERAL TRANSPORT

The average mineral abundances of the non-magnetic heavy mineral fractions in the 0.07—0.125 mm fraction from esker samples are given in Table 1. Minerals are classified into two

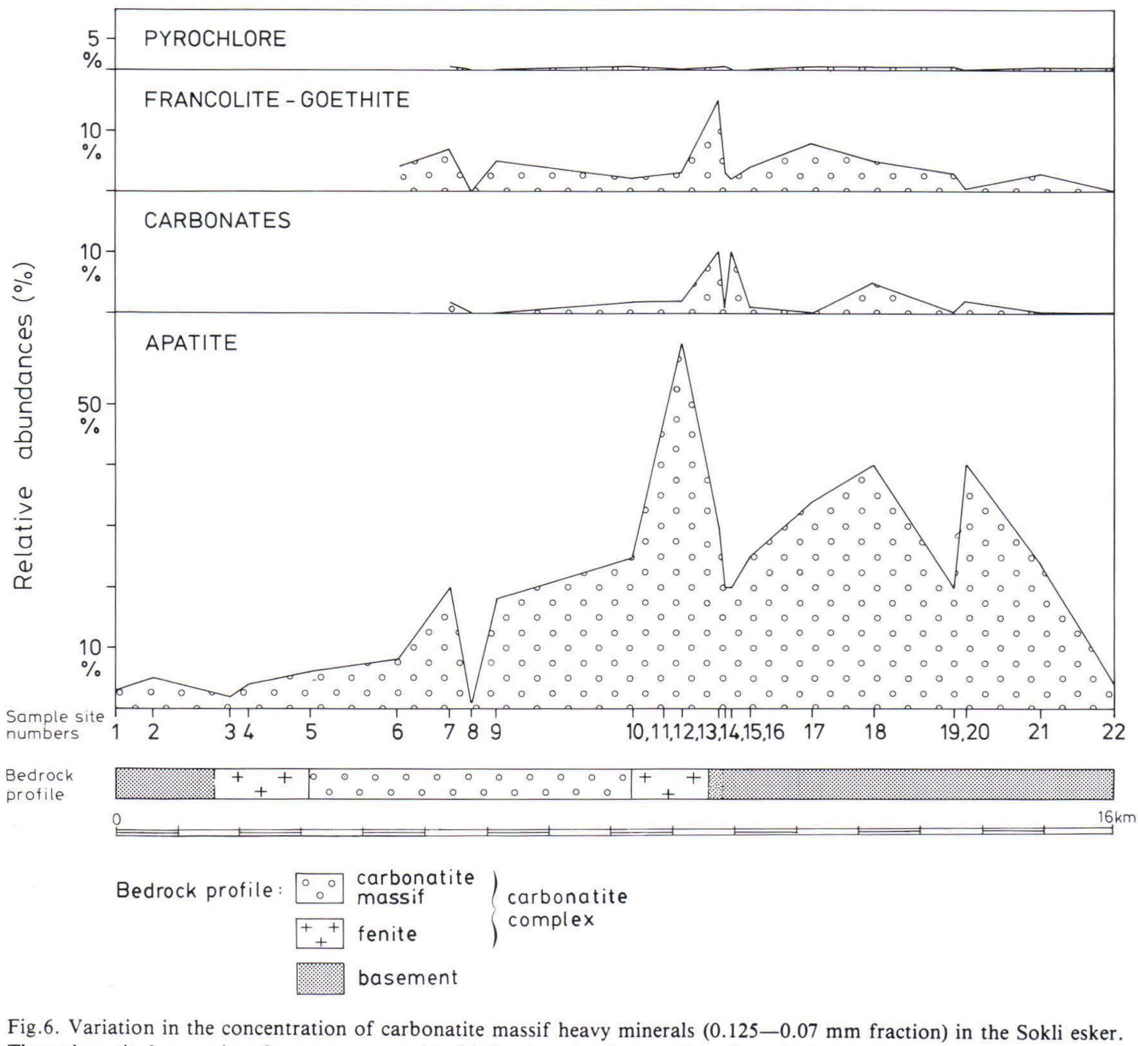

Fig.6. Variation in the concentration of carbonatite massif heavy minerals (0.125—0.07 mm fraction) in the Sokli esker. The carbonatite heavy minerals are concentrated in this fraction. A minor portion of apatite (m.a. 4%) is derived from basement.

groups; those from the basement and those from the carbonatite massif. For reference, approximate modal mineral compositions for basement rocks and the carbonatite massif are also given in Table 1. Figure 6 shows the variation in the concentrates of carbonatite heavy minerals in the Sokli esker.

The samples taken from the esker over basement represent background values of non-magnetic heavy minerals with no contribution from the carbonatite massif. They contain on average 3.5 % apatite, which corresponds to an enrichment factor of more than 10 times with respect to the source rocks. Other minerals present in the carbonatite massif are absent from the background samples.

Basement-derived minerals are present in all the esker samples. Garnet, the main basement mineral is naturally less abundant over the carbonatite massif and on the distal side of the massif relative to the basement. Rutile and light minerals (quartz, feldspars) are fairly evenly dispersed in all the samples.

The distribution of the carbonatite massif minerals in the esker samples allows an evaluation of the transport distance of heavy minerals in the Sokli esker. The distal samples are classified into four groups in Table 1 in relation to distance from the contact of the carbonatite massif. The two largest groups show a uniform pattern of heavy minerals. The apatite content of 30—35 %, francolite of 5—7 % and carbonates of 2.5—5 %. The first two are higher than the corresponding amounts within the carbonatite massif proper. This indicates that signifant transport of minerals has taken place over a distance of at least 4 kilometres.

Samples 5.0—6.5 kilometres from the distal contact of the carbonatite massif still show a distinct effect of mineral transport, but beyond 7.5 kilometres of the contact, all minerals from the carbonatite massif are absent and apatite is at background level.

Non-magnetic opaques are unformly concentrated between 12 and 17 % in all esker samples. Although the quantity of opaque minerals in the carbonatite massif is much higher than in the basement (Table 1), the non-magnetic opaques are most probably derived from the basement because magnetite is the dominant opaque mineral known from the carbonatite massif. Also, the even distribution of opaques reflects their basement origin.

ELECTRON MICROPROBE ANALYSES OF GARNET, ILMENITE AND RUTILE AND DISCUSSION ON THEIR SOURCE

Several minerals have particular ranges of composition which may be indicative of the presence of kimberlites or even diamondiferous kimberlites. In order to check this and to evaluate the potential of the source rocks some electron microprobe work has been done on garnet, ilmenite, rutile and zirconium-rich rutile.

Garnet

A total of 33 garnet grains were analyzed from three esker samples (1, 9 and 16, Figure 2). With slight compositional variations the garnets can be grouped as Mg-almandine, almandine and Fe-grossular (Table 2). Mg-almandine is prevalent (64—82 %), but only one grain of Fe-grossular

Table 2. Electron microprobe analyses of garnets from three Sokli esker samples.

Sample	1		9		16		
Garnet group	Mg-almandine %	Almandine %	Mg-almandine %	Almandine %	Mg-almandine %	Almandine %	Fe-grossular %
SiO_2	38.80	37.20	38.10	37.00	39.30	38.20	37.80
TiO_2	0.08	0.06	0.06	0.03	0.05	0.09	0.08
Al_2O_3	22.20	20.60	21.90	20.70	22.20	21.00	20.60
*FeO	25.30	27.20	25.10	29.20	24.90	26.60	23.90
MnO	0.38	1.38	0.30	0.95	0.41	0.87	0.51
MgO	11.30	4.70	11.20	5.60	11.40	1.50	1.50
CaO	1.60	6.11	1.20	5.40	1.50	6.90	15.40
Cr_2O_3	0.05	0.02	0.05	0.04	0.05	0.01	0.05

* Total iron calculated as FeO.

occurs in population.

The distinct and consistent degree of correlation between Mg-almandine and almandine in all the esker samples reflects a common source rock containing two compositional garnet types. On the other hand an increasing proportion of Mg-almandine can be observed over a distance of ten kilometres (Samples 1—16, Figure 2), suggesting Mg-rich garnets are more resistant during glaciofluvial transport.

The most probable source rocks for the garnets in the Sokli esker occur within the granulite area of Inari, which extends to within about 40 km of Sokli. According to published garnet analyses the garnets of the Inari area can be defined as those from the granulite complex and those from the surrounding rocks. The MgO-FeO-CaO diagram (Figure 7) illustrates close affinities between the Mg-almandines and almandines of the Sokli esker and the Inari granulite area. If the

Table 3. The similarities between minor components of comparative garnets suggests a close relationship between the Mg-almandines and almandines of the Sokli esker and the Inari granulite area.

	Mg-almandines		**Almandines**	
	Sokli esker %	Granulite complex %	Sokli esker %	Rock zones around granulites %
TiO_2	0.06	0.05	0.04	0.05
Cr_2O_3	0.05	0.05	0.03	0.01
MnO	0.36	0.46	1.17	2.05

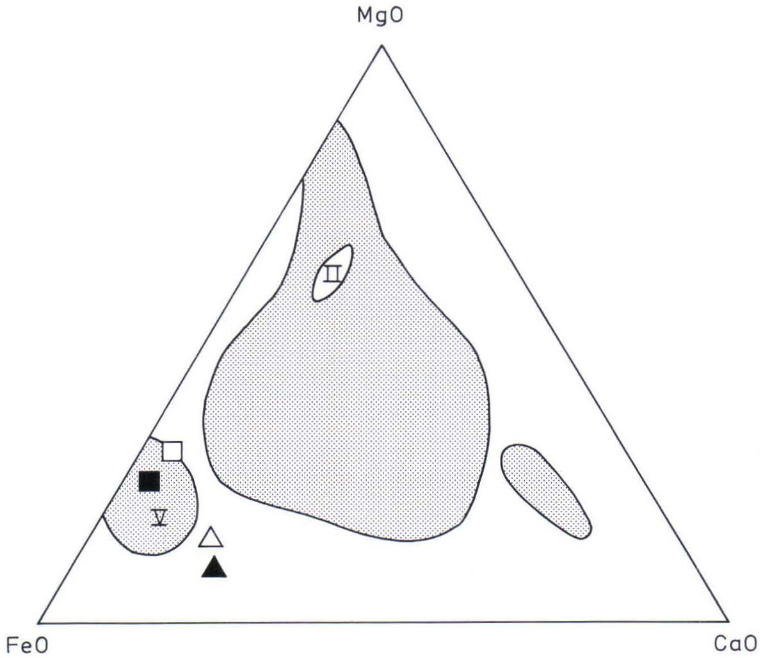

Fig. 7. MgO-FeO-CaO diagram for garnets. Stippled fields for garnets from kimberlites after Dawson and Stephens (1975): Field II high-titanium pyrope from kimberlites only. Field V magnesium almandine from kimberlites, eclogites and diamond inclusions. Open square denotes Mg-almandines (23) and open triangle almandines (8) from the Sokli esker. Filled square denotes garnets (17) from the Inari granulite complex. The filled triangle denotes garnets (12) from the rock zones surrounding the Inari granulite complex. The number of analyses is given in parentheses.

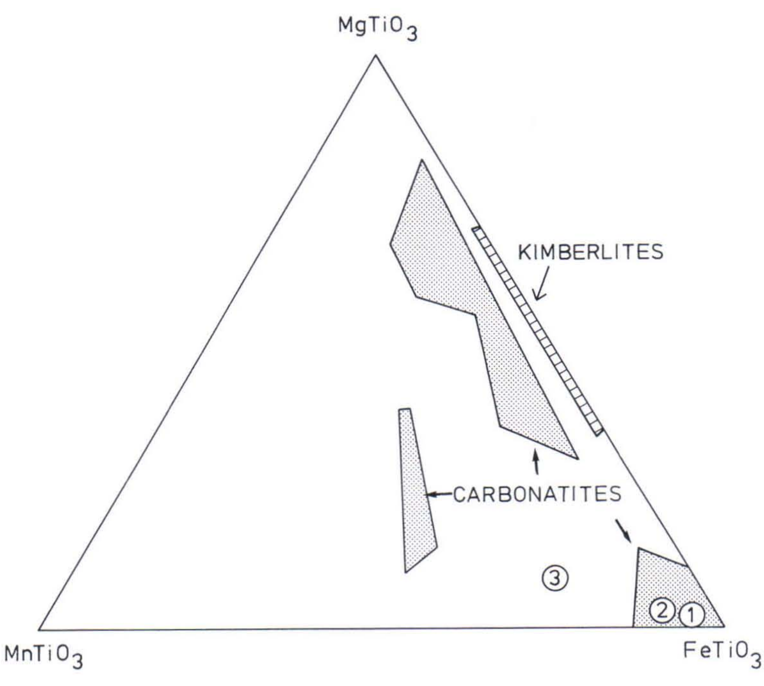

Fig. 8. Compositional fields of kimberlite and carbonatite ilmenites in the system $MgTiO_3$-$FeTiO_3$-$MnTiO_3$ according after Mitchell (1986). Numbers 1, 2 and 3 refer to ilmenite groups from the Sokli esker samples.

interpretation that Mg-rich garnets are more resistant during transport is correct then it can be hypothesized that Mg-rich garnet variants have been enriched in the Sokli esker compared to the source rocks (see Figure 9). The similarities between the minor components of comparative garnets also suggests a close relationship (Table 3).

Dawson and Stephens (1975) presented a MgO-FeO-CaO diagram in which they statistically separated garnets from kimberlites and associated xenoliths into 12 groups. In Figure 7 the composite fields of kimberlite garnets have been compiled. Only two fields have been separated; group II High-Titanium pyrope, occurring only in kimberlites, and group V Mg-almandine, which is found in kimberlites, eclogites and as inclusions in diamonds. The magnesian almandines of the Sokli esker samples fall at the margins of the Mg-almandine field and almandines outside of it. The possibility of a kimberlitic origin for the Sokli esker Mg-almandines is thus very small. The presence of the granulite complex Mg-almandines in field V supports this conclusion.

Ilmenite

Thirteen ilmenite grains have been analyzed from the same esker samples as the garnets. The ilmenites can be separated into three groups as shown in the Table 4. Plotting of the average ilmenite compositions on the diagram of the system $MgTiO_3$-$FeTiO_3$-$MnTiO_3$ (Figure 8) reveals how groups 1 and 2 (12 ilmenite grains) are located in the field of Fe-rich carbonatite ilmenites and group 3, those rich in Mn, outside of it. It is clearly evident that Sokli ilmenites are compositionally distinct from the ilmenites of kimberlites.

The results in Table 4 and Figure 8 suggest that the main source of the Sokli esker ilmenites is the carbonatite massif, although ilmenite only occurs in the Sokli carbonatite massif as variably sized exsolutions in magnetite (Heinänen and Vartiainen 1981).

Table 4. Average compositions of 13 ilmenite grains analyzed by electron microprobe.

Group	1	2	3
Number of grains	9	3	1
	%	%	%
TiO_2	49.40	49.40	49.60
Al_2O_3	0.03	0.01	0.01
Cr_2O_3	0.05	0.02	0.00
*FeO	46.10	44.20	35.0
MnO	1.50	4.40	11.20
MgO	0.19	0.65	2.40

* Total iron calculated as FeO.

Table 5. Electron microprobe analyses of rutile from Sokli esker samples N = normal rutile, Zr = zirconium rutile, N/Zr = number of analyses for N and Zr.

Esker sample numbers	N/Zr	TiO_2 N %	TiO_2 Zr %	ZrO_2 N %	ZrO_2 Zr %	Nb_2O_5 N %	Nb_2O_5 Zr %	FeO N %	FeO Zr %
1	1/4	95.6	95.7	0.09	0.51	0.85	0.23	0.49	0.06
3	2/2	95.6	95.3	—	0.66	0.39	0.35	0.20	0.05
6	1/4	97.2	95.7	0.05	0.40	—	0.36	0.10	0.10
9	0/5	—	96.1	—	0.24	—	0.17	—	0.07
10	4/0	97.2	—	0.05	—	0.08	—	0.36	—
12	4/1	96.3	96.0	0.07	0.49	0.24	0.24	0.08	0.07
14	0/5	—	96.7	—	0.69	—	0.37	—	0.04
20	0/4	—	96.6	—	0.37	—	0.21	—	0.05

Rutile

Rutile is present in all esker samples, amounting to 1—4 % of heavy mineral fractions. A total of 37 rutile grains have been analyzed from eight esker samples. Normal and zirconium-rich varieties are present (Table 5).

The compositional averages of the rutile are shown in Table 6. All the rutile comes from the basement.

Table 6. The compositional averages of the rutile.

	Number of analyses	TiO_2 %	ZrO_2 %	Nb_2O_5 %	FeO %
Normal rutile	12	96.5	0.05	0.24	0.23
Zr-rutile	25	96.1	0.40	0.27	0.05

DISCUSSION

It is evident from this study that the mechanical properties of given source rocks control the abundances and dispersal of clasts within eskers, as Virkkala (1958) concluded from his investigation of the Hämeenlinna esker in southern Finland. Figure 2 indicates how the Sokli esker has incorporated material as it traversed approximately equivalent intervals underlain respectively by fenite, phosphorus ore and carbonatites. Figure 4 shows that the more resistant fenite clasts clearly predominate over the softer phosphorus ore and carbonatite clasts. This difference is further accentuated by the tendency for fenites to show extensive tectonic fracturing, and also by the more intense weathering of carbonatites, with only isolated occurrences of fresh material available. The behavior of phosphorus ore clasts is intermediate between the above two, in that transport distances are comparable to those of fenite, while abundances are distinctly lower. For example whereas fenite clast abundances are between 35—50 % at a distance of 1 km from the proximal contact of the fenite aureole and 30—40 % at a distance of 3—4 km, phosphorus ore clasts only comprise 5—15 % of the total population at a distance of 3—4 km from the proximal contact. In general, however, clasts first appear in the Sokli esker closer to proximal contacts than is the case with the eskers in southern Finland, where the first appearance of indicator clasts has been found to be 5—8 km (Hellaakoski 1930, Virkkala 1958, Perttunen 1989).

Heavy mineral fractions from the Sokli esker show the same trends as clasts (Figures 6 and 10). Mineral distributions are however more sensitive to variations in source rocks and have generally travelled further. Carbonate remaining in the heavy mineral fraction also shows the same distribution pattern as apatite (Figure 6).

The first appearance of heavy minerals derived from the carbonatite massif occurs at a distance of 1.5 km from the proximal contact, where they comprise 4 % of the population. Their abundances remain high for a greater distance than those of clasts (Figures 4 and 6), that is, over distances of 4—5 km.

Apatite predominates in the heavy mineral fraction because it is present in all lithologies throughout the carbonatite complex, with an additional component, amounting to 3—4 % of the total, being derived from the surrounding basement. Due to the mass effect it is transported furthest. The sensitivity of the heavy mineral fraction is indicated by the distribution of francolite-goethite, which is characteristic of the Loitso phosphorus ore body. Pyrochlore is present throughout the esker lying on the carbonatite massif, being on average 0.5 %, but because of its resistance to abrasion, it is transported relatively further than other minerals. It is significant that garnet is abundant in the Sokli esker at distances of 30 to 40 kilometres from its source, testifying to its durability during transport. Comparable results have been obtained for eskers in southeastern Finland (Perttunen 1989).

In conclusion it can be stated that overall transport distances are short, the transport for the majority of carbonatite complex clasts and carbonatite massif heavy minerals being only some 4—5 km (Figs. 9 and 10). The transport mode of clasts of the Sokli esker, from the distal contact of the carbonatite complex, corresponds to the transport of esker materials in southern Finland referred to above, even though they are far

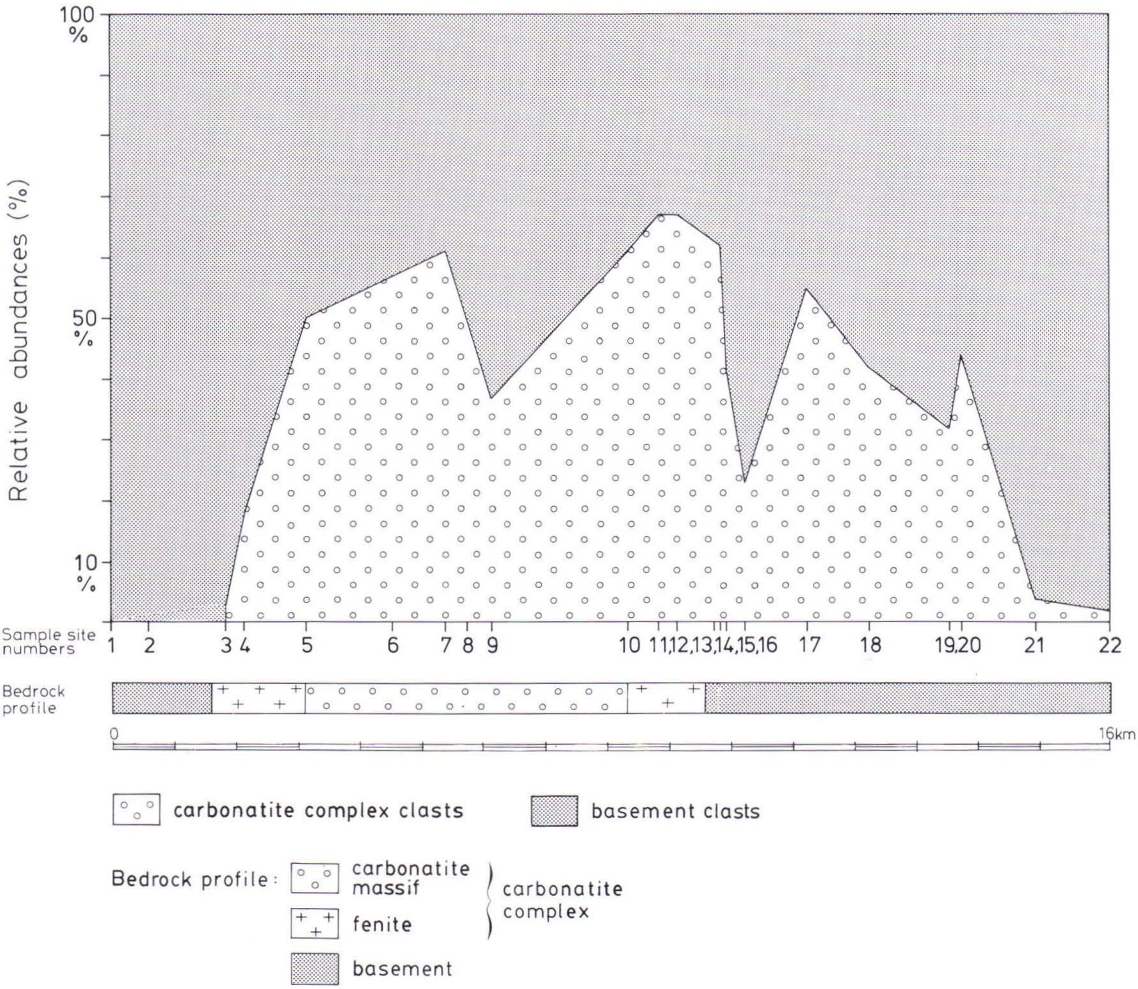

Fig. 9. Variation in the concentration of carbonatite complex clasts (Phosphorus ore, Carbonatites and Fenites) and basement clasts in Sokli esker samples.

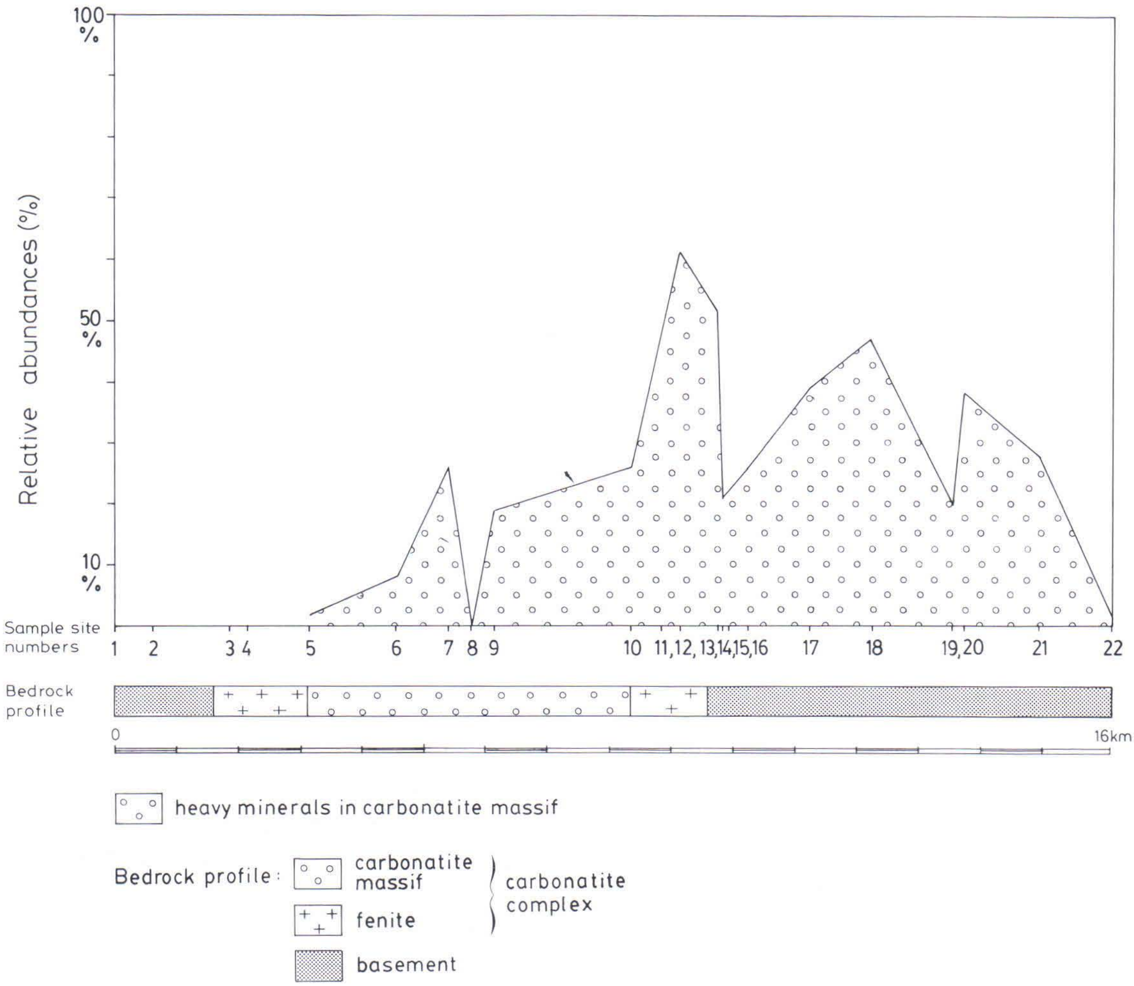

Fig. 10. Variation in the concentration of heavy minerals derived from the carbonatite massif. A background value, of around 4 %, due to apatite in the Precambrian basement, has been subtracted from the total apatite content of the samples.

away from the ice divide zone. The first appearance of the clasts in the Sokli esker is closer to the proximal contact of the source rocks than in eskers in southern Finland or other countries (Shilts and McDonald 1975, Bolduc, Klassen and Evenson 1987, Lilliesköld 1990).

Indicator clasts and soft heavy minerals within surficial esker materials are useful for mineral exploration in areas of the last deglaciation of Weichselian glaciation.

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