

# A REVISION OF THE PROTEROZOIC-ARCHEAN BOUNDARY OF THE NORTHERN BOTHNIAN SCHIST BELT WITH A DISCUSSION OF THE GEOCHEMISTRY OF RELATED BASIC METAVOLCANICS

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Geophysical analysis suggests the need for a revision of the eastern border of the early Proterozoic Northern Bothnian (or Kiiminki) schist belt. Recent geological field work has revealed places where the discordance and hiatus between Proterozoic and Archean formations are seen or have been constructed.

The geochemistry of the basic rocks (mainly metavolcanics) on both sides of the discordance is compared on the basis of XRF-analyses for major and some trace (Zr, Cr, Ni, V, Cu, Zn and Sr) elements from 80 samples and neutron activation analysis for rare earth elements (REE) from 26 samples. The rocks are divided into groups (the Archean volcanigenic amphibolites of Puutturi and Käkipärä, the Archean metagabbros of Kalliomaa, the Proterozoic metadiabases of Puutturi and Käkipärä, and the Proterozoic metabasalts of the Kiiminki schist belt), all of which have individual geochemical characteristics.

The basic rocks tend to have tholeiitic affinities (as revealed by Ti/Zr and V/Zr diagrams) but the Archean amphibolites of Puutturi are calc-alkaline. The latter group and the metagabbros of Kalliomaa are higher in Cr than are the other groups (at low Zr) and the Proterozoic metadiabases are lower in Cr than are the metabasalts of the schist belt (at low Zr). Chondrite-normalized REE patterns vary from consistent LREE enrichments in the Puutturi amphibolites to LREE depletions in the MORB-like pillowed metabasalts of the schist belt. The metadiabases are enriched in LREE but have convex-up patterns. The amphibolites of Käkipärä and the metagabbros of Kalliomaa display both depletions and enrichments in LREE.

Fractional crystallization has caused some of the variation within the groups but cannot be the cause of all the features observed. It is also evident that the Proterozoic metadiabases and the metabasalts of the schist belt are not comagmatic.

Key words: Proterozoic, Archean, metasediments, metabasalts, geochemistry, trace elements, rare earth elements.

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## Introduction

The Northern Bothnian (Pohjois-Pohjanmaa) Proterozoic schist belt is situated in northern Finland at the margin of Archean (to the NE) and Proterozoic (to the SW) terrains. The Finnish name was given by Enkovaara *et al.* (1953) in their explanation to the 1 : 400 000 geological map sheets of Oulu and Tornio. The belt is also known as the Kiiminki schist belt and this name is used here, too. Honkamo (1980) regards the belt as a Kalevian complex. The most common formations are conglomerates and greywackes of sedimentary origin. Among the greywackes there are also basic volcanics and some chemical sediments. In many places the Kalevian sedimentation began directly onto Archean basement. Thus, Jatulian formations are either absent or rare.

The extent of the schist belt is shown in Fig. 1 after Simonen (1980a and b), who drew the boundaries according to Geological Survey map sheets. The extent of the belt has not yet been fully determined on a stratigraphical basis.

Rautaruukki Oy carried out ore exploration in the Northern Bothnian schist belt between 1979 and 1984. The field operations were concentrated on the middle and eastern parts of the belt in an area dominated by basic volcanics and chemical sediments. In connection with these studies aerial and ground geophysical (magnetic, electromagnetic and gravity) data were analysed. It was revealed that, in some areas of Kalevian rocks, older formations may exist in windows or embayments and thus the area in question might consist of dissimilar complexes.

These problems are discussed in this paper by presenting some geophysical and geological observations on the eastern and southeastern part of the schist belt as a contribution to later mapping and stratigraphic studies. Much of the evidence is given in the form of geochemical comparison of basic rocks. Similar survey is called for on the other side of the belt as well.

## Evaluation from geophysical data

The Northern Bothnian schist belt has been mapped by modern aerogeophysical methods, which can be used for evaluating the geological structures and extent of the belt. The most prominent directions of the anomaly axes in the schist belt are c. NW—SE, corresponding to the Karelian strike. Magnetic anomaly axes to the east and north of the schist belt strike more or less N—S as is common for upper Archean schist belts in Finland. By examining the direction of the anomalies and the nature of their magnetic and gravity fields, T. Shulga (Sevzapgeologija, Leningrad) compiled an unpublished interpretation map of the geophysical fields as part of an iron ore prognosis project for Rautaruukki Oy in 1980—1984. Generalizing of this map permits a simple interpretation to be made (Fig. 2). The hatched areas represent combinations of geophysical fields typical of the schist belt and the stippled areas those typical of upper Archean formations (*e.g.* Kuhmo schist belt). It is geophysically feasible that the Northern Bothnian schist belt can be limited to cover the hatched area only. The extent would then be somewhat smaller than that indicated in Fig. 1. For instance, the long staurolite-mica schist unit forming a distinct magnetic anomaly at the eastern edge of schist belt could be Archean in age and have continuations northwards in the Pudasjärvi basement area. The boundaries cannot, however, be determined exactly by this interpretation alone, because of the lack of accuracy of generalizations and the thin, subhorizontal Proterozoic formations known to exist in the eastern part of the belt. We conclude that geophysical analysis gives only an approximately correct impression of the main tectonic units; it remains for geological mapping to provide a more precise picture.

## The general geological setting

The bedrock in the area investigated consists of the Archean Pudasjärvi Granite Gneiss

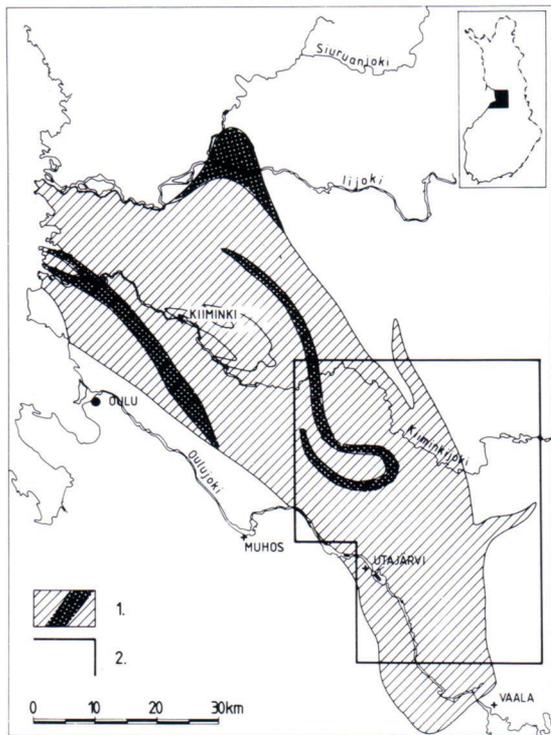


Fig. 1. 1 = The Northern Bothnian schist belt according to Simonen (1980a and b). Volcanic rocks are shown as dark.  
2 = The location of Fig. 3.

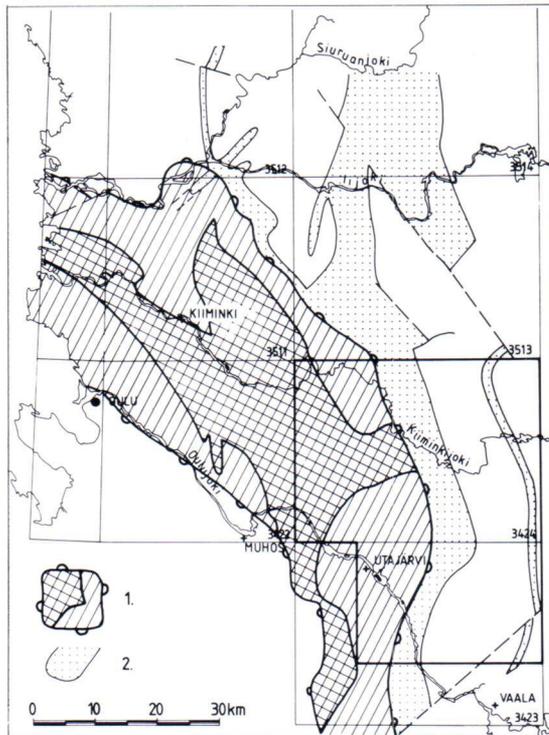


Fig. 2. See text for explanation. The area of Fig. 3 is shown.

Complex overlain by the Proterozoic Northern Bothnian schists, also known as the Kiiminki schist belt.

The geology of this region has been described by Mäkinen (1916), Wilkman (1931), Enkovaara *et al.* (1953) and Honkamo (1980, 1985). Rautaruukki Oy has carried out systematic geological mapping on sheets 3424 02, 05 and 08 and in the Puutturi, Kattilasalme and Kalliomaa areas, and field reports on these areas were drawn up for internal use by Arhe (1983 a and b). The geological information on the remaining area in Fig. 3 was compiled during various exploration programmes and is thus rather unsystematic. The field observations by Honkamo were also used in the outlining of the geological features of the southern part of the area. Open swamps and moraine formations cover large areas and make it difficult to study the bedrock. As much geo-

physical information as possible has been utilized in the construction of the geological map of the area.

The basement complex underlying the Proterozoic schists can be divided into at least three different types: 1. Migmatitic gneiss in which the nebulitic paleosome is composed of medium-grained banded mica gneiss or quartz-feldspar gneiss, and the neosome of heterogeneous granitic or trondhjemitic material. 2. Rather homogeneous medium-grained, generally foliated orthogneissic granodiorite. 3. Heterogeneous granitic gneiss. No attempt has been made on the geological map to distinguish between different types of gneiss. Amphibolitic metavolcanics associated with more acidic members are encountered as isolated patches in the granite gneiss area; they do not form continuous greenstone belts.

Metadiabase dykes, varying in size and direc-

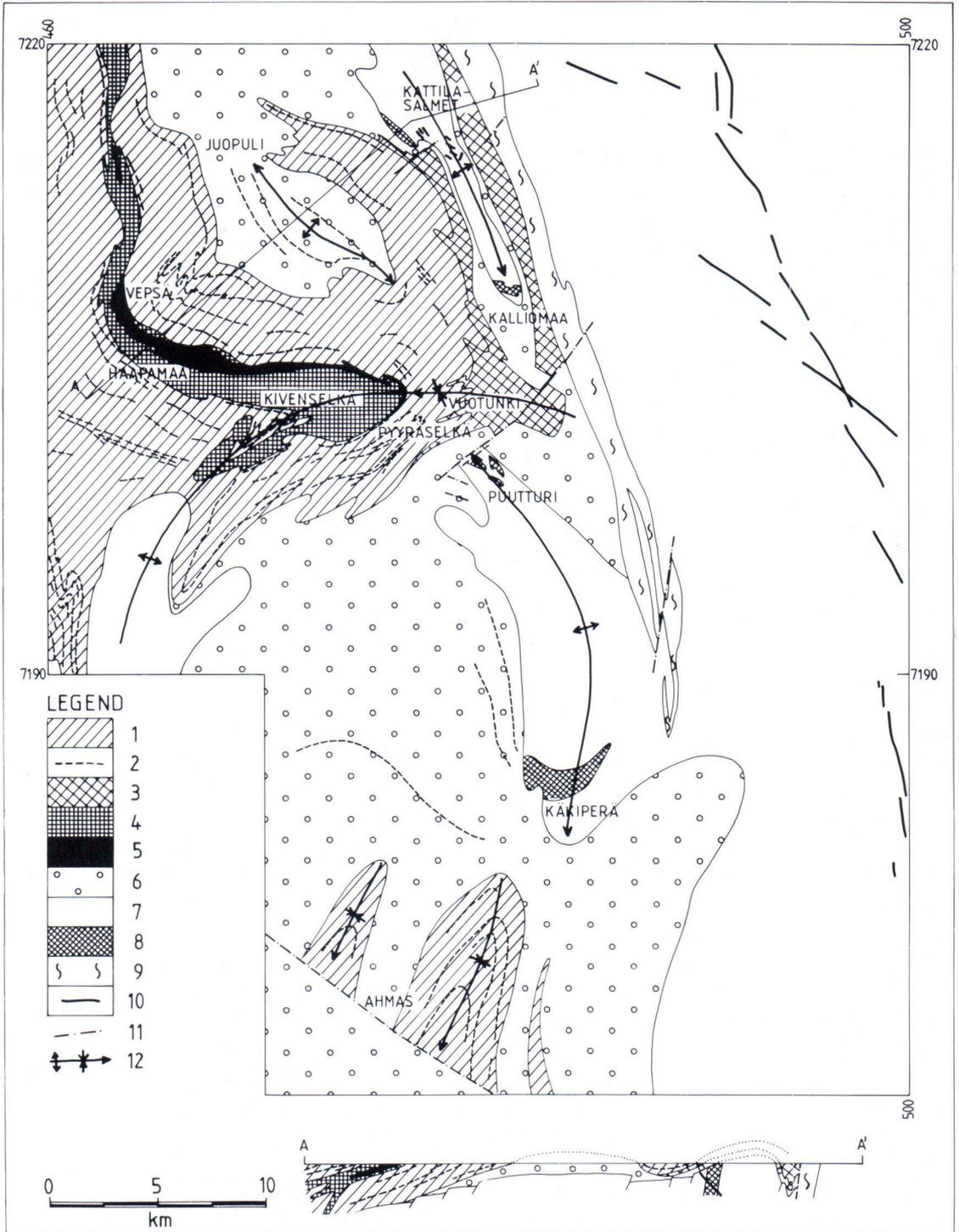


Fig. 3. Geological map of the area investigated. Proterozoic rocks: 1 = Greywacke. 2 = Black schist. 3 = Mica schist. 4 = Basic volcanics. 5 = Chemical sediments. 6 = Arkose and conglomerate. Archean rocks: 7 = Granite gneiss. 8 = Amphibolite and metagabbro. 9 = Magnetite-bearing staurolite-mica gneiss. Other symbols: 10 = Metadiabase. 11 = Fault. 12 = Antiform, synform, axial plunge.

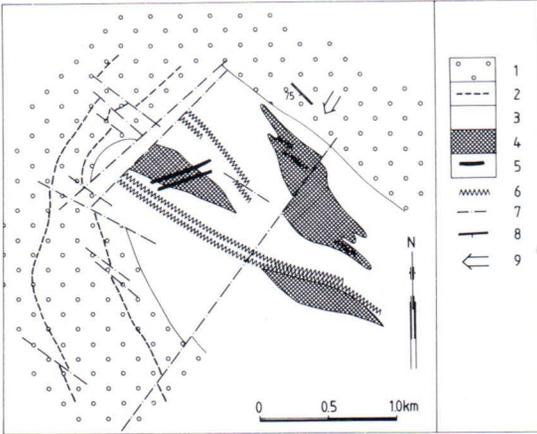


Fig. 4. Geological map of Puutturi. 1 = Arkose and conglomerate. 2 = Black schist. 3 = Granite gneiss. 4 = Amphibolite. 5 = Metadiabase. 6 = Breccia zone. 7 = Fault. 8 = Bedding plane. 9 = Bottom direction of sedimentation.

tion, are fairly common in the granite gneiss area, but have never been met with in the Proterozoic area.

The Proterozoic sedimentation on the granite gneiss usually started with arkose and conglomerate. In Puutturi these rocks may be underlain by remnants of weathering crust and possibly by Sariolan conglomerate. In the Kattilasalmei area, there is a layer of arkose just a few metres thick between the granite gneiss and andalusite-, cordierite-, and staurolite-bearing mica schists, but here the contact may be tectonic.

The very gentle dip of the bedding planes is characteristic of the Proterozoic area investigated, and in many places the sediments appear to be overlying the basement in their original position. In the eastern part, the folding was more intense, and the faulting also affected the structure of the area. Because of the gentle crossfolds, stratigraphically lower units and the basement are often exposed in the culminations. The upper units in the stratigraphic succession are exhibited in synclines and depressions, *e.g.* in the Ahmas area.

The arkoses and conglomerates represent formations deposited in the base-of-slope setting of the sedimentary basin (see also Honkamo 1985).

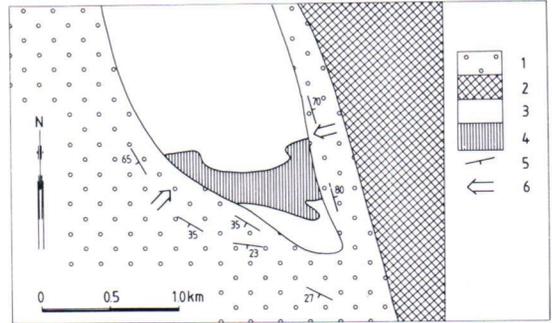


Fig. 5. Geological map of Kalliimaa. 1 = Arkose and conglomerate. 2 = Mica schist. 3 = Granite gneiss. 4 = Metagabbro. 5 = Bedding plane. 6 = Bottom direction of sedimentation.

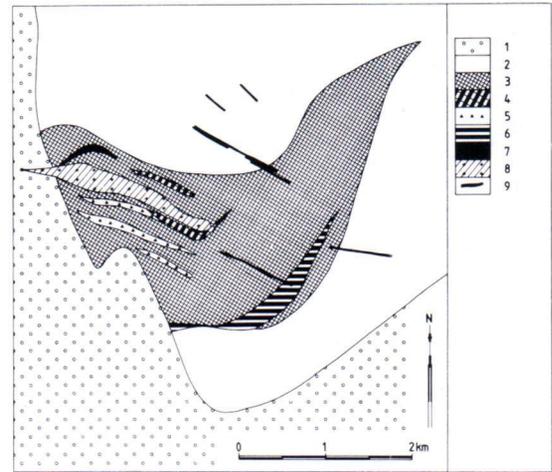


Fig. 6. Geological map of Käkipera. 1 = Arkose and conglomerate. 2 = Granite gneiss. 3 = Amphibolite. 4 = Mica schist. 5 = Skarn. 6 = Quartz-feldspar schist. 7 = Sulphide ore. 8 = Pegmatite. 9 = Metadiabase.

The sediments of the shelf facies have probably been eroded.

In the Puutturi area (Fig. 4) most of the Proterozoic material is arkose; conglomeratic material is met with only as thin intercalations. Fine-grained mica schist and black schist intercalations are also rather common. The clasts of conglomerate are composed mainly of quartz and various types of granite gneiss. Angular schist fragments also met with are probably autobreccia fragments formed during sedimentation. Graded bedding is a common feature in the Puutturi

arkoses. The amphibolites in Puutturi are characterized by heterogeneities of texture and composition. The rock is often volcanoclastic agglomerate, tuff and tuffite, but some are possibly of lava origin. The proportion of originally pumiceous material is quite high in places. The metadiabases in Puutturi are homogeneous, non-oriented rocks, often with gabbroic affinities.

The Proterozoic rock in the Kalliomaa area (Fig. 5) and its vicinity is mainly conglomerate. Its matrix is mica-bearing arkose and clasts are quartz and granitoidic gneisses. Staurolite-mica-gneiss and garnet-mica-gneiss pebbles are also met with in the conglomerate. Just a few pebbles occur in many parts of the conglomerate and, in general, the sorting is poor or absent. Cross-bedding and carbonate bearing intercalations are occasionally encountered. The metagabbro in Kalliomaa is a medium-grained plagioclase-amphibole rock, often with rather well preserved blastophitic and blastopoikilitic textures. Amphiboles are often relics after pyroxene.

In the Käkiperä area (Fig. 6) there are only a few outcrops in the Proterozoic arkose and conglomerate. The Archean amphibolites are heterogeneous with tuffs and rocks of lava origin (*e.g.* flow-breccias). Skarn, mica schist and quartz-feldspar-schist occur as intercalations in the metavolcanic formation. The metadiabases are much like those in the Puutturi area and do not display the signs of polyphase deformation so evident in the amphibolites.

The contact between the arkose-conglomerate formation and the greywacke formation in the Kiiminki schist belt has been outlined on the basis of features visible on aeromagnetic maps. The greywacke has been intersected by drilling, *e.g.* in the Vepsä area where it contains abundant Al-rich porphyroblasts (cordierite, andalusite and staurolite), and the primary structures are partly destroyed. Farther east, clastic arenite beds and mica schist beds alternate and the rock type is more easily recognizable as greywacke.

Black schist intercalations distinguishable as electric conductors because of their graphite con-

tent are very common in the greywacke formation.

If the beds in the Vepsä area are, as it now seems, in their original stratigraphic sequence, the greywackes are overlain by the products of volcanic activity. Lowest of all there is usually a bed of tuffs and lavas. After they had deposited, volcanic activity calmed down for a while, and exhalative chemical sediments (including chert, iron formation and dolomite) precipitated during the intereruptive period. Clastic sedimentation producing mica schists also occurred. Its material was partly pelitic weathering products, partly tuffs. The thickness of the volcanic sedimentary formation is 200–500 m.

During the main period of volcanism lava flows erupted. The lavas often show amygdaloidal pillow structures and volcanic breccias, but massive lava types are also common. Pyroclastic rocks are rare in the main volcanic formation. The eruption of the lava flows was probably associated with the fissures opened during the basin-building tectonic movements. Clastic sedimentation continued after the volcanic period with deposition of the upper greywackes.

The samples from Vepsä represent the lower volcanic unit whereas those from Pyyräselkä, Kivenselkä and Haapamaa represent the main period.

### **Geochemical characteristics of the basic rocks**

The geochemical features typical of the basic rocks studied are given in Figures 7–11 (see also Table 1). Differences between tholeiitic and calc-alkaline affinities are not always obvious on AFM diagrams. In these cases in particular Ti/Zr and V/Zr diagrams are useful for distinguishing between tholeiitic trends (marked increase in Ti and V between 50–150 ppm Zr) and calc-alkaline trends.

The metavolcanics of the Kiiminki schist belt are characteristically basalts with tholeiitic affinities (Fig. 7 a). They are mostly low-K rocks,

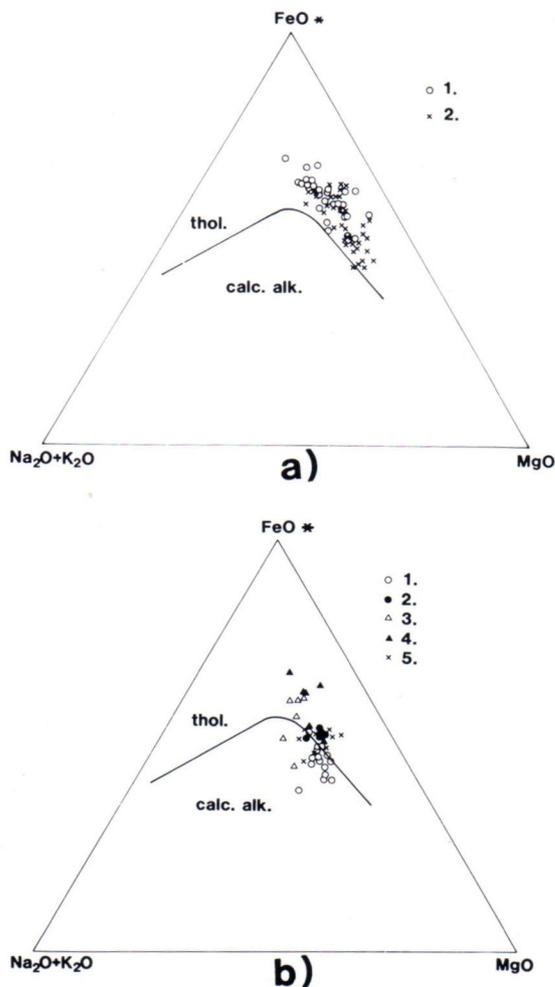


Fig. 7. AFM diagrams of rocks analysed. a. Metavolcanics from the Kiiminki schist belt. Circles correspond to samples from the Vepsä area, other samples are shown by crosses. b. 1 = Puutturi, amphibolites. 2 = Puutturi, metadiabases, 3 = Käkiperä, amphibolites. 4 = Käkiperä, metadiabases. 5 = Kalliomaa, metagabbros. Tholeiitic/calc-alkaline boundary from Irvine and Baragar (1971).

although the samples from Vepsä include many medium-K and (among the tuffites) even high-K types (Fig. 8 a). The amphibolites of Puutturi are medium-K and high-K basalts and basaltic andesites with calc-alkaline affinities whereas the metadiabases from Puutturi are mostly medium-K basalts with tholeiitic affinities (Fig. 7 b and 8 b). In the Käkiperä area both the am-

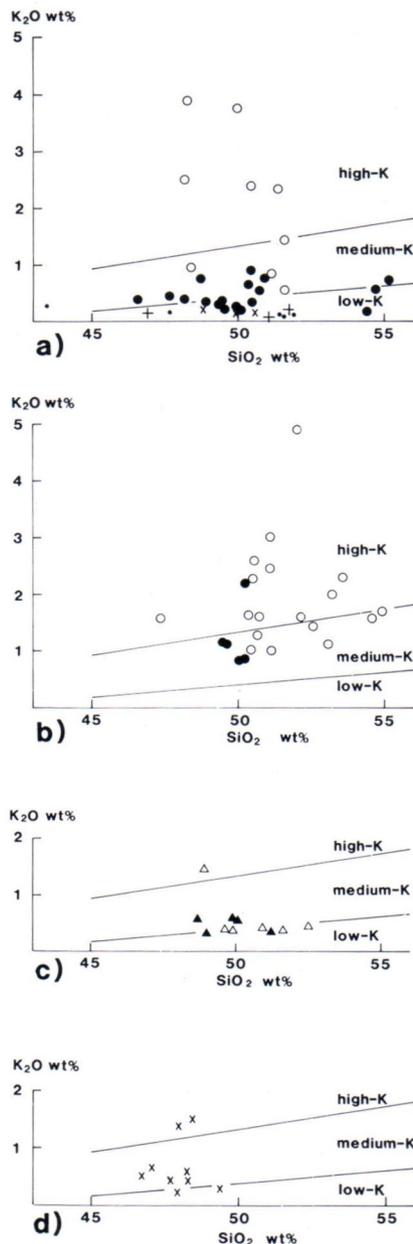
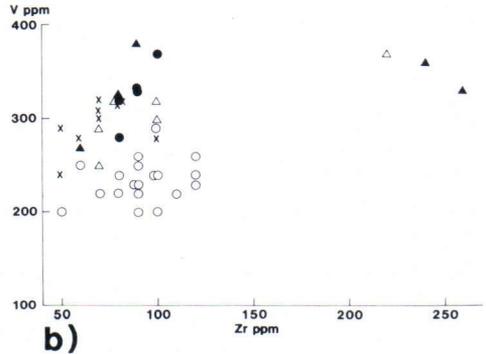
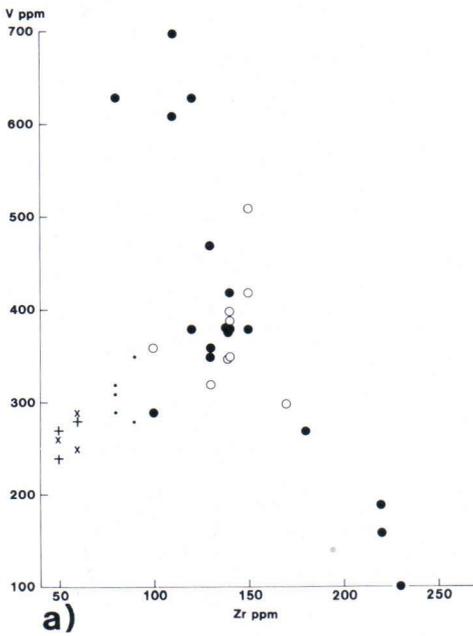
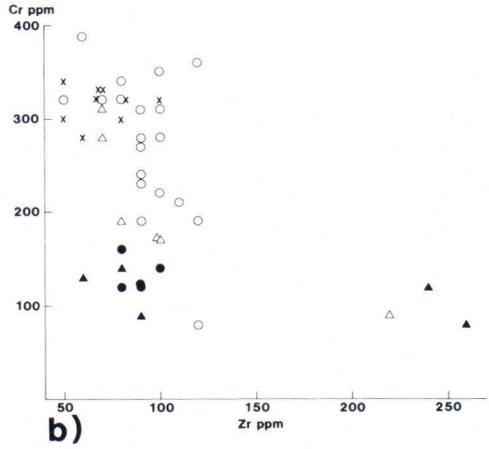
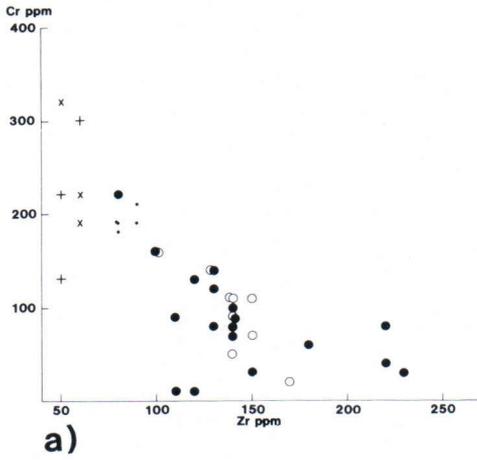
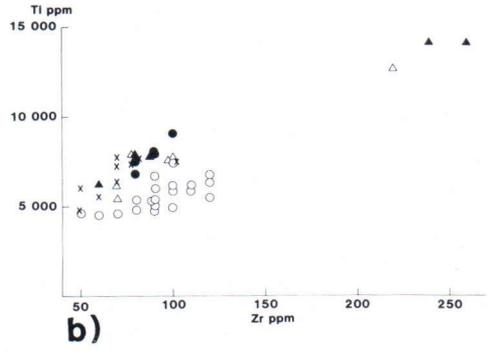
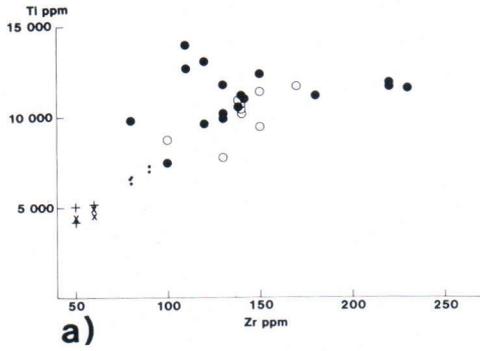


Fig. 8.  $K_2O/SiO_2$  diagrams of the rocks analysed. Based on values in Table 1 and unpublished data of Rautaruukki Oy. Sums of oxides have been calculated to 100 %. Low-K, medium-K and high-K fields from Gill (1981). a. *Kiiminki schist belt*. Points: Pyyräselkä. Crosses: Kivenselkä. Diagonal crosses: Haapamaa. Closed circles: Vepsä in general. Open circles: Tuffites of Vepsä. b. *Puutturi*. Open circles: Amphibolites. Closed circles: Metadiabases. c. *Käkiperä*. Open triangles: Amphibolites. Closed triangles: Metadiabases. d. *Kalliomaa*.



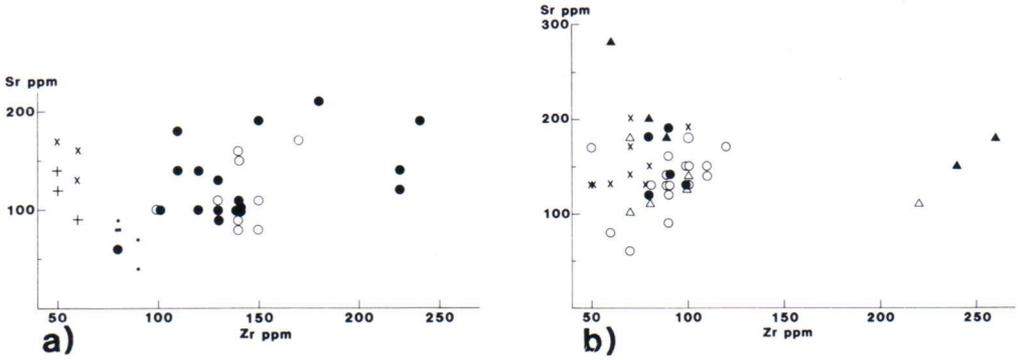


Fig. 9. Ti/Zr, V/Zr, Cr/Zr, and Sr/Zr diagrams of the rocks analysed. Data sources and symbols as in Fig. 8. a. Kiiminki schist belt, b. Puutturi, Käkipä and Kalliomaa.

phibolites and the metadiabases have tholeiitic affinities (Fig. 7 b) and they generally straddle on the low-K/medium-K boundary (Fig. 8 c). The metagabbros of Kalliomaa range from low-K to high-K rocks (Fig. 8 d). According to the AFM diagram they have both tholeiitic and calc-alkaline affinities but on the basis of the Ti/Zr and V/Zr diagrams the tholeiitic affinities are more relevant.

The differences between the calc-alkaline amphibolites of Puutturi and the tholeiitic rocks now studied are easily seen when Ti and V contents are compared at a fairly high level of Zr (Fig. 9). The Puutturi amphibolites have Ti < 7500 ppm (mostly < 7000 ppm) and V < 290 ppm (mostly < 260 ppm) when Zr contents are c. 100 ppm, whereas the groups with tholeiitic affinities have Ti > 7400 ppm and V > 280 ppm at 100 ppm Zr.

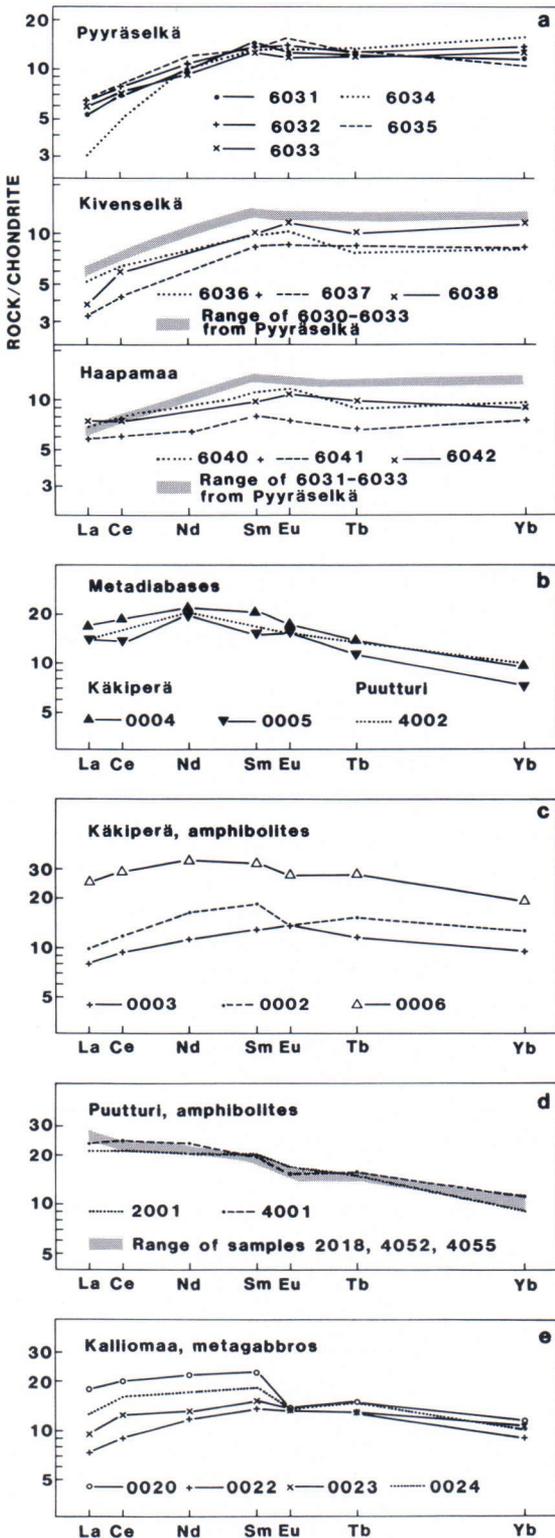
The Cr contents of all the groups decrease more or less with increasing Zr (Fig. 9). There are significant differences in Cr when the groups are compared at a relatively low level of Zr. Thus differences in the compositions of the least evolved magmas are apparent. The amphibolites of Puutturi and the metagabbros of Kalliomaa are higher in Cr (> c. 260 ppm) than the metabasalts of the Kiiminki schist belt (Cr < c. 260 ppm) and the metadiabases of Puutturi and Käkipä in particular (c. 100–160 ppm Cr), when comparisons are made at c. 75 ppm Zr.

Cr ranges in the amphibolites of Käkipä between 190–310 ppm at Zr 70–80 ppm. Thus they constitute an intermediate group between the higher-Cr and lower-Cr groups, and are considerably higher in Cr than the metadiabases with equal Zr.

Similar differences are not apparent for Ni although it, too, generally decreases with increasing Zr. The amphibolites of Puutturi range between 40–130 ppm Ni at 80 ppm Zr whereas the metadiabases of Puutturi and Käkipä range between 70–130 ppm Ni at 80 ppm Zr (Table 1 and unpublished data of Rautaruukki Oy).

The Sr contents in the rocks studied are always < 300 ppm and, excluding two samples, ≤ 200 ppm. In the Kiiminki schist belt the low-K metabasalts of Pyräselkä, Kivenselkä and Haapamaa display a decrease in Sr with increasing Zr whereas the metavolcanics of Vepsä exhibit a slight, though widely scattered, increase in Sr with increasing Zr. The amphibolites of Puutturi display an increase in Sr with increasing Zr but here, too, the scattering is wide. The metadiabases of Puutturi and Käkipä are often relatively high in Sr (180–280 ppm Sr).

Differences are also seen in the REE patterns of the various groups. The samples analysed for REE from the Kiiminki schist belt (Fig. 10 a) are among the least evolved of the metabasalts of the belt. (This is deduced from their Ti, V, Zr and Cr contents.) They are all depleted in LREE



(ratio of chondrite-normalized values of La and Yb,  $La_N : Yb_N = 0.19-0.82$ ) and have a flat HREE pattern ( $Tb_N : Yb_N = 0.8-1.2$ ) at levels La 3–8 x, Sm 8–14 x and Yb 7–16 x chondrites. The patterns are not always parallel, the patterns of the samples from Haapamaa and of sample 6036 from Kivenselkä generally being flatter than those from Pyyräselkä and Kivenselkä.

The tholeiitic metadiabases of Käkiperä and Puutturi (Fig. 10 b) have LREE-enriched ( $La_N : Yb_N = 1.4-1.9$ ) patterns which are slightly convex-up ( $La_N = 14-17$ ,  $Sm_N = 15-21$ ,  $Yb_N = 7-10$ ). The patterns are roughly parallel with each other and clearly different from those of the amphibolites of these two localities. The non-smooth pattern of sample 0005 is probably caused by analytical inaccuracies.

The calc-alkaline amphibolites of Puutturi (Fig. 10 d) are all enriched in LREE ( $La_N : Yb_N = 2.1-3.1$ ) with La 20–30 x, Sm 18–22 x and Yb 8–12 x chondrites. These features are typical of calc-alkaline volcanics in general. The patterns have slight differences, however. In sample 2001 ( $La_N : Sm_N = 1.07$ ), for example, the pattern between La and Sm is flatter than in the other four samples ( $La_N : Sm_N = 1.23-1.44$ ).

Among the tholeiitic amphibolites of Käkiperä (Fig. 10 c) sample 0003 is less evolved (lower in REE, Zr, Ti and V; higher in Cr and Ni) than sample 0002. The REE patterns of these two samples are crossly parallel; both are convex-up and slightly depleted in LREE ( $La_N : Yb_N = 0.78-0.82$ ) at levels La 8–10 x, Sm 12–18 x and Yb 9–13 x chondrites. The Eu minimum in sample 0002 is indisputable. The highly evolved amphibolite 0006 (high in REE, Ti and Zr) also has a convex-up REE pattern ( $La_N = 24$ ,  $Sm_N = 32$ ,  $Yb_N = 14$ ) but it deviates from the two considered above in its slight enrichment in

Fig. 10. Chondrite-normalized REE-patterns of the rocks studied. Chondrite: Leedy 6 (values of Masuda *et al.* 1973, divided by factor 1.2; see Jahn *et al.* 1980). a. Metabasalts of the Kiiminki schist belt; b. Metadiabases of Käkiperä and Puutturi; c. Amphibolites of Käkiperä; d. Amphibolites of Puutturi; e. Metagabbros of Kalliomaa.

LREE ( $La_N : Yb_N = 1.3$ ). Note also that it lacks a distinct Eu minimum.

The metagabbros of Kalliomaa (Fig. 10 e) display both LREE-depleted ( $La_n : Yb_N = 0.8-0.9$  for medium-K samples 0022 and 0023) and slightly LREE-enriched ( $La_N : Yb_N = 1.2-1.6$  for high-K samples 0020 and 0024) patterns. They are roughly parallel from Tb to Yb and define a narrow range (e.g.  $Yb_N = 9-11$ ). Another common feature is the regular increase from  $La_N$  (7-18) to  $Sm_N$  (12-22). The Eu minima become deeper concurrently with the increase in LREE and K. The non-smooth pattern of sample 0022 is probably due to analytical inaccuracies.

### Tectonomagmatic and petrogenetic discussion

#### General

Trace elements are a valuable tool for studies on the evolution of igneous rocks (e.g. Allégre and Hart 1978, Hanson 1980). They also give clues to the original tectonic setting of volcanic rocks (e.g. Pearce and Cann 1973, Pearce 1982 and 1983).

The present paper examines the possible effects of alterations and sedimentary mixing, and the feasibility of comagmatic relations within (and partly between) the groups. The discussion of consanguinities is based on the following features (see e.g. Hanski 1983 for mineral/melt partition coefficients or D-values): (1) In basaltic rocks the dominant crystallizing minerals are olivine ± pyroxenes ± plagioclase ± Cr-spinel ± magnetite. (2) Zr contents increase with progressive fractionation. (3) Cr contents decrease when Cr-spinel and/or pyroxenes fractionate. (4) Ni contents decrease when olivine in particular (and/or pyroxenes and/or magnetite) fractionate. (5) Sr contents decrease when plagioclase fractionates. (6) V contents increase when olivine and/or orthopyroxene and/or plagioclase fractionate. (7) The level of REE increases with increasing fractionation but the shape of chondrite-normalized patterns does not significantly change

in basaltic systems. Eu is a major exception because, in systems with low oxygen fugacity, it can become relatively depleted from residual liquids if plagioclase is fractionated. (8) When a combination of minerals fractionates the changes are determined by relative proportions of the phases.

The rocks now being discussed are mostly basaltic. Thus they are ultimately derived by partial melting of ultramafic sources, i.e. mantle. Primary melts in equilibrium with the mantle have  $FeO^* : MgO$ -ratios 0.48-0.90 and Cr contents about 400-800 ppm (see Basaltic Volcanism Study Project 1981, Table 1.4.2.2.). The volcanics studied have  $FeO^* : MgO$  ratios exceeding unity and Cr contents of 300-400 ppm at maximum. Therefore, even the most primitive of them are not primary melts but their compositions have been influenced by differentiation processes.

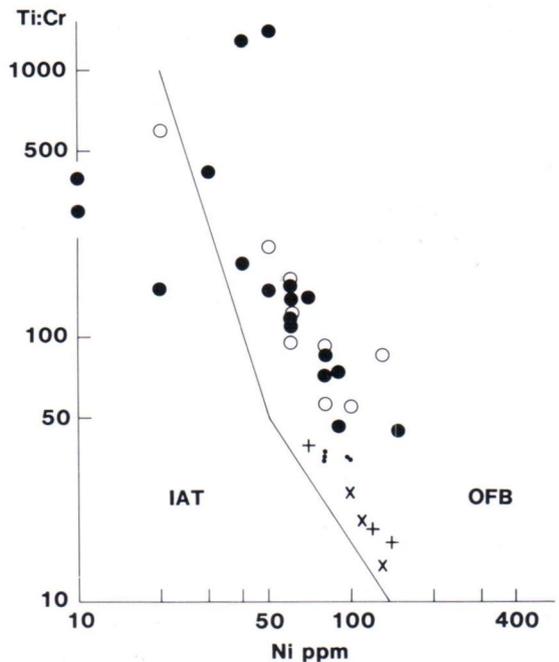


Fig. 11. (Ti:Cr)/Ni diagram of the metabasalts from Kii-minki schist belt. Symbols and data sources as in Fig. 8a. The boundary between IAT (island arc tholeiites) and OFB (ocean floor basalts) is from Beccaluva *et al.* (1979). Note that the three filled circles at 10-20 ppm Ni are the highly evolved ( $SiO_2$  54-55 %, Zr 220-230 ppm) rocks of Vepsä.

Table 1. Representative major and trace element analyses of the rocks studied. Major elements: weight %. Minor elements: ppm. FeO\* : total Fe as FeO. »Total» contains Fe as Fe<sub>2</sub>O<sub>3</sub> and trace elements as oxides.

	Pyyräselkä				Kivenselkä			Haapamaa			Vepsä					
	7381-6031	7381-6032	7381-6033	7381-6034	7381-6035	7381-6036	7381-6037	7381-6038	7381-6040	7381-6041	7381-6042	7281-2153	7281-2154	7281-2178	7281-2182	7281-2251
SiO <sub>2</sub>	51.27	50.33	49.89	46.57	42.37	51.06	50.00	45.02	47.04	48.86	48.20	54.40	49.02	48.01	47.61	54.69
TiO <sub>2</sub>	1.11	1.10	1.07	1.17	1.22	0.85	0.71	0.87	0.83	0.73	0.76	1.98	1.70	1.70	2.33	1.95
Al <sub>2</sub> O <sub>3</sub>	12.72	13.60	12.39	13.40	13.45	13.21	13.93	14.31	14.13	14.38	13.69	13.77	12.77	14.42	13.52	13.01
FeO*	12.10	11.90	12.45	15.12	16.95	12.37	11.24	13.28	12.10	10.20	11.12	15.20	14.56	14.75	16.06	14.97
MnO	0.22	0.20	0.21	0.25	0.27	0.21	0.19	0.23	0.22	0.21	0.19	0.22	0.21	0.16	0.23	0.21
MgO	7.34	6.68	7.44	8.31	8.36	6.89	8.32	9.02	7.34	7.73	7.88	4.87	6.23	8.49	5.36	4.38
CaO	8.68	8.74	9.51	8.07	10.38	10.11	9.20	10.19	10.79	11.82	9.19	4.80	8.92	5.38	8.29	5.36
Na <sub>2</sub> O	3.55	3.25	2.27	2.60	1.80	2.09	2.78	1.15	2.04	2.12	2.55	2.20	2.35	1.09	3.22	2.37
K <sub>2</sub> O	0.12	0.08	0.12	0.17	0.27	0.21	0.08	0.14	0.19	0.15	0.13	0.18	0.18	2.49	0.45	0.57
P <sub>2</sub> O <sub>5</sub>	0.11	0.14	0.06	0.05	0.09	0.08	0.07	0.06	0.08	0.08	0.07	0.35	0.21	0.24	0.18	0.36
Total	98.77	97.62	97.04	97.68	97.47	98.65	97.94	95.95	96.34	97.76	95.30	99.96	98.02	99.60	99.87	99.97
Zr	80	80	80	90	90	50	50	60	60	50	60	220	130	140	110	220
Cr	190	190	180	190	210	130	220	300	190	320	220	80	120	110	10	40
Ni	100	100	80	80	80	70	120	140	100	130	110	20	80	80	50	10
V	320	290	310	350	280	270	240	280	290	260	250	190	360	390	700	160
Cu	20	80	20	90	350	80	40	0	70	100	50	70	50	130	170	50
Zn	120	110	110	140	130	100	90	120	100	90	80	120	150	170	140	170
Sr	80	80	90	70	40	110	140	90	160	170	130	140	90	90	180	120
La	1.65	2.0	1.91	0.94	2.1	1.59	1.01	1.18	2.2	1.8	2.3					
Ce	5.6	6.2	5.8	4.0	6.4	5.1	3.4	4.7	6.4	4.9	6.0					
Nd	6.0	6.2	5.7	6.2	7.2	—	—	—	5.4	3.8	—					
Sm	2.7	2.6	2.4	2.4	2.5	1.87	1.61	1.88	2.1	1.54	1.84					
Eu	0.88	0.99	0.87	0.96	1.09	0.75	0.63	0.84	0.83	0.54	0.77					
Tb	0.58	0.60	0.58	0.64	0.60	0.37	0.39	0.48	0.42	0.31	0.46					
Yb	2.5	2.8	2.6	3.3	2.2	1.71	1.73	2.4	1.97	1.53	1.86					

Major and trace elements (excluding REE) by XRF from pressed rock powder briquettes at Raahe laboratory of Rautaruuki Oy. REE by instrumental neutron activation analysis at the Reactor Laboratory of the Technical Research Centre of Finland (Rosenberg 1977). A list of all analyses used is available from the authors on request. See Appendix I for petrography.

### *The metabasalts of the Kiiminki schist belt*

The low-K pillowed metabasalts of the main volcanic period of the Kiiminki schist belt bear a close resemblance to present-day N-type mid-ocean ridge basalts (MORB) in their LREE-depleted patterns (Fig. 10) and (Ti : Cr)/Ni ratios (Fig. 11). The common occurrence of tuffites and greywackes, however, suggests, that the basin was neither very large nor very deep because the pillowed basalts are often amygdaloidal.

The low-K metabasalts of Pyyräselkä, Kivenselkä and Haapamaa exhibit increases in Ti and V and general decreases in Ni, Cr and Sr with increasing Zr so that the metabasalts of

Pyyräselkä are highest in Zr. The Pyyräselkä metabasalts are on the whole also higher in REE (especially from Sm to Yb) than those of Kivenselkä and Haapamaa, and their REE patterns (especially samples 6031—6033) are parallel with the patterns of samples 6037 and 6038 from Kivenselkä. Thus it is possible that the metabasalts of Pyyräselkä are derived from magmas with compositions resembling those in samples 6037 and 6038 through fractional crystallization of mafic phases and plagioclase. Calculations using the Rayleigh equation suggest 40 % fractionation of olivine, clinopyroxene and plagioclase at ratios of 15 : 15 : 70 (Appendix II). The model suggested gives fairly good agreement between

Table 1 (cont.)

	B. Puutturi					C. Käkipерä					D. Kalliomaa				
	Amphibolites					Meta- dia- base	Amphibolites			Metadia- bases	Metagabbros				
	7281- 2001	7281- 2018	7281- 4052	7281- 4055	7281- 4001	7183- 4002	7383- 0002	7383- 0003	7383- 0006	7383- 0004	7383- 0005	7383- 0020	7383- 0022	7383- 0023	7383- 0024
SiO <sub>2</sub>	53.06	53.93	50.56	50.99	48.64	48.82	51.16	50.15	48.47	46.63	47.19	45.32	44.01	42.82	44.94
TiO <sub>2</sub>	1.02	0.89	1.06	1.13	0.85	1.13	1.32	1.04	2.12	1.32	1.04	0.79	1.01	0.93	1.07
Al <sub>2</sub> O <sub>3</sub>	13.99	13.98	14.02	13.83	13.54	13.00	14.68	16.41	12.06	12.78	14.15	14.26	13.61	13.65	15.58
FeO*	10.87	9.32	11.03	11.63	10.65	12.11	10.80	10.96	14.89	12.98	11.33	10.78	11.36	9.59	9.49
MnO	0.20	0.22	0.26	0.22	0.17	0.25	0.39	0.33	0.31	0.21	0.18	0.20	0.28	0.49	0.18
MgO	7.29	7.67	7.38	6.45	7.46	6.92	5.17	5.58	5.57	6.79	6.86	7.60	7.84	6.59	6.53
CaO	8.43	7.89	10.26	10.23	9.46	9.37	7.77	9.84	8.59	9.72	11.11	9.04	12.40	12.68	10.14
Na <sub>2</sub> O	2.35	2.01	1.93	2.54	3.20	3.19	4.13	3.86	2.63	3.04	2.70	2.58	1.68	2.39	3.00
K <sub>2</sub> O	1.12	1.55	1.59	0.99	0.97	0.81	0.44	0.38	0.38	0.58	0.32	1.41	0.51	0.59	1.30
P <sub>2</sub> O <sub>5</sub>	0.02	0.12	0.12	0.12	0.09	0.09	0.12	0.06	0.18	0.10	0.08	0.14	0.11	0.09	0.11
Total	99.93	98.81	99.67	99.67	96.43	97.27	97.49	97.18	97.15	95.80	96.42	93.60	94.29	91.12	93.69
Zr	100	90	120	120	90	80	80	70	220	80	60	50	50	60	70
Cr	220	270	190	80	240	160	190	310	90	140	130	300	340	280	330
Ni	70	50	90	70	100	90	90	170	30	130	110	120	140	140	150
V	240	230	240	260	230	280	320	290	370	320	270	240	290	280	310
Cu	50	10	70	110	100	50	30	30	200	150	90	40	50	50	90
Zn	150	180	130	120	90	110	120	80	110	100	90	120	120	110	100
Sr	150	120	170	140	140	120	110	180	110	200	280	130	130	130	150
La	6.5	7.7	9.0	8.9	7.3	4.3	3.1	2.5	7.7	5.2	4.4	5.6	2.3	3.0	3.9
Ce	17	16	18	20	20	13	9.3	7.5	23	15	11	16	7.2	10	13
Nd	12	13	13	12	14	12	9.7	6.8	20	13	12	13	7.0	7.4	10
Sm	3.7	3.4	3.8	4.0	3.6	3.2	3.5	2.4	6.2	3.9	2.9	4.3	2.6	2.9	3.5
Eu	1.2	1.0	1.2	1.2	1.1	1.1	0.97	0.98	2.0	1.2	1.1	0.91	0.95	0.98	0.98
Tb	0.68	0.64	0.64	0.73	0.73	0.62	0.71	0.54	1.3	0.65	0.53	0.70	0.62	0.63	0.68
Yb	1.9	2.0	1.9	2.5	2.3	2.1	2.6	2.0	3.9	2.0	1.51	2.3	1.9	2.2	2.1

the observed and calculated derivative compositions but there are some uncertainties *e.g.*: (1) the D-values vary to some degree (*e.g.*  $D_{Cr}^{\text{pl}}$ , which often exceeds 0.2, see compilation of Hanski 1983). (2) The role of Cr-spinel was not considered. (3)  $C_0$  is partly from a single sample and partly from averages. (4) Sr is probably more mobile than, say, Zr. (5) Major element modelling was not done. Besides these, in MORB, low pressure fractionation is dominated by plagioclase and olivine.

Although largely resembling samples 6037 and 6038 in Ti, V, Cr, Ni, Sr and Zr, sample 6036 (from Kivenselkä) and samples 6040-6042 (from Haapamaa) are not plausible parents for the fractionation described above because of their crossing REE patterns. Sample 6036 is further

relatively low in Cr. These features may be due to heterogeneities in the mantle or to dynamic melting (see *e.g.* Basaltic Volcanism Study Project 1981, p. 154). Using calculations like those in Appendix II we find that samples 6040 and 6042 from Haapamaa can be derived from sample 6041 by c. 20 % fractionation of 70–80 % plagioclase, 20 % olivine and some Cr-spinel (spinel to explain the notably steep decrease in Cr.) It is admitted that these ratios do not conform with the observed relics of phenocrysts (see Appendix I).

The REE patterns of samples 6034 and 6035 from Pyyräselkä cross each other and the narrow range of the patterns of samples 6031–6033. In sample 6035 these incongruencies are probably due to alterations in pillow matrix (note here the

slight increase in K and also the low Sr). Alteration in a small pillow is suggested for sample 6034.

In any case, the consistent LREE depletions in the low-K metabasalts of Kiiminki schist belt indicate that the mantle from which they melted was depleted in LREE. The depletion involved quite a large area because LREE depleted basic Karelian volcanics are known from the Puolanka and Kemi areas, about 60 km E and 120 km NW, respectively, of the present study area (Laajoki 1975, Huhma 1984).

The tuffites of Vepsä often have high potassium contents but otherwise resemble the other metavolcanics of Vepsä in Ti, V, Cr, Ni, Sr and Zr. They (like the metabasalts of the schist belt in general) contain less than 0.13 % P (Table 1 and unpublished data by Rautaruukki Oy). Because P contents in alkaline and shoshonitic basalts are often higher (*e.g.* 0.19–0.28 % in Pearce 1982) the high-K nature of these tuffites is probably not a primary feature of magma. The tuffites have apparently been mixed with pelitic material (P is below 0.13 % in various clays and shales of Koritnig 1978) with high contents of K but the mixing did not cause significant disturbances in the contents of Ti, V, Cr, Ni, Sr and Zr.

The cross distribution of the metavolcanics of Vepsä on the Ti/Zr, V/Zr, Cr/Zr and Ni/Zr diagrams (including the changes in slopes and the location on the continuations of the trends of Pyyräselkä, Kivenselkä and Haapamaa) could be attributed to the continued fractionation of mafic phases and the commencement of fractionation of magnetite at 130–150 ppm Zr. The behaviour of Sr, however, does not permit fractionation of plagioclase at Vepsä, and comagmatic relations with, say, the metabasalts from Pyyräselkä are not plausible. Note also that the non-tuffitic rocks of Vepsä are partly of medium-K, not low-K, type. A third feature to be noted is the occurrence of high-V, high-Ti and low-Cr metabasalts at 110–120 ppm Zr. All in all these features suggest that at Vepsä we have numerous

separate magma bodies differing slightly in composition. The diversities are emphasized by mixing with sediments, by hydrothermal alterations and possibly by assimilation with the crust. (Remember that the metabasalts of Vepsä belong to the lower volcanic period of the schist belt.) The highly evolved rocks of Vepsä (high Zr,  $\text{SiO}_2 = 54\text{--}55\%$ , low V) indicate considerable fractionation of magnetite in any case.

#### *The metadiabases of Puutturi and Käkipä*

The metadiabases are associated with rifting of a continent in the early Proterozoic and probably predated the metabasalts that erupted into the basin now constituting the Kiiminki schist belt. The metadiabases differ from the metabasalts of the schist belt in being generally lower in Cr at c. 70 ppm Zr, and in displaying REE patterns enriched in LREE. Thus these two Karelian groups of basaltic rocks are not comagmatic. Questions beyond the scope of the present study are whether the LREE enrichments in the metadiabases are features of the mantle, products of contamination by the continental crust or due to some other cause (see *e.g.* the articles in the book by Hawkesworth and Norry 1983 for relevant discussions).

The metadiabases of Puutturi are higher in K than those of Käkipä. The two groups have, however, numerous characteristics in common, *e.g.* tholeiitic affinities, low Cr at low level of Zr and almost parallel REE patterns. These features suggest that they have a largely, though not totally, common origin. The two highly evolved metadiabases of Käkipä (240–260 ppm Zr) are exceptions because their Cr and Sr contents are roughly the same as those in metadiabases with 60–100 ppm Zr. Thus they are hardly comagmatic with the typical metadiabases discussed above. They may even be Archean in age because diabasic rocks occurring among Archean metavolcanics can be either Proterozoic or Archean (possibly feeder dykes and sills in the latter case).

*The amphibolites of Käkiperä*

Although the amphibolites of Käkiperä have tholeiitic affinities, their REE patterns and Cr contents distinguish them from the Karelian metadiabases that cut these polyphase-deformed schists. Fractionation of mafic phases could largely explain the steep decreases in Cr and Ni with increasing Zr and the nearly parallel REE patterns in samples 0002 and 0003. However, the role of plagioclase would pose difficulties. Sr tends to display slight increase from 100 ppm to 140 ppm when Zr increases from 70 ppm to 100 ppm but sample 0003 with 180 ppm Sr at 70 ppm Zr is an exception. So, fractionation of plagioclase is not plausible for the majority of the amphibolites of Käkiperä. There is no Eu anomaly in sample 0003 but a distinct Eu minimum occurs in sample 0002. At first sight, sample 0002 could be derived from sample 0003 by fractionation of plagioclase (behaviours of Sr and Eu) and mafic phases (Cr, Ni).

Approximations on the degree of fractional crystallization implied (based on calculations presuming bulk  $\bar{D}$  for Zr, La, Sm, Tb and Yb to approach zero and use the contents of these elements in samples 0002 and 0003) give F values (Appendix II) between 0.7–0.9. Fractionations like these are too small to be able to produce the decrease in Sr and the large negative Eu anomaly in sample 0002. For example if F were 0.7 and  $D_{Sr}$  for plagioclase were 2.2, the Rayleigh equation would suggest that the solid residue should contain about 100 % plagioclase and no room would be left for pyroxenes and olivine (to explain the decreases in Cr and Ni). Thus fractional crystallization alone can hardly explain the changes in the chemical composition of the amphibolites of Käkiperä. This holds true for sample 0006, too, because it displays LREE enrichment (whereas samples 0002 and 0003 LREE depletion) and is relatively high in K.

*The metagabbros of Kalliomaa*

The basic rocks of Kalliomaa differ from the

volcanic rocks studied in being metagabbros. They do not generally contain more amphibole (which occurs partly as relics after pyroxene phenocrysts) than the lower-Cr metadiabases of Puutturi and Käkiperä (Appendix I), and sample 0022 with 70 vol. % amphibole (340 ppm Cr) does not contain significantly more Cr than do samples with 40–50 vol. % amphibole (280–330 ppm Cr). Therefore, the relatively high Cr contents in the metagabbros are not obviously due to accumulation of mafic silicates, but rather are a primary feature of magma.

The chemical characteristics of the metagabbros are difficult to explain by fractional crystallization (ranges of Zr, Cr and HREE are narrow, but ranges in K and LREE are wider) or by variable degrees of partial melting (liquids of lowest percentage of fusion should leave a residue rich in plagioclase to produce Eu anomalies). Since mineral effects are not apparent either (proper minerals are not abundant enough), mixing of magmas or early alteration would seem to be the more plausible processes.

*The amphibolites of Puutturi*

The amphibolites of Puutturi have indisputable calc-alkaline affinities. In terms of plate tectonics calc-alkaline volcanics are typically associated with converging plate margins. Whether this is the case for the amphibolites of Puutturi, too, is not relevant in the present context; important is the fact that they differ totally from basic rocks in Karelian sequences, which regularly have tholeiitic affinities (Pekkarinen 1979, Honkamo 1980, Perttunen 1983, present study).

Geological mapping and geophysical data suggest that the amphibolites of Puutturi belong to the basement underlying the Kiiminki schist belt. Further, though not absolute, support for their Archean age is provided by their high Cr and low Sr contents. Cr averages for Archean metabasalts with variably defined calc-alkaline affinities range between 175 and 250 ppm (Condie 1976, 1981; Goodwin 1977). Although the

range of Cr averages in Recent calc-alkaline basalts (65—378 ppm, Ewart 1982 Appendix 2) includes the range of Archean Cr averages the Puutturi amphibolites have higher average Cr (about 280 ppm) than do Recent calc-alkaline metabasalts on the whole. Recent calc-alkaline basalts have Sr averages exceeding 300 ppm (Ewart 1982, Pearce 1982) whereas the Sr averages in their Archean equivalents are below 200 ppm (Condie 1976, 1981; Goodwin 1977). Thus the Sr contents (60—180 ppm) of the Puutturi amphibolites are very similar to those in Archean calc-alkaline metabasalts.

The behaviour of Cr, Ni, Ti and V in the Puutturi amphibolites could be attributed to by fractionation of mafic phases in general and early commencement of fractionation of magnetite. Partly crossing REE patterns, an increase in Sr with increasing Zr and marked variability in the contents of K indicate that processes other than fractional crystallization must also be considered. These include partial melting, variable enrichments of the mantle by fluids with high, but diverse, contents of LREE, K and Sr (*e.g.* IRS fluids of Gill 1981), assimilation of pre-existing crust or volcanic-sedimentary pile, mixing during possible reworking (tuffites), and alterations at various stages. For example the sample with nearly 5 % K<sub>2</sub>O is not high in P and sedimentary mixing or alteration are probable reasons for high K in this case.

## Summary

Generalized interpretations of aerogeophysical data suggest that the eastern margin of the Proterozoic Kiiminki schist belt covers a smaller area than that proposed earlier.

During systematic field studies for prospecting purposes numerous places were found where the underlying Archean basement and the lowermost parts of the schist belt are exposed at culminations.

Some differences are revealed when basic rocks

from both sides of the discordance are compared. The Archean metavolcanics from Käkiperä and Puutturi are often of pyroclastic origin whereas the metabasalts of the Proterozoic schist belt are more often of lava origin. Particularly the (upper) main volcanic unit of the belt contains appreciable pillow basalts.

The basic groups studied also display numerous individual geochemical features.

The Proterozoic metabasalts of the Kiiminki schist belt are tholeiitic. The metabasalts of the main volcanic period, which are often pillowed, bear a particularly marked resemblance to present-day MORB in their low potassium contents, LREE depletion and (Ti : Cr)/Ni ratios. Fractional crystallization can account partly, but not totally, for the compositional variations observed. The earlier volcanic unit (represented by data from Vepsä) is often more »evolved» than the rocks of the main period as is indicated by higher Zr, Ti and V, and lower Cr and Ni in the former. However, because the lower unit is relatively high in K and Sr it is not wholly comagmatic with the metabasalts of the main period. Further, the high potassium contents in the tuffites at Vepsä (closely associated with non-tuffitic rocks) are caused by mixing with pelites. Being low in V and high in Zr a few highly evolved rocks of Vepsä indicate late fractionation of magnetite.

The Proterozoic metadiabases of the Puutturi and Käkiperä areas are associated with rifting of the Archean craton. They are also tholeiitic but their Cr contents (even at low Zr) are relatively low. They are medium-K rather than low-K rocks and display slightly LREE-enriched convex-up REE patterns. They are clearly not consanguineous with the metabasalts of the Kiiminki schist belt (which apparently post-date them).

Of the groups regarded as Archean, the metagabbros of Kalliomaa are high in Cr. This is probably a feature of magma that is not to be attributed to accumulation of mafic silicates. They range from low-K or nearly low-K types (with LREE depletion) to high-K types (with

slight LREE enrichment). The latter also display Eu minima. The changes in composition can hardly be attributed to fractional crystallization; mixing of magmas or early alteration are more likely.

The Archean amphibolites of Käkiperä are tholeiitic rocks falling mostly at the low-K/medium-K boundary. Their Cr contents decrease steeply with increasing Zr but are still higher (at low Zr) than those in the Proterozoic metadiabases. The amphibolites display both LREE-depleted and LREE-enriched patterns and they are not related to each other through fractional crystallization.

The Archean amphibolites of Puutturi are medium-K/high-K and high-Cr&low-Sr rocks with

calc-alkaline affinities, stressing their similarity with other Archean calc-alkaline metabasalts. Their REE patterns display consistent LREE enrichments. Partly crossing REE patterns and a general increase in Sr with increasing Zr indicates that fractional crystallization of mafic minerals and plagioclase cannot relate the rocks to each other; there must be some other reason.

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## References

- Allègre, C. J. & Hart, S. R. (eds)*, 1978. Trace Elements in Igneous Petrology. A Volume in Memory of Paul W. Gast. Developments in Petrology 5. Elsevier, Amsterdam. 272 p. (Reprinted from Earth Planet. Sci. Lett. V. 38, No 1.)
- Arhe, M.*, 1983 a. Geologinen kartoitus Kiimingin liuskealueella karttalehtien 3424 02, 05 ja 08 alueella. Unpubl. rep. OU 11/83. Rautaruukki Oy Malminetsintä, Oulu.
- , 1983 b. Geologinen kartoitus Kattilasalmien alueella Ylikiimingin Alavuotossa. Unpubl. rep. OU 18/83. Rautaruukki Oy Malminetsintä, Oulu.
- Basaltic Volcanism Study Project*, 1981. Basaltic Volcanism on the Terrestrial Planets. Pergamon Press, Inc., New York. 1286 p.
- Beccaluva, L.; Ohnenstetter, D. & Ohnenstetter, M.*, 1979. Geochemical discrimination between ocean-floor and island-arc tholeiites — application to some ophiolites. Can. J. Earth Sci. 16, 1874—1882.
- Condie, K. C.*, 1976. Trace-element geochemistry of Archean greenstone belts. Earth-Sci. Rev. 12, 393—417.
- , 1981. Archean Greenstone Belts. Developments in Precambrian Geology 3. Elsevier, Amsterdam. 434 p.
- Cox, K. G.; Bell, J. D. & Pankhurst, R. J.*, 1979. The Interpretation of Igneous Rocks. George Allen & Unwin Ltd, London. 450 p.
- Enkovaara, A.; Härme, M. & Väyrynen, H.*, 1953. Kivilajikartan selitys. Lehdet C5 Oulu — B5 Tornio. Suomen geologinen yleiskartta 1 : 400 000.
- Ewart, A.*, 1982. The mineralogy and petrology of Tertiary-Recent orogenic volcanic rocks: with special reference to the andesitic-basaltic compositional range. Pp. 25—95 in R. S. Thorpe (ed.) Andesites. Orogenic Andesites and Related Rocks. John Wiley & Sons, Chichester. 724 p.
- Gill, J. B.*, 1981. Orogenic Andesites and Plate Tectonics. Minerals and Rocks 16. Springer-Verlag, Berlin. 390 p.
- Goodwin, A. M.*, 1977. Archean volcanism in Superior Province, Canadian Shield. Pp. 206—241 in W. R. A. Baragar, L. C. Coleman and J. M. Hall (eds) Volcanic Regimes in Canada. Geol. Ass. Canada Spec. Paper 16.
- Hanski, E. J.*, 1983. Alkuaineiden jakautuminen mineraalien ja silikaattisulan kesken: Jakaantumiskertoimet. Arkeisten alueiden malmiprojekti. Raportti 15. Oulun yliopisto.
- Hanson, G. N.*, 1980. Rare earth elements in petrogenetic studies of igneous rocks. Ann. Rev. Earth Planet. Sci. 8, 371—406.
- Hawkesworth, C. J. & Norry, M. J. (eds)*, 1983. Continental Basalts and Mantle Xenoliths. Shiva Publishing Limited, Cheshire. 272 p.
- Honkamo, M.*, 1980. Stratigraphy of the Northern-Pohjanmaa schist area, 49—54. In: Jatulian geology in the eastern part of the Baltic Shield. Proceedings of a Finnish-Soviet Symposium held in Finland 21st—26th August 1979, ed. by A. Silvennoinen. The Committee for Scientific and Technical Co-operation between Finland and Soviet Union. Rovaniemi 1980. 251 p.
- , 1985. On the Proterozoic metasedimentary rocks of the Northern Pohjanmaa schist area, Finland. Geol. Surv. Finland, Bull. 331, 117—129.
- Huhma, H.*, 1984. Nd-isotopic composition and age of

- Proterozoic basalts from northern Finland. *Terra cognita* 4, 192.
- Irvine, T. N. & Baragar, W. R. A.*, 1971. A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci.* 8, 523—548.
- Jahn, B.-M.; Auvray, B.; Blais, S.; Gapdevila, R.; Cornichet, J.; Vidal, R. & Hameurt, J.*, 1980. Trace element geochemistry and petrogenesis of Finnish greenstone belts. *J. Petrol.* 21, 201—244.
- Koritnig, S.*, 1978. Phosphorus. 15-K. Abundance in common sediments and sedimentary rock types. Pp. 15-K-1—15-K-6 in K. H. Wedepohl (ed.) *Handbook of Geochemistry*. Springer-Verlag, Heidelberg.
- Laaajoki, K.*, 1975. Rare-earth elements in Precambrian iron formations in Väyrylänkylä, South Puolanka area, Finland. *Bull. Geol. Soc. Finland* 47, 83—107.
- Masuda, A.; Nakamura, N. & Tanaka, T.*, 1973. Fine structures of mutually normalized rare-earth patterns of chondrites. *Geochim. Cosmochim. Acta* 37, 239—248.
- Mäkinen, E.*, 1916. Översikt av de prekambriskas bildningarna i Mellersta Österbotten i Finland. *Bull. Comm. Géol. Finlande* 47.
- Pearce, J. A.*, 1982. Trace element characteristics of lavas from destructive plate margins. Pp. 525—548 in R. S. Thorpe (ed.) *Andesites. Orogenic Andesites and Related Rocks*. John Wiley & Sons, Chichester. 724 p.
- , 1983. Role of sub-continental lithosphere in magma genesis at active continental margins. Pp. 230—249 in C. J. Hawkesworth and M. J. Norry (eds) *Continental Basalts and Mantle Xenoliths*. Shiva Publishing Limited, Cheshire. 272 p.
- Pearce, J. A. & Cann, J. R.*, 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. *Earth Planet. Sci. Lett.* 19, 290—300.
- Pearce, J. A. & Norry, M. J.*, 1979. Petrogenetic implications of Ti, Zr, Y, and Nb variations in volcanic rocks. *Contrib. Mineral. Petrol.* 69, 33—47.
- Pekkarinen, L. J.*, 1979. The Karelian formations and their depositional basement in the Kiihtelysvaara-Värtsilä area, East Finland. *Geol. Surv. Finland, Bull.* 301.
- Perttunen, V.*, 1983. Peräpohjan eteläosan geologia. Unpubl. Lic. Thesis. Department of Geology, University of Helsinki.
- Rosenberg, R. J.*, 1977. Instrumental neutron activation analysis as a routine method for rock analysis. Technical Research Centre of Finland. Electrical and nuclear technology. Publ. 19.
- Shervais, J. W.*, 1982. Ti-V plots and the petrogenesis of modern and ophiolitic lavas. *Earth Planet. Sci. Lett.* 59, 101—118.
- Simonen, A.*, 1980 a. Prequaternary rocks of Finland 1 : 1 000 000. Geological Survey of Finland.
- , 1980 b. The Precambrian in Finland. *Geol. Surv. Finland, Bull.* 304.
- Wilkman, W. W.*, 1931. Kivilajikartan selitys. Lehti C4 Kaajaani. Suomen geologinen yleiskartta 1 : 400 000.

Appendix I. General petrography of the samples analysed for REE.

LOCALITY/ sample	PLAGIO- CLASE	QUARTZ	AMPHI- BOLE	BIOTITE	REMARKS
<b>PYYRÄSELKÄ</b>					
7381-6031	olig-andes, x	a	act, x (70—80 %)		From a pillow 20 cm in ø. Relics after varioles (see 6032) are rare.
-6032	olig-andes, x		act, x (70 %)		From a pillow 80 cm in ø. Relics after varioles (presently radiating clusters of amphibole) are abundant.
-6033	olig-andes, x	a	act, x (70 %)		From a pillow 70 cm in ø.
-6034	olig-andes, x	a	act, x (70—80 %)	a	From a pillow 10 cm in ø with material less than 5 % from matrix. Relics after phenocrystic and possible skeletal pyroxene, and amygdules occur.
-6035	x		act, x	a	Consists of small chips from pillow matrix with 20—30 % material from pillows. No thin section, mineral composition approximated from rock powder.
<b>KIVENSELKÄ</b>					
7381-6036	olig-andes, x	x	act/hbl, x (60 %)		From a slightly jointed massive lava. Pseudomorphs after pyroxene phenocrysts amount to 30—40 %, ø 1 mm.
-6037	andes, x	x	act, x (70 %)		From a strongly elongated pillow. Amygdules rich in plagioclase and quartz are obvious.
-6038	andes, x	a	act, x (70 %)	a	From an elongated pillow. Relics after pyroxene do occur. Amphibole grains in elongated patches, c-axis at high angle across the long dimension of patches; probable relics of dentritic pyroxene.
<b>HAAPAMAA</b>					
7381-6040	andes, x		act, x (70 %)		From a possible pillow in a jointed lava. Nematoblastic, no primary microscopic features remain.
-6041	andes, x		act, x (70 %)		From a possible pillow. Obvious relics after phenocrysts of pyroxene occur (ø to 0.5 mm).
-6042	andes, x	a	act, x (70 %)	a	From a jointed lava. Relics after phenocrystic (ø to 1 mm, ca. 50 vol. %) and some poikilitic pyroxenes occur.
<b>PUUTTURI</b>					
7281-2001	andes, x	x (~5 %)	hbl, x (60—70 %)	x (5 %)	A weakly to non-oriented amphibolite. Nematoblastic, but with some affinities to metagabbro. Two thin sections.
-2018	andes-olig, x	x (5—20 %)	hbl/act, x (40—60 %)	x (5—20 %)	Slight compositional layering occurs. Possibly volcanoclastic in origin. Medium-grained oriented nematoblastic amphibolite. Two thin sections.

7282-4052	olig-alb, x	x ( $< 10\%$ )	hbl/act, x (60—70 %)	x (5—20 %)	Stratified tuff or tuffite. A fine-grained well oriented nematoblastic amphibolite. Two thin sections.
-4055	olig-andes, x	a ( $\sim 5\%$ )	hbl, x (50—60 %)	a (5 %)	A moderately oriented, fine-grained homogeneous nematoblastic amphibolite. Two thin sections.
7283-4001	andes, x	a ( $\sim 5\%$ )	hbl, x (50—60 %)	x (10 %)	Fine- to medium-grained nematoblastic amphibolite.
-4002	andes, x		hbl, x (70 %)	x (10 %)	Amphibole occurs as blastopoikilitic pseudomorphs after pyroxene phenocrysts ( $\varnothing$ to 3 mm). A metadiabase with affinities to metagabbro.
<b>KÄKIPERÄ</b>					
7383-0002	andes-labr, x	x ( $\sim 10\%$ )	hbl, x (40 %)	a	From a fragment in a possible flow-breccia. A medium-grained, well oriented nematoblastic amphibolite.
-0003	andes, x	x ( $\sim 10\%$ )	hbl, x (40 %)	a	From a fragmented (flow-breccia?) strata. An even- and medium-grained oriented nematoblastic amphibolite.
-0006	andes, x	x	hbl, x (70—80 %)		A fine-grained, oriented nematoblastic amphibolite of possible lava origin.
-0004	andes, x	x ( $\sim 10\%$ )	hbl, x (60 %)		0.5 m from the contact of the metadiabase. Blastopoikilitic grains of amphibole (formerly pyroxene) up to 4 mm in $\varnothing$ .
-0005	andes, x	a	hbl, x (60—70 %)		3.5 m from the contact of the metadiabase. Blastopoikilitic grains of amphibole (formerly pyroxene) up to 4 mm in $\varnothing$ .
<b>KALLIOMAA</b>					
7383-0020	labr, x	a (5 %)	act/hbl, x (40—50 %)	x (10—20 %)	The primary texture of a gabbro is well discernable, the texture is partly almost blastophitic. Amphibole could be relic of pyroxene.
-0022	labr, x		hbl/act, x (70 %)		The typical texture of a gabbro is not obvious.
-0023	andes-labr, x	a	hbl, x (40—50 %)	a ( $< 1\%$ )	The fairly well preserved texture of a gabbro has blastophitic affinities.
-0024	andes, x	a (5 %)	hbl/act, x (40 %)	a (5 %)	The texture of a gabbro is well identifiable and it approaches blastophitic. Plagioclase has been partly granulated and replaced by quartz.

x: a major phase ( $> 5$  vol. %).

a: a minor or accessory phase.

act in the column of amphibole denotes pale green »actinolitic« amphibole.

Samples from Pyyräselkä are from a pillowed flow in a single outcrop. Samples from Puutturi are from drill cores.

Samples 0004 and 0005 from Käkiperä are from a single dyke.

Appendix II. Derivation of samples 6031-6033 from samples 6037-6038 by 40 % fractional crystallization of PLAG<sub>0.7</sub>CPX<sub>0.15</sub>OL<sub>0.15</sub>; comparison of calculated and observed compositions.

	Zr	Sr	Cr	Ni	V	La	Sm	Eu	Yb
C <sub>O</sub>	50	115	260	130	260	1.01	1.61	0.63	1.73
C <sub>L</sub> , calc.	82	87	198	86	283	1.59	2.56	0.93	2.6
C <sub>L</sub> , obs.	80	80	180	80	290	1.65	2.4	0.87	2.5
		-90	-190	-100	-320	-2.0	-2.7	-0.99	-2.8
D-values used									
D <sub>cpx</sub>	0.1	0.07	10	2	5	0.07	0.26	0.2	0.28
D <sub>ol</sub>	0.01	0.001	0.2	10	0.1	0.001	0.002	0.002	0.002
D <sub>plag</sub>	0.01	2.2	0.01	0.01	0.1	0.2	0.07	0.3	0.03

The calculations are based on the Rayleigh equation  $C_L = C_0 F^{(D-1)}$  where

$C_L$  is the concentration of the element in the residual melt

$C_0$  is the concentration of the element in the parental melt

$F$  is the proportion of melt left

$\bar{D}$  is the bulk distribution coefficient ( $\bar{D} = \sum XD$ , where  $X$  is the fraction of each mineral in the solid residue and  $D$  the distribution coefficient of each mineral)

$F = 0.6$  was approximated from  $\frac{Zr_O}{Zr_L} = \frac{50}{80}$  (given that  $\bar{D}_{Zr}$  approaches zero for a fractionated solid residue composed of PLAG + CPX + OL).

Composition of solid residue (70 % PLAG, 15 % CPX, 15 % OL) was initially approximated from Sr, Cr and Ni in samples 6031-6033 and 6037-6038 (given that e.g.  $\bar{D}_{Sr}$  is just slightly influenced by CPX and OL; the proportion of PLAG in the solid residue can then be approximated from changes in Sr).

$C_0$  for Zr and REE from sample 6037, and for Sr, Cr, Ni and V as averages from samples 6037-6038.

$C_{L, obs.}$  is the range in samples 6031-6033.

$D$  values for Sr, Cr, Ni and REE from Cox et al. (1979, La extrapolated from the other REE).  $D_{Zr}$  from Pearce and Norry (1979).  $D_V$  approximated from data in Hanski (1983), except  $D_V^{cpx}$ , which is from Shervais (1982) for augite at

$f_{O_2} = 10^{-12}$  (a reasonable approximation of oxygen fugacity in MORB, see Basaltic Volcanism Study Project 1981, p. 138).