Bulletin of the Geological Society of Finland, Vol. 75 (1–2) pp. 29–50

The earliest Paleoproterozoic supracrustal rocks in Koillismaa, northern Finland – their petrographic and geochemical characteristics and lithostratigraphy

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Abstract

The 2.44 Ga Koillismaa layered igneous complex (KLIC) in northern Finland is interpreted to have formed as a consequence of early Paleoproterozoic continental rifting. Associated with the mafic layered intrusions are felsic to intermediate volcanic and plutonic rocks of approximately the same age. The supracrustal rocks on top of the KLIC have been divided into three stratigraphic groups. The lowermost of these, the Sirniö Group, is thought to predate the KLIC and thus to represent the original roof. The overlying Kynsijärvi and Hautavaara Groups are somewhat younger than the layered intrusions. The Sirniö Group comprises two formations of felsic and intermediate volcanic rocks. The Sirniövaara Formation, also called as the Koillismaa granophyre, consists of a thick rhyodacitic unit with granophyric groundmass and some breccia interlayers. The Sirniövaara rhyodacite consists of plagioclase, quartz and biotite. Minor and accessory phases include ilmenite, magnetite, apatite, titanite, zircon and fluorite. Low-grade metamorphic minerals such as chlorite, epidote, carbonate and sericite are also commonly present. The granophyric texture is considered to have formed as a consequence of contact metamorphism and hydrothermal alteration associated with the emplacement of the KLIC. Above the Sirniövaara Formation is the Unijoki Formation, a heterogeneous group of felsic to intermediate volcanic rocks. The felsic rocks of the Unijoki Formation resemble the Sirniövaara rhyodacite whereas the intermediate rocks generally contain amphibole, instead of biotite, as the predominant mafic mineral. The rocks of the Sirniö Group show A-type geochemical character, e.g., high alkali content, Fe/Mg, 10000*Ga/Al, LREE, Y and Zr. In addition to primary compositional variation, metamorphic, and possibly hydrothermal, disturbance are recorded in the Sirniö Group lithologies. We consider them to be an example of early Paleoproterozoic rift-related volcanic rocks and tentatively correlative to the Salla Group in northern Finland. Similar rift-related volcanic rocks of ~2.44 Ga age have also been described elsewhere in northern Finland, northwest Russia and the Kola Peninsula, commonly in close association with the 2.44 Ga mafic layered intrusions.

Key words: metavolcanic rocks, granophyre, mineralogy, geochemistry, lithostratigraphy, layered intrusions, rifting, Paleoproterozoic, Koillismaa, Finland

1. Introduction

Granophyre is defined both as an irregular microscopic intergrowth texture between quartz and alkali feldspar and as a porphyritic rock type displaying this kind of texture in the groundmass (Bates & Jackson, 1987). A less commonly used definition is the one proposed by Vogelsang (1867), who defined granophyre as a porphyritic rock of granitic composition characterized by a crystalline-granular groundmass (see Bates and Jackson, 1987). The granophyric texture has been suggested to form by simultaneous crystallization of alkali feldspar and quartz from ternary eutectic granitic melt in the presence of excess water (e.g., Hughes, 1971). Alternatively, within a silicate melt that experiences rapid undercool-

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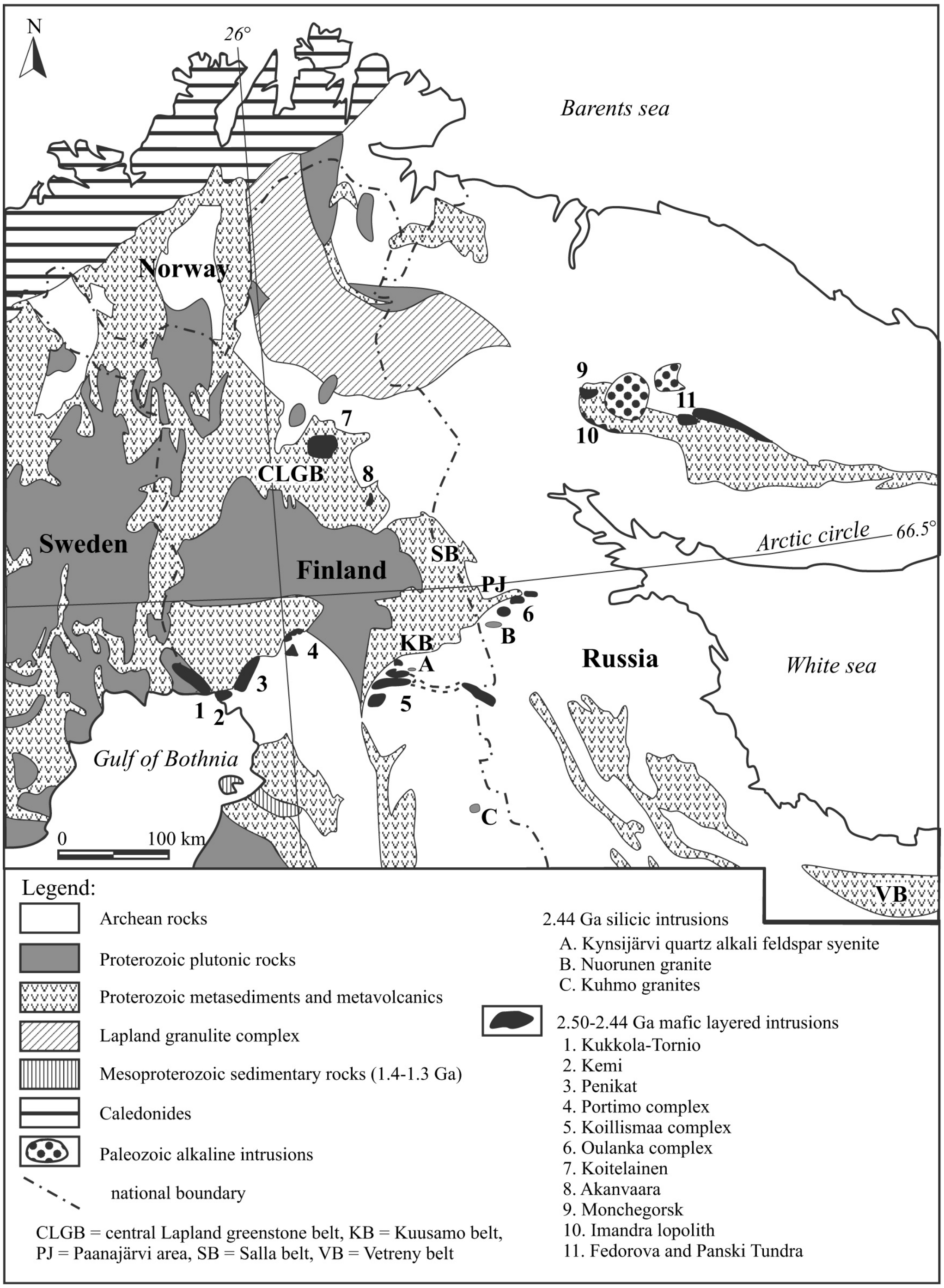

Fig. 1. General bedrock geology of the northern Fennoscandian Shield (modified after Alapieti and Lahtinen, 1989; Korsman et al., 1997).

ing, alkali feldspar-quartz symplectite may nucleate on plagioclase phenocrysts (Lowenstern et al., 1997). Metamorphic solid state recrystallization has been proposed for the formation of some granophyres (e.g., Smith, 1974; Walraven, 1985). Also, central parts of very thick (several tens to hundreds of metres), densely welded ignimbrites commonly display a granophyric texture due to slow cooling and crystallization of the formely glassy components such as welded shards and pumice (McPhie et al., 1993).

Mafic layered intrusions of various ages are commonly associated with coeval silicic rocks. Rocks displaying a granophyric texture are particularly common, e.g., in the Bushveld Complex, South Africa (Walraven, 1985), the Skaergaard intrusion, Greenland (e.g., Hirschmann, 1992) and the Muskox intrusion, Canada (e.g., Irvine, 1975). Granophyres are not only associated with mafic layered intrusions, they are also found in association with felsic volcanic rocks and granites. In felsic suites the granophyres commonly represent hypabyssal or subvolcanic variants, that are comagmatic with the supracrustal or plutonic rocks (Hughes, 1971; Lipman et al., 1997; Lowenstern et al., 1997). The genesis of the granophyric rocks in the mafic complexes is usually more complicated and, in general, relatively little studied. Interstitial granophyric material is common in the upper cumulates of many mafic layered intrusions (e.g., Alapieti, 1982) and some granophyres, especially those occurring as thin dikes, possibly represent fractionation products of mafic magmas (e.g., Miller & Ripley, 1996). In other cases the amount of silicic granophyric rocks is too large to represent fractionated mafic magma and thus a more plausible explanation for the generation of granophyres is partial melting or recystallization of roof and wall rocks (e.g., Smith, 1974; Irvine, 1975; Walraven, 1985).

The Koillismaa layered igneous complex, described by Alapieti (1982), belongs to a group of early Paleoproterozoic layered intrusions extending from western Lapland to the Kola Peninsula and the Russian Karelia (e.g., Alapieti et al., 1990). These ~2.44 Ga mafic complexes are interpreted to have been emplaced in a continental rift environment and are associated with silicic plutonic and volcanic rocks of similar age (Fig. 1). The silicic rocks in the Koillismaa area comprise the 2442±3 Ma Kynsijärvi quartz alkali feldspar syenite pluton (Lauri & Mänttäri, 2002), and several distinct volcanic units, some of which display a granophyric texture in groundmass (Juopperi, 1976; Honkamo, 1979; Lahti & Honkamo, 1980; Alapieti, 1982; Karinen, 1998; Landén, 1999). The plutonic rocks form a bimodal association but the volcanic rocks show a continuous range of compositions from intermediate to felsic varieties.

The purpose of this paper is to present a petrographic and geochemical description of the ~2.44 Ga volcanic rocks. We present an updated lithostratigraphic description of the Paleoproterozoic supracrustal rocks in the study area and discuss the possible origin of the granophyric rocks and their relation to the Koillismaa layered igneous complex. The ~2.44 Ga supracrustal rocks in Koillismaa are also compared to other known occurrences in the northern Fennoscandian Shield.

2. Sampling and analytical methods

The study area was mapped in 1996-2001 during the Layered Igneous Complexes in Northern Finland -project of the Geological Survey of Finland (GTK). Grab samples were collected from outcrops, mostly by the authors. Geophysical measurement profiles (magnetometry, VLF) were made at several locations and based on these, diamond drilling was carried out. The drill cores were logged and sampled by the authors. The total number of whole rock samples used in this study was 192, 162 of these were felsic volcanic rocks and 30 intermediate in composition.

The whole rock chemical analyses were made at the geochemical laboratory of the GTK. Samples were crushed with a Mn-steel jaw crusher and pulverized in a carbon steel ring mill. Major elements and Ba, Cl, Cr, Cu, Ga, Nb, Ni, Pb, Rb, S, Sr, V, Zn and Zr were analyzed by XRF

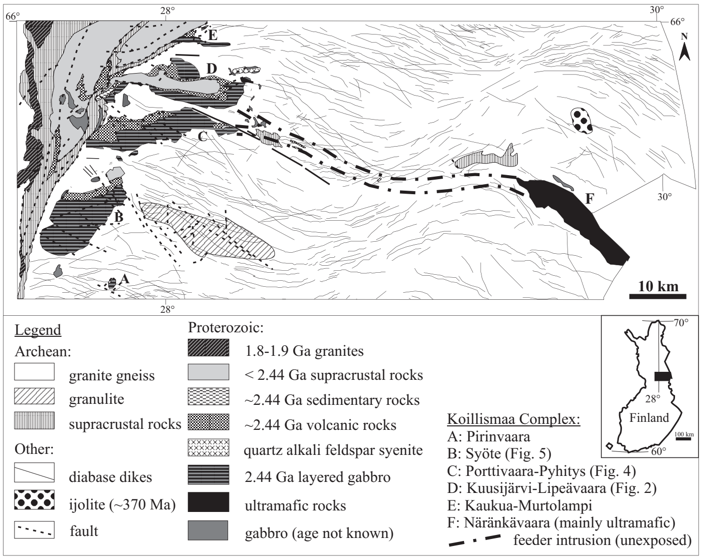

Fig. 2. General bedrock geology of the Koillismaa area (modified after Räsänen et al., 2003).

from pressed powder pellets. For the determination of the rare earth elements (REE) and several other trace elements (Y, Sc, Th, U), a subsample was digested in a mixture of HF and $HClO_4$ in a teflon dish, evaporated and dissolved in nitric acid. The solution was filtered, the filter ashed and fused in a mixture of Li-metaborate and Na-perborate, followed by dissolution of the fused bead in nitric acid and combination with filtrate. The REE, Y, Sc, Th and U were analyzed by ICP-MS. Mineralogical analyses were made at the GTK with a Cameca Camebax SX50 electron microprobe. For silicate and oxide analyses, the accelerating voltage was 20 kV, the probe current 30 nA and the beam diameter 5 µm. For apatite analyses, the corresponding values were 15 kV, 10 nA and 10 µm. Natural minerals were used as standards.

3. Regional geology

The bedrock of the Koillismaa area comprises several units of different age (Fig. 2). The oldest rocks are Archean (2.9–2.6 Ga) granitoid gneisses of the Kuhmo block (Gaál and Gorbatschev, 1987; Silvennoinen, 1991). The Paleoproterozoic (~2.44 Ga) mafic and felsic magmas have intruded the Archean gneiss complex, forming e.g. the Koillismaa layered igneous complex (Alapieti, 1982) and the Kynsijärvi quartz alkali feldspar syenite pluton (Lauri & Mänttäri, 2002). The Koillismaa layered igneous complex consists of three parts, (1) the Näränkävaara intrusion at the Finnish-Russian border, (2) the western intrusion which has been tectonized into several blocks, and (3) a dike which connects the eastern and western outcropping parts. The dike is not exposed but is clearly discernible as an aeromagnetic and gravimetric anomaly that can be traced on the surface by narrow veins of volcanic breccia/conglomerate. The top of the mafic dike has been interpreted to lay at a depth of ~1–1.5 km (e.g., Hjelt et al., 1977).

Fine-grained silicic rocks displaying a granophyric texture in the groundmass cap all parts of the Koillismaa western intrusion (Alapieti, 1982; Karinen, 1998; Landén, 1999). In places, felsic to intermediate metavolcanic rocks that do not show granophyric texture occur together with the granophyric rocks and both are overlain by metasedimentary rocks. On the western side of the Koillismaa complex there is a thick sequence of metavolcanic and metasedimentary rocks. This NS-trending schist belt has formerly been described as a continuation of the Paleoproterozoic Kuusamo belt (Silvennoinen,

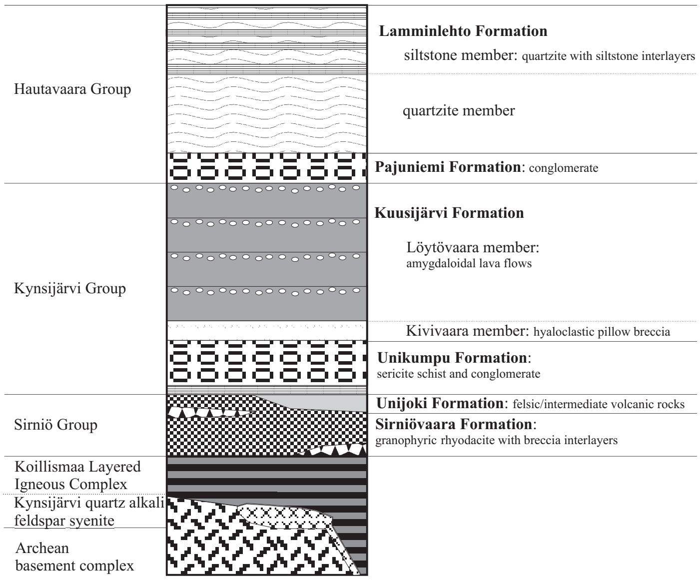

Fig. 3. Lithostratigraphic column of the Kuusijärvi–Lipeävaara area.

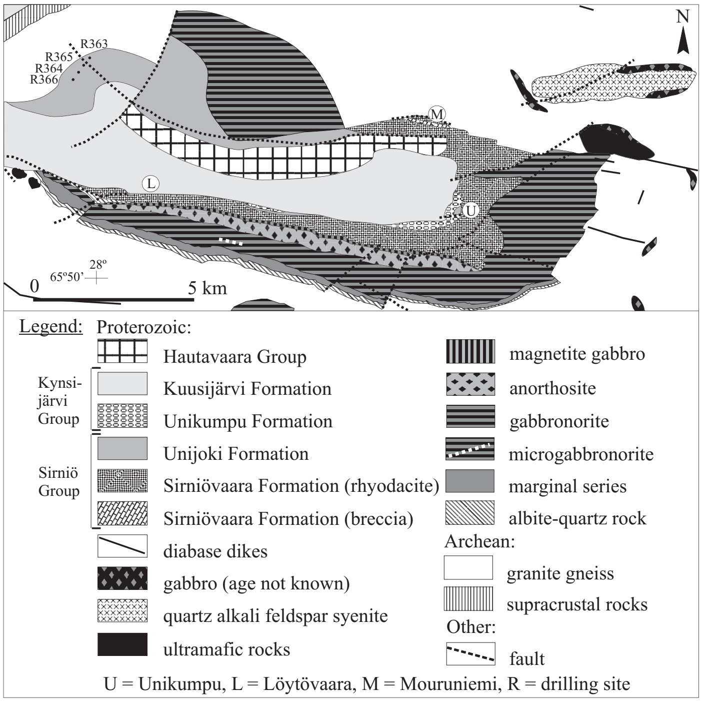

Fig. 4. Bedrock geology of the Kuusijärvi–Lipeävaara area (modified after Räsänen et al., 2003).

1991) but is now considered to be Archean in age (Räsänen & Vaasjoki, 2001). In the Kuusijärvi–Lipeävaara area (Figs. 3, 4), younger mafic metavolcanic and metasedimentary rocks overlay the granophyric rocks and associated felsic and intermediate metavolcanic rocks. The younger units resemble the lowermost units of the Kuusamo belt and can be correlated to them lithostratigraphically (Juopperi, 1976; Karinen, 1998). Several generations of diabase dikes occur in the area, cutting both Archean and Paleoproterozoic rocks (Vuollo, 1994). The youngest

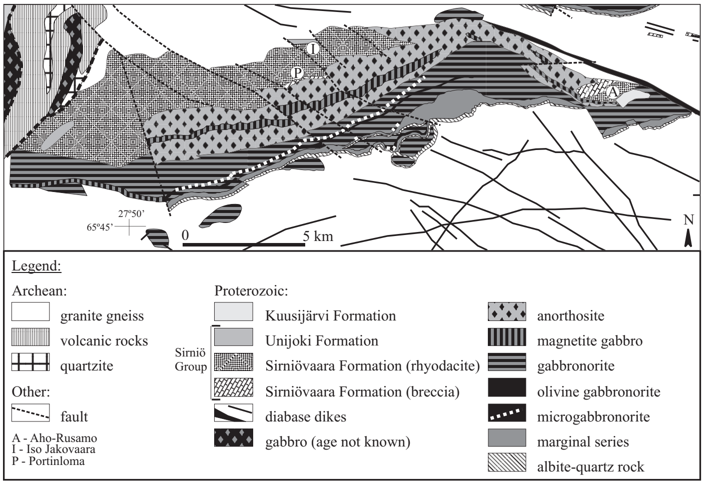

Fig. 5. Bedrock geology of the Porttivaara area (modified after Räsänen et al., 2003).

rocks in the area form the ~370 Ma ijolite intrusion of Iivaara (Kramm et al., 1993).

3.1. Lithostratigraphy

The most complete stratigraphic section of the Paleoproterozoic supracrustal rocks in the region (Fig. 3) is seen in the Kuusijärvi-Lipeävaara area (Fig. 4). The current interpretation is modified after Karinen (1998) and Karinen & Salmirinne (2001). All rocks in the area are metamorphosed but for simplicity the prefix meta- is omitted from the descriptions.

The Archean granite gneiss complex forms the depositional basement for the Paleoproterozoic volcanic and sedimentary rocks. The sill-like western intrusion of the Koillismaa complex is thought to have intruded along the unconformity between the Archean basement and the pre-intrusion supracrustal rocks (e.g., Alapieti, 1982). The lowermost supracrustal sequence, the Sirniö Group, is thought to be slightly older than the layered intrusion, although no age determination is available yet. The Sirniö Group comprises two formations of felsic to intermediate volcanic rocks. The Sirniövaara Formation, also called as granophyre (e.g., Alapieti, 1982), consists of rhyodacitic rocks with a granophyric groundmass as well as some breccia interlayers and overlies the gabbroic and anorthositic cumulates of the layered intrusion. In the Kuusijärvi area, the thickness of the Sirniövaara Formation is several hundred meters, which suggests that it may represent a large ignimbrite sheet or several separate flows. Above the Sirniövaara Formation is the more heterogeneous Unijoki Formation that consists of felsic to intermediate volcanic rocks without granophyric groundmass. Most of the rocks are crystal tuffs but some lavas, mostly of intermediate composition, are also present. The Unijoki Formation is only some tens of meters thick, probably due to extensive erosion shortly after the extrusion of the volcanic rocks.

The Sirniövaara Formation is exposed in some locations but in most places it is covered by thick Quaternary deposits. The contacts to the surrounding rock units are commonly unexposed. In the Portinloma area, Porttivaara block (Fig. 5), the contact zone between the Sirniövaara Formation and the layered rocks is somewhat exposed and consists of a breccia with mafic volcanic fragments in a more felsic groundmass that, in places, shows granophyric texture. The breccia is also exposed in the Aho-Rusamo area (Fig. 5) where it is adjacent to the rocks of the Unijoki Formation and the granophyric rhyodacite seems to be absent. In the Mouruniemi area of the Kuusijärvi block (Fig. 4), the breccia seems to form an in-

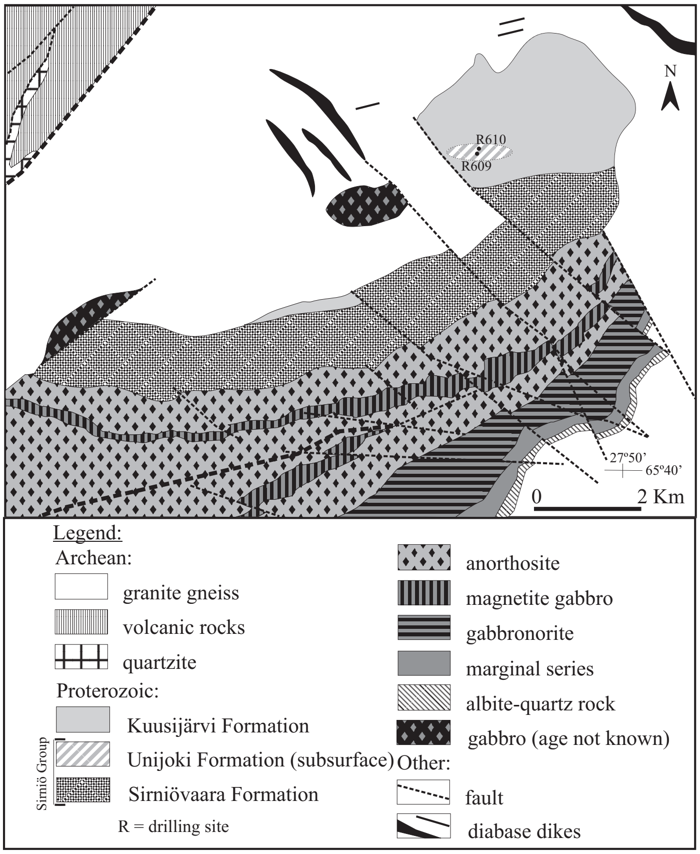

Fig. 6. Bedrock geology of the Syöte area (modified after Räsänen et al., 2003).

terlayer in the granophyric rhyodacite, but the lack of outcrops makes the interpretation difficult. On the Kuusijärvi (Fig. 4) and Porttivaara blocks the Sirniövaara Formation is relatively well exposed whereas the upper parts of the Syöte (Fig. 6) and Lipeävaara (Fig. 4) blocks are mostly covered with thick sand deposits. Only the rocks of the Sirniövaara Formation crop out in the Syöte area. The rocks of the Unijoki Formation have been found only in the subsurface underneath the rocks of the Kuusijärvi Formation in two drill cores (Fig. 6). The drill cores from the Lipeävaara area (R363–R366) consist of volcanic material of the Unijoki Formation and the Sirniövaara Formation seems to be either very thin or absent. In the Porttivaara block, the Sirniövaara Formation is rather wide, due to folding and thrusting which is visible in the Iso Jakovaara area (Fig. 5). In the Kuusijärvi and Porttivaara blocks, the lower parts of the Sirniövaara Formation contain mafic, amphibole bearing veins and patches, which are considered to be hypabyssal equivalents of the slightly younger mafic volcanic rocks of the Kuusijärvi Formation.

Locally the Unijoki Formation grades into the overlying sedimentary rocks of the Unikumpu Formation that forms the lowermost unit of the Kynsijärvi Group. In some places the contact is sharp. The Kynsijärvi Group comprises two formations. The Unikumpu Formation is characterized by sedimentary rocks, mainly conglomerates, but also a thin layer of sericite schist that is thought to represent a weathering surface. It has been suggested that the thickness of the conglomerate may reach 500 m (Juopperi, 1976) but this estimate is based on only one observation of layering and might be questionable due to deformation. The Unikumpu conglomerates are texturally and mineralogically immature and unsorted. The size of the phenoclasts varies from less than 1 cm to boulders of over 1 m in diameter. The conglomerate most probably represents a talus formation deposited in a rift graben. Both the phenoclasts and the matrix contain volcanic material of the Sirniö Group (mainly from the Unijoki Formation) although the majority of the clasts consists of granite gneiss eroded from the surrounding Archean basement. Gabbroic clasts from the layered intrusion have so far not been found in the Unikumpu Formation. The next unit is the volcanic Kuusijärvi Formation. It is divided into a basal Kivivaara member and an upper Löytövaara member (Fig. 3). The Kivivaara member consists of hyaloclastic pillow breccias of basaltic andesitic composition. The size of the breccia blocks varies from small 1 cm fragments to deformed pillows of over 50 cm in diameter. The pillows and fragments consist of green lava that occasionally contains amygdules filled with quartz and/or carbonate. The matrix is light green and slightly more quartz-rich than the fragments. The Löytövaara member consists of at least five flows of basaltic lava (e.g., Löytövaara area, Karinen, 1998) (Fig. 4). The flow tops contain amygdules filled with quartz, feldspar and carbonate, whereas the lower parts of the flows are massive.

The major sedimentary unit in the study area, the Hautavaara Group, overlies the Kynsijärvi Group. On the northern side of the Hautavaara Group the Kynsijärvi Group is missing and the contact against the Sirniö Group is strongly sheared (Fig. 4). The basal Pajuniemi Formation consists of a matrix–supported polymictic conglomerate. The matrix is composed mostly of volcanic material, probably derived from the underlying Kuusijärvi Formation. The clasts consist of Archean granitic gneisses and different kinds of mafic and felsic volcanic rocks including granophyric rhyodacite. Vein quartz fragments are also commonly encountered. The overlying Lamminlehto Formation comprises two members, the lower quartzite member and the upper siltstone member. The quartzite member consists of quartz arenites and minor subarkose arenites. The siltstone member is characterized by quartzites with metapelitic interlayers. Sedimentary structures such as grading and cross-bedding that are common in the Lamminlehto Formation allowed Karinen (1998) to establish the synclinal structure of the Kuusijärvi–Lipeävaara area. Paleocurrent directions are mostly to the west.

4. Petrography and mineral chemistry

4.1 Sirniövaara Formation

The weathered surface of the granophyric rhyodacite of the Sirniövaara Formation is creamy white or light brown. The mafic minerals are commonly weathered and only plagioclase and quartz remain visible, giving the surface a grainy texture. Most outcrops show weak to moderate schistosity, and in some places the rock is heavily deformed. The fresh surface is dark gray or dark greenish gray in chlorite-bearing varieties. Small, euhedral plagioclase phenocrysts may give the rock a pink or light green tint. The quartz is light blue or purple. It also fills the small vesicle-like cavities that are found in several places in the rhyodacitic unit. Most outcrops in the area are cut by tension veins or joints filled with quartz, epidote, chlorite and carbonate. The veins vary in width from a few millimeters to several meters. Some sulphides (pyrite, chalcopyrite) are occasionally present, commonly in thin quartz veinlets.

In thin section the rhyodacite is fine-grained and microporphyritic (Fig. 7a). Most samples show one or two weak schistosities, commonly present as an orientation of mica crystals. Stronger deformation is seen in some samples. Later brittle deformation is indicated by thin quartz, epidote and carbonate veinlets commonly cutting the schistosities. The major rock forming minerals are plagioclase, quartz and biotite. In some samples chlorite is more abundant than biotite, although it is usually present as an accessory mineral. Other accessory phases include potassium feldspar, zircon, apatite, fluorite, oxide minerals and sulphides. Amphi-

Table 1. Representative feldspar compositions of the Sirniö group.

	Phenocrysts							Granophyric intergrowths		
	Sirniövaara formation			Unijoki formation				Sirniövaara formation		
Sample	R334 17.00	LSL98107	R333 50.10	LSL98112 felsic	R336 56.90 felsic	R336 33.10 felsic	LSL0018 intermediate	LSL98107/grf	R334 17.00/ grf	R333 50.10/ grf
SiO_2	68.46	66.28	68.03	67.86	67.47	68.43	68.04	67.58	67.69	67.37
Al_2O_3	19.53	20.11	19.39	19.64	19.35	19.50	19.63	19.77	19.70	19.66
FeOtot	0.07	0.61	0.39	0.11	0.88	0.38	0.08	0.43	0.14	0.37
CaO	0.08	0.91	0.06	0.19	0.09	0.05	0.20	0.63	0.10	0.57
Na_2O	11.66	11.15	11.42	11.75	11.30	11.79	11.91	11.29	11.80	11.38
K_2O	0.06	0.05	0.03	0.07	0.03	0.04	0.04	0.05	0.04	0.20
Total	99.86	99.11	99.32	99.61	99.12	100.19	99.92	99.75	99.47	99.55
Number of ions on the basis of 32 oxygen atoms										
Si	11.98	11.75	11.97	11.92	11.93	11.96	11.92	11.88	11.91	11.87
Al	4.03	4.20	4.02	4.07	4.03	4.02	4.05	4.09	4.08	4.08
X-site	16.00	15.96	15.99	15.99	15.96	15.97	15.97	15.97	15.99	15.96
Fe^{2+}	0.01	0.09	0.06	0.02	0.13	0.06	0.01	0.06	0.02	0.05
Ca	0.02	0.17	0.01	0.04	0.02	0.01	0.04	0.12	0.02	0.11
Na	3.96	3.83	3.90	4.00	3.87	3.99	4.05	3.85	4.03	3.89
K	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.04
Z-site	3.99	4.11	3.97	4.07	4.03	4.07	4.11	4.04	4.08	4.09
Total	19.99	20.07	19.96	20.06	19.99	20.04	20.08	20.01	20.07	20.05
An	0.38	4.32	0.31	0.88	0.45	0.24	0.92	3.00	0.46	2.67
Ab	99.29	95.40	99.50	98.76	99.38	99.55	98.85	96.73	99.29	96.24
Or	0.33	0.28	0.19	0.36	0.18	0.21	0.23	0.26	0.25	1.10

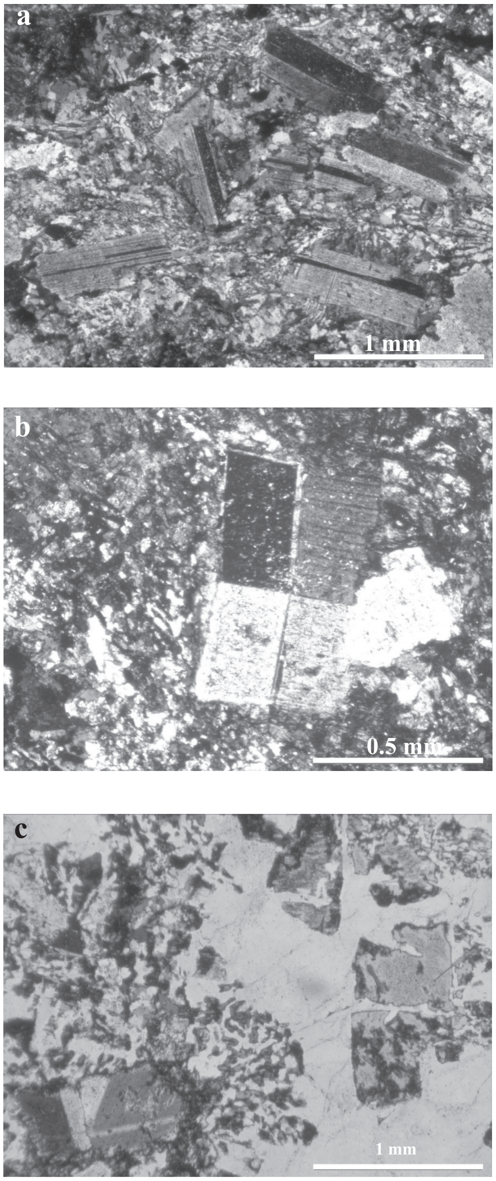

Fig. 7. Photomicrographs of the rhyodacite of the Sirniövaara Formation (a-e) and the felsic volcanic rocks of the Unijoki Formation (f-g). a) Euhedral plagioclase crystals in a groundmass that shows a granophyric texture of irregular radiating fringe type, sample LSL-98-18, crossed polars. b) Detail of a plagioclase phenocryst, sample R333 17.45, crossed polars. c) Anhedral quartz crystal with vermicular granophyric intergrowths of albite, sample LSL-00-65, crossed polars.

bole is rare, and in one sample it occurs together with stilpnomelane. Secondary minerals such as epidote, clinozoisite, carbonate and sericite are common in accessory amounts, but may also be major minerals in the more altered samples. Biotite, chlorite, epidote, clinozoisite, carbonate and sericite are metamorphic, possibly hydrothermal, in origin.

Plagioclase occurs as euhedral phenocrysts up to 2 mm in length (Fig. 7a, b). In many samples, the phenocrysts are broken into several pieces. In places they occur in the form of glomerophyric clusters. The shape of the phenocrysts is blocky or elongated. They are commonly twinned according to albite, Carlsbad, Baveno or pericline laws, the first two being the most common. Faint zoning is visible in some crystals. The phenocrysts are somewhat altered to sericite and saussurite, whereas the albite in granophyric intergrowths is less altered. The plagioclase is mostly albitic, but in a few samples oligoclase is observed (Table 1). The feldspar in the granophyric groundmass is compositionally similar to the phenocrysts. The feldspar compositions probably reflect hydrothermal albitization of the original rock and thus do not represent magmatic compositions.

Many of the plagioclase phenocrysts are surrounded by thin albite rims grading into a granophyric intergrowth of albite and quartz, the albite being in optical continuity with the phenocryst. The intergrowths commonly form incomplete radiating fringes around the feldspar phenocrysts (Fig. 7a). The larger, anhedral quartz crystals (1-2 mm in diameter) are, at the margins, commonly vermicularily intergrown with albite (Fig. 7c). The granophyric quartz patches probably formed as a consequence of remelting of the rock. In deformed samples, the plagioclase phenocrysts are commonly rounded and occasionally broken and the granophyric intergrowth is replaced by a fine-grained groundmass of anhedral or granoblastic albite and quartz. Quartz also occurs as veins.

Biotite is brown, pleochroic and commonly contains small zircon inclusions surrounded by pleochroic haloes. It forms either aggre-

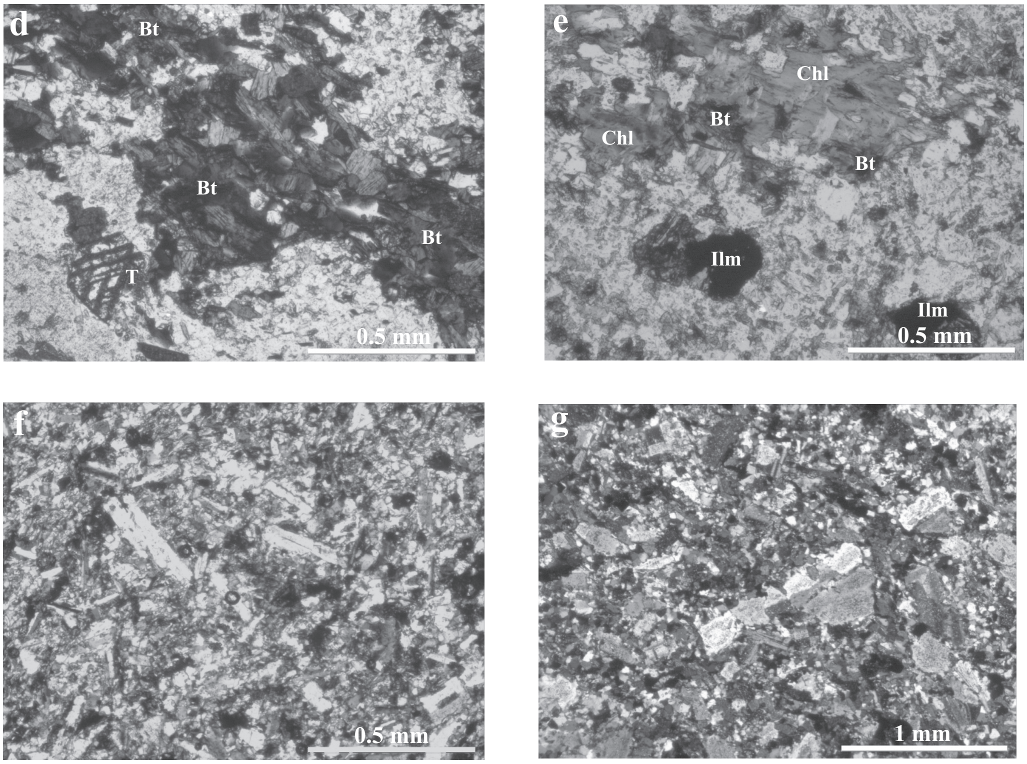

Fig. 7. (cont.) d) Irregular patch of biotite crystals (Bt) and a skeletal titanite (T), sample LSL-98-92, plane-polarized. e) Patch of chlorite (Chl) and biotite (Bt) and several ilmenite crystals (Ilm), sample LSL-00-65, plane-polarized. f) Felsic lava, sample LSL-98-112, crossed polars. g) Crystal tuff, sample LSL-00-14, crossed polars.

gates of small, randomly oriented crystals (Fig. 7d) or single plates that define the schistosity. Green, Fe-rich chlorite is also present in varying amounts (Fig. 7e). Biotite and chlorite commonly occur together as lamellar intergrowths. Biotite compositions (Table 2) fall between siderophyllite and annite (Fig. 8). Large variation of $[Fe^{2+}/(Fe^{2+}+Mg)]$ indicates possible metamorphic disturbance of the original magmatic compositions. The Fe/Mg ratio of the chlorites follows quite closely that of the coexisting biotites. Chlorite compositions fall between clinochlore and chamosite. More clinochlore-rich chlorites occur in the lower parts of the Sirniövaara Formation. Schwartz (1958) describes a commonly encountered alteration sequence of biotite under mesothermal conditions that resembles the features seen in the granophyric rhyodacite of the Sirniövaara Formation. The mildest degree of alteration has resulted in polycrystalline aggregates of brown biotite that in places preserve the outlines of the original magmatic biotite crystals. More intense hydrothermal alteration results in the formation of green biotite and, in later stages, chlorite. The alteration of biotite in the rhyodacite is most intense in the lower parts of the formation and also in the local shear zones, that may have acted as pathways to the hydrothermal fluids.

Apatite occurs as long, thin, broken needles. Zircon is found as small, euhedral, turbid crystals. Fluorite forms small, anhedral crystals. The most common oxide mineral is ilmenite which is euhedral to subhedral, in places skeletal. Magnetite is also quite common. Most ilmenite crystals are rimmed by very fine-grained titanite which seems to be an alteration product or a reaction rim. Titanite also fills the interstices of the skeletal ilmenite crystals. Sulphides (pyrite, chalcopyrite) occur as small, anhedral to euhe-

Table 2. Representative biotite and chlorite analyses of the Sirniö Group.

	biotites				chlorites			
Sample	R333 50.10/bt[a]	LSL-00-9/bt[a]	LSL-98-106/bt[a]	R336 33.10/bt[b]	R333 50.10/chl[a]	LSL-00-9/chl[a]	LSL-98-106/chl[a]	R336 33.10/chl[b]
SiO_2	33.97	34.11	37.04	32.41	24.08	23.84	27.15	23.32
TiO_2	2.13	3.04	1.74	2.49	0.11	0.12	0.06	0.33
Al_2O_3	16.25	15.80	17.61	17.04	20.69	19.71	20.92	21.27
Cr_2O_3	0.13	0.00	0.00	0.07	0.09	0.00	0.00	0.04
FeOtot	26.89	30.11	18.52	31.38	33.95	39.37	23.30	39.18
MnO	0.16	0.43	0.08	0.34	0.28	0.89	0.13	0.52
MgO	5.81	2.36	10.63	2.33	8.60	3.22	16.56	3.04
CaO	0.01	0.03	0.00	0.17	0.04	0.05	0.03	0.03
Na_2O	0.03	0.06	0.03	0.02	0.00	0.01	0.02	0.07
K_2O	9.61	9.28	10.08	8.35	0.11	0.06	0.00	0.84
Total	95.07	95.27	95.80	94.69	87.97	87.30	88.19	88.78
Number of ions on the basis of 22 O					Number of ions on the basis of 36 (O, OH, F)			
Si	5.434	5.525	5.590	5.306	5.327	5.504	5.602	5.300
Al^{IV}	2.566	2.475	2.410	2.694	2.673	2.496	2.398	2.700
Al^{VI}	0.497	0.540	0.722	0.594	2.716	2.863	2.684	2.994
Ti	0.256	0.370	0.198	0.306	0.018	0.020	0.009	0.057
Cr	0.016	0.000	0.000	0.010	0.016	0.001	0.000	0.007
Fe^{2+}	3.597	4.078	2.337	4.296	6.280	7.601	4.020	7.449
Mn	0.022	0.059	0.010	0.047	0.053	0.175	0.023	0.100
Mg	1.386	0.569	2.392	0.570	2.835	1.107	5.093	1.029
Ca	0.002	0.005	0.000	0.030	0.009	0.012	0.006	0.008
Na	0.009	0.020	0.008	0.006	0.000	0.004	0.007	0.031
K	1.960	1.917	1.941	1.745	0.031	0.017	0.001	0.244
OH	2.000	2.000	2.000	2.000	15.983	15.916	15.898	15.957
F	0.000	0.000	0.000	0.070	0.000	0.141	0.204	0.062
Cl	0.170	0.040	0.070	0.070	0.033	0.026	0.000	0.024
$Fe^{2+}/(Fe^{2+}+Mg)$	0.72	0.88	0.49	0.88	0.69	0.87	0.44	0.88

[a] Sirniövaara Formation, [b] Unijoki Formation.

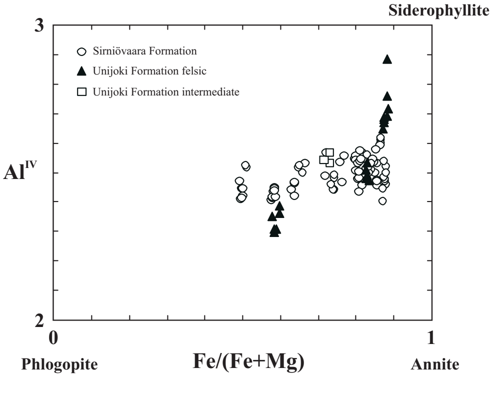

Fig. 8. Biotite composition of the rocks of the Sirniö Group.

dral crystals, either disseminated through the rock or in quartz veinlets.

Blue-green amphibole forms small, subhedral to anhedral crystals that contain inclusions of other minerals. Epidote and clinozoisite are found as subhedral to euhedral crystals of varying size, the smallest being the saussurite microlites inside the plagioclase phenocrysts. Epidote also forms veins, in places together with quartz and carbonate. Anhedral carbonate occurs as thin veins and replaces other minerals, mainly plagioclase. Sericite is found as small, subhedral to euhedral crystals oriented along the planes of schistosity.

4.2. Unijoki Formation

The rocks of the Unijoki Formation resemble the Sirniövaara rhyodacite in the outcrop but are more fine-grained. Some are lavas, but the majority consist of crystal tuffs, which at least in places are redeposited. In felsic varieties the weathered surface is light gray to white, in intermediate varieties it is light bluish gray. The fresh surface is gray in both varieties. In Unikumpu (Fig. 4) and Iso Jakovaara (Fig. 5), the felsic volcanic rocks contain some coarse-grained quartz porphyry fragments in a fine-grained groundmass. In Unikumpu, above a massive lava layer there are remnants of a thin ash layer containing accretionary lapilli and a spherulitic lava layer.

The felsic volcanic rocks of the Unijoki Formation have a broadly similar mineral composition as the granophyric rhyodacite of the Sirniövaara Formation. Most have small, euhedral plagioclase phenocrysts in a very fine-grained groundmass consisting of anhedral quartz and albite and subhedral to euhedral biotite (Fig. 7f, g). The granophyric intergrowth of albite and quartz is lacking from the rocks of the Unijoki Formation. Some samples show textures that to some degree resemble bedding and cross-bedding that may be either pyroclastic or epiclastic in origin.

In the compositionally intermediate rocks of the Unijoki Formation, the major minerals are plagioclase, amphibole, epidote and quartz. Accessory minerals include carbonate, biotite, chlorite, titanite, hematite, scapolite and rare zircon. The texture resembles a fine-grained lava with relics of amphibole and plagioclase phenocrysts. The plagioclase is pervasively saussuritized and, in places, replaced by scapolite. Some amphibole crystals are euhedral and twinned. The cores of the crystals consist of very light green amphibole, probably of the tremolite-actinolite series. In addition, most crystals have a thin, dark green, more strongly pleochroic rim of hornblende. Subhedral biotite and chlorite form a very fine-grained groundmass together with subhedral to euhedral epidote and granoblastic quartz. Carbonate is secondary and replaces other minerals.

5. Geochemistry

5.1. Sirniövaara Formation

The rhyodacite has SiO_2-values ranging from 64.4 wt.% to 70.4 wt.% (Fig. 9), with the lowermost values in the lower parts of the unit. TiO_2 (0.8–1.0 wt.%) and Al_2O_3 (10.6–13.4 wt.%) show trends that may indicate fractional crystallization throughout the unit. TiO_2-values higher than 1.0 wt.% occur in the lower parts, especially near the younger Kuusijärvi Formation gabbro veins, where the mafic magmas seem to have melted the wallrock rhyodacite and mixed with it. CaO varies between 0.3–4.5 wt.%, the higher values reflecting the large amount of secondary calcite in the rock. $[FeO_{tot}/(FeO_{tot}+MgO)]$ is high, in average close to 0.9. Lower values (0.6–0.8) mainly concentrate to the lower parts of the unit and to the more deformed parts of the formation where chlorite predominates over biotite. Large variation in MgO-values (0.3–5.0 wt.%) is probably caused by hydrothermal disturbance associated with the emplacement of the Koillismaa layered intrusion. Na_2O (2.5–5.0 wt.%) and K_2O (0.2–4.0 wt.%) are also badly scattered and have been mobile. Total alkalis (Na_2O+K_2O) vary from 3.4–8.3 wt.% and in most samples Na_2O/K_2O is >1. All the samples are subalkaline and most of the least altered samples are metaluminous with A/CNK<1.1 and A/NK>1. The more altered samples are peraluminous. P_2O_5-values concentrate around 0.3 wt.% and MnO-values around 0.1 wt.%.

Trace element data are presented in Figs. 10 and 11 and Table 3, in which the individual samples are representative of the unit and relatively little altered according to petrographic investigation. Incompatible elements are enriched relative to the compatible elements with enrichment factors of up to 100 times primitive mantle values in the former and up to 10 times in the latter. Ba (81–1087 ppm) and Rb (15–134 ppm) show very scattered values that still correlate quite well with K_2O-values, indicating that they have been mobile in the same processes. Sr (14–297 ppm) is also scattered and shows a deep negative anomaly (Fig. 10a). Nb, P and Ti also

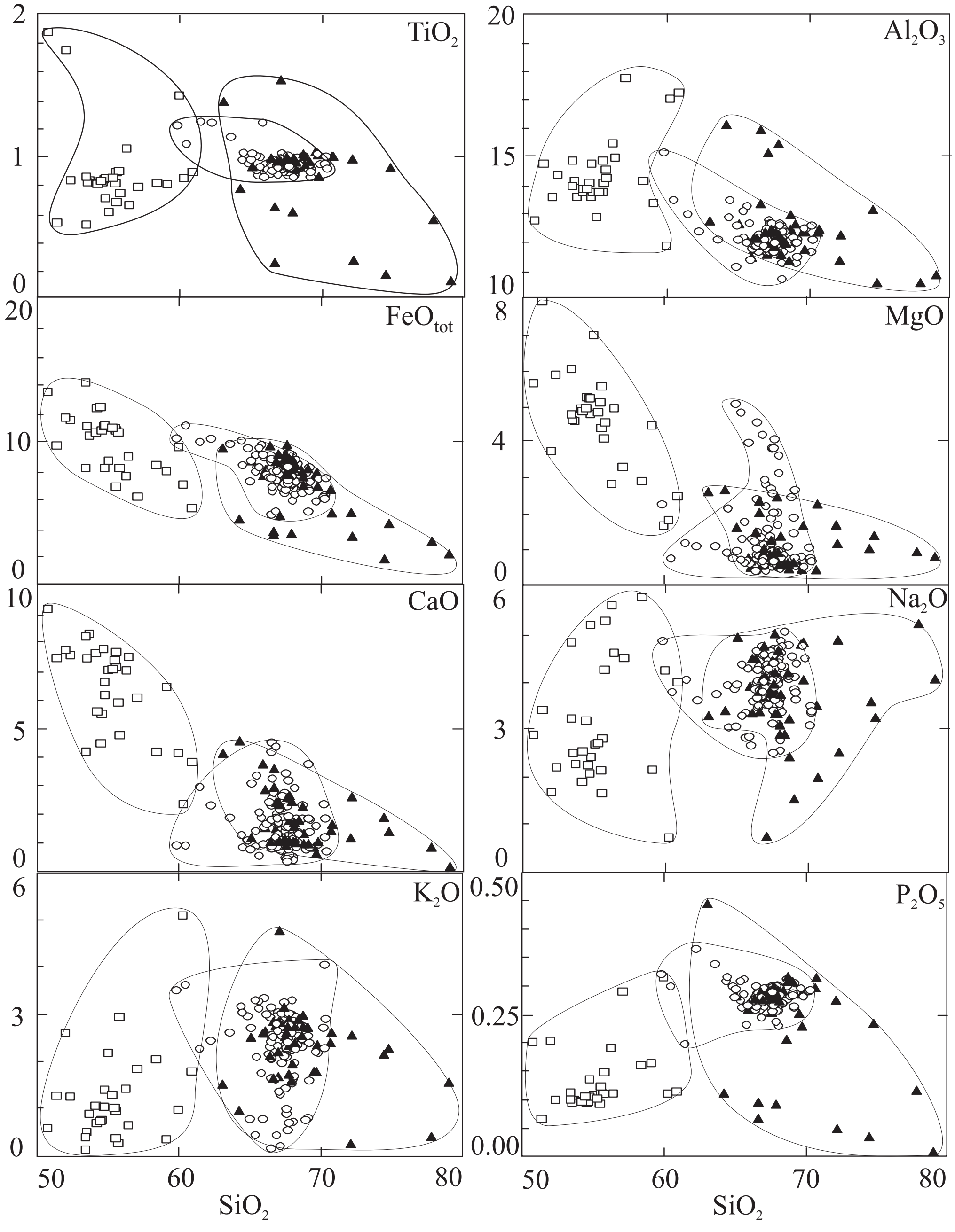

Fig. 9. Major element composition of the rocks of the Sirniö Group. Open circles: Sirniövaara Formation, closed triangels: Unijoki Formation felsic group, open squares: Unijoki Formation intermediate group.

Table 3. Representative whole rock analyses of the Sirniö Group. Oxides in wt. %, trace elements in ppm.

Sirniövaara Formation					Unijoki Formation				
					felsic rocks			intermediate rocks	
Sample	R333 50.10	LSL-98-107	TTK-99-83	LSL-99-193	LSL-00-30.2	LSL-98-112	R336 71.50	LSL-98-43	LSL-00-18
Location	Kuusijärvi	Porttivaara	Syöte	Pirinvaara	Porttivaara	Kuusijärvi	Kuusijärvi	Kuusijärvi	Porttivaara
SiO_2	69.1	69.9	67.0	65.5	67.0	74.8	68.1	54.8	60.0
TiO_2	0.93	0.94	0.91	0.86	0.93	0.92	0.93	0.84	1.43
Al_2O_3	11.9	12.4	12.0	12.0	11.5	10.5	11.5	13.7	11.8
FeOtot	6.57	7.33	7.86	8.09	8.34	4.25	8.32	11.1	9.53
MnO	0.05	0.04	0.11	0.13	0.13	0.07	0.13	0.17	0.14
MgO	1.41	0.47	0.73	1.25	0.57	1.35	0.74	5.17	1.61
CaO	1.85	0.93	1.68	3.32	2.44	1.42	1.58	6.59	4.11
Na_2O	3.80	4.46	3.98	3.26	3.59	3.23	2.88	2.38	4.19
K_2O	2.53	2.18	2.65	2.09	1.68	2.29	2.75	1.04	0.98
P_2O_5	0.28	0.28	0.27	0.26	0.26	0.24	0.29	0.11	0.32
Total	98.42	98.93	97.19	96.76	96.44	99.07	97.22	95.90	94.11
Cl	270	100	160	170	60	110	140	70	130
Ba	539	520	732	510	550	735	683	319	236
Rb	60	76	107	77	81	74	81	27	45
Sr	50	60	211	157	165	82	73	134	106
Th	8.08	7.00	7.17	7.66	8.20	7.53	7.77	4.46	5.35
U	2.08	1.56	1.60	2.20	1.95	1.71	2.21	0.84	1.23
Zr	285	257	265	257	263	216	279	106	176
Nb	13	13	11	-	12	-	11	-	-
Ga	22	24	23	27	23	21	24	24	23
Y	30.4	16.1	29.8	39.7	40.2	14.6	32.6	18.6	24.4
Sc	12.3	10.8	12.3	12.9	13.9	8.2	13.8	32.7	23.4
V	62	81	75	74	33	90	68	233	93
Zn	25	-	119	94	77	38	118	105	114
Cr	-	-	-	-	-	-	-	65	-
Cu	-	-	-	-	34	30	-	86	75
Ni	-	-	-	-	-	-	-	52	-
La	37.7	14.7	29.9	34.1	45.8	19.8	37.5	15.9	24.5
Ce	81.5	31.7	62.7	72.0	90.8	40.4	80.0	30.8	53.0
Pr	9.37	3.48	7.30	8.58	10.8	4.64	9.24	3.63	6.55
Nd	35.2	13.2	28.5	34.4	41.2	17.6	35.8	13.7	25.3
Sm	6.43	2.35	5.46	6.79	8.02	3.05	6.61	2.95	4.80
Eu	1.33	0.49	1.09	1.46	2.19	0.54	1.19	0.86	1.37
Gd	5.57	2.29	5.68	6.78	7.58	3.04	6.12	3.20	5.01
Tb	0.87	0.36	0.88	1.07	1.12	0.42	0.95	0.55	0.71
Dy	5.29	2.29	4.97	5.91	6.40	2.34	5.29	3.05	4.16
Ho	1.04	0.50	0.99	1.24	1.25	0.48	1.11	0.65	0.85
Er	3.29	1.65	2.98	3.72	3.60	1.36	3.24	1.90	2.46
Tm	0.46	0.28	0.42	0.57	0.55	0.22	0.51	0.29	0.38
Yb	3.48	1.93	2.91	3.62	3.43	1.42	2.94	1.60	2.46
Lu	0.48	0.31	0.44	0.54	0.48	0.24	0.46	0.25	0.38
$(La/Sm)_N$	3.8	4.0	3.5	3.2	3.7	4.2	3.7	3.5	3.3
$(Gd/Lu)_N$	1.4	0.9	1.6	1.6	2.0	1.6	1.6	1.6	1.6
Eu/Eu*	0.66	0.64	0.59	0.65	0.85	0.54	0.56	0.85	0.85

Note:- under detection limit

XRF detection limits (ppm) were: 500: Na; 200: Fe, Mg; 100: Si, Al, Cl; 60: P; 50: Ca, K; 40: Mn; 30: Cr, Ti, V; 20: Ba, Cu, Ga, Ni, Zn; 10: Nb, Rb, Sr, Zr.

ICP-MS detection limits (ppm) were: 0.5: Sc, Th; 0.2: Nd, Sm, U; 0.15: Er, Gd, Yb; 0.1: Ce, Dy, Eu, Ho, La, Lu, Pr, Tb, Tm, Y.

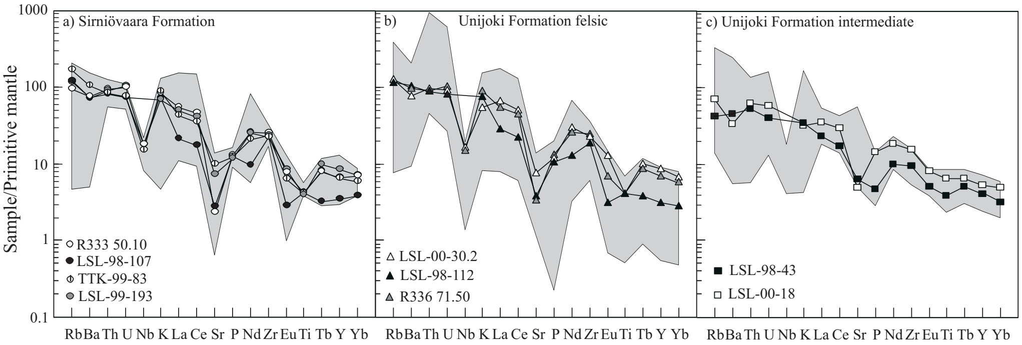

Fig. 10. Primitive mantle-normalized trace element diagrams for the Sirniö Group, a) Sirniövaara Formation, b) Unijoki Formation felsic group, c) Unijoki Formation intermediate group. Gray field: range of all analyses. Normalizing values after Sun and McDonough (1989).

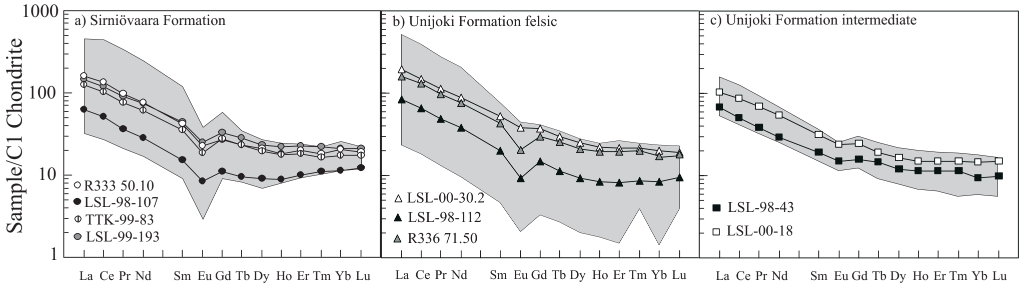

Fig. 11. C1 chondrite-normalized rare earth element diagrams for the Sirniö Group, a) Sirniövaara Formation, b) Unijoki Formation felsic group, c) Unijoki Formation intermediate group. Gray field: range of all analyses. Normalizing values after Sun and McDonough (1989).

show negative anomalies. Rb/Sr is mostly between 0.1–1.5. Zr-values fall between 200–300 ppm. Cr, Cu, Ni, S and Pb were mostly below the detection limit. S, Ni and Cu-values above the detection limit are associated with the presence of sulphides. Rare earth elements (REE) show enrichment of light REE (Fig. 11a), with $(La/Sm)_N$ between 1.9–4.9 (average 3.6). Middle and heavy REE abundances show less variation with $(Gd/Lu)_N$ mostly between 1.0–2.0 (average 1.5). Most samples show a negative Eu-anomaly (Eu/Eu* between 0.45–0.85).

5.2. *Unijoki Formation*

The volcanic rocks of the Unijoki Formation form a heterogeneous group and, according to their SiO_2-content, have been divided into a "felsic group" with SiO_2>63 wt.% and an "intermediate group" with SiO_2<63 wt.% (Fig. 9). The individual samples chosen for Table 3 and Figs. 10 and 11 are representative of the variation and also relatively little altered according to petrography.

In the felsic group the SiO_2-content ranges from 63.1 to 79.1 wt.%, the highest values seem to be caused by secondary silicification. The rocks are subalkaline and metaluminous to peraluminous with A/CNK between 0.7–1.9. Total alkalis (Na_2O+K_2O) vary between 4.3–7.4 wt.%, Al_2O_3-content between 10.5–16.1 wt.% and CaO-content between 0.9–4.5 wt.%. Fe and Mg show very scattered values with FeO_{tot} between 1.8–9.7 wt.% and MgO between 0.4–2.7 wt.%. [FeO_{tot}/(FeO_{tot}+MgO)] is quite high, in average 0.9, although the lowest values are close to 0.6. Trace elements show enrichment of incompatible elements relative to the com-

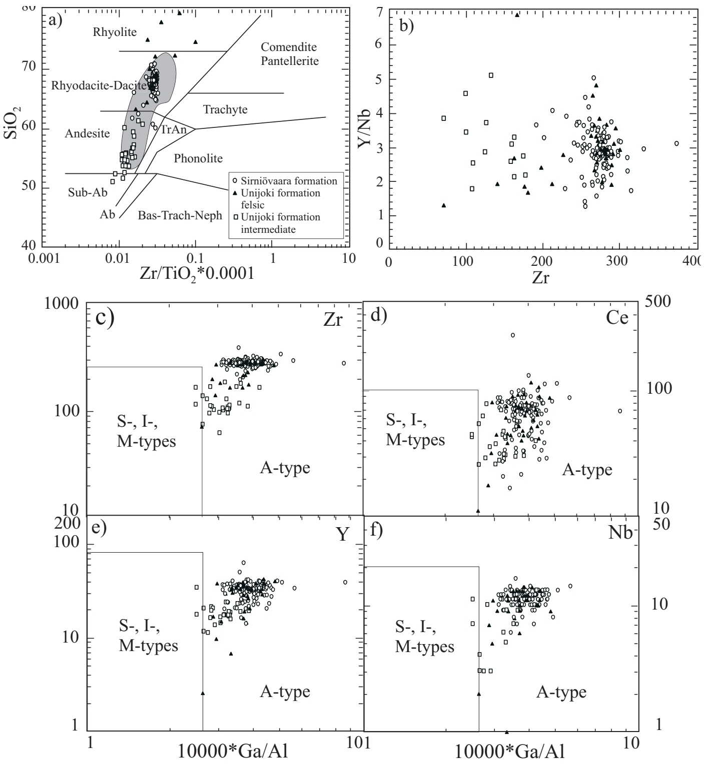

Fig. 12. a) Sirniö Group plotted in the classification diagram of Winchester and Floyd (1977). Gray field: volcanic rocks of the Salla Formation (Manninen, 1991), b) Y/Nb vs. Zr of the Sirniö Group. Symbols as in a). c–f) Sirniö Group plotted in the discrimination diagrams of Whalen et al. (1987), symbols as in a). c) Zr vs. 10000*Ga/Al, d) Ce vs. 10000*Ga/Al, e) Y vs. 10000*Ga/Al, f) Nb vs. 10000*Ga/Al.

patible elements, similarly with the Sirniövaara Formation, although the variation is more extreme (Fig. 10b). Negative anomalies in Nb, Sr, P and Ti are present also in the felsic group. Rb/Sr varies between 0.1–3.0. Zr-content is over 200 ppm in most samples (276 ppm in average). Of the compatible elements, Cr shows values exceeding the detection limit in several samples. REE trends show enrichment of light REE over middle REE with $(La/Sm)_N$ between 2.5–8.5. Middle to heavy REE are less fractionated with $(Gd/Lu)_N$ between 0.8–2.7 (Fig. 11b). Most samples have a small negative Eu-anomaly with Eu/Eu* between 0.52–0.85.

The intermediate group is characterized by SiO_2-contents between 50.7–60.9 wt.%. Most samples are subalkaline (Na_2O+K_2O=2.0–5.8) but some have slightly elevated alkali contents and are thus alkaline according to the classification of Irvine and Baragar (1971). $[FeO_{tot}/(FeO_{tot} + MgO)]$ ranges from low (0.55) to high (0.86), the ratio being higher in the rocks containing more SiO_2. Al_2O_3 (11.8–17.7 wt.%) and CaO (2.3–9.8 wt.%) are quite scattered. Compatible trace elements (Cr, V, Ni, Cu, Zn) show slightly higher values than the Sirniövaara Formation and the felsic group, incompatible trace element values (Zr, Rb) are somewhat lower (Table 3, Fig. 10c). Nb and Sr show clear negative anomalies, similarly with the felsic group and the Sirniövaara Formation. Rb/Sr is between 0.0–1.2. Samples from the intermediate group are also enriched in light REE compared to middle or heavy REE with $(La/Sm)_N$ varying between 2.2–4.4 and $(Gd/Lu)_N$ between 1.6–3.3 (Fig. 11c). A small negative Eu-anomaly is present in most samples (Eu/Eu*=0.63–1.00).

5.3. *Geochemical classification based on immobile elements*

Geochemical classification of the Sirniö Group is difficult because subsequent hydrothermal alteration and metamorphism has affected the contents of several major and trace elements. At least the alkalis, MgO and CaO have been mobile. The diagrams in Fig. 9 suggest that TiO_2 and Al_2O_3 are perhaps the most immobile major elements. Trace elements such as Ba, Rb and Sr have been mobile, whereas the REE, Y, Ga, Nb, Sc and Zr show a more immobile behavior. The geochemical classification of the Sirniö Group is thus based on these elements.

The classification of Winchester & Floyd (1977) is based on immobile element ratios such as Zr/TiO_2 and should be applicable to both unmetamorphic and metamorphic rocks. Most of the samples from the Sirniövaara Formation and the felsic rocks of the Unijoki Formation classify as rhyodacites (Fig. 12 a). The rhyolitic samples in the Unijoki Formation commonly show petrographic evidence of secondary silicification. Most of the intermediate rocks of the Unijoki Formation are andesitic, although the samples with the lowest SiO_2-values classify as basalts. The ~2.44 Ga old Salla Formation, described by Manninen (1991), closely resembles the rocks of the Sirniö Group (Fig. 12 a). The Zr/TiO_2 ratios of both the Sirniö Group and the Salla Formation follow the sub-alkaline differentiation trend of Winchester & Floyd (1977). Y/Nb is more variable, but is mainly in the range 2–4 in both the felsic and intermediate rocks of the Sirniö Group (Fig. 12 b). No published Y or Nb data exist on the Salla Formation.

The diagrams of Whalen et al. (1987) use immobile elements to discriminate the A-type (anorogenic) silicic rocks from other rocks of granitic composition. The rocks of the Sirniö Group show typical A-type characteristics such as high Zr-content and high 10000*Ga/Al. Other immobile trace elements (Ce, Y, Nb) also indicate A-type geochemical character for the Sirniö Group (Fig. 12c–f). A-type silicic magmatism is most often connected to an extensional tectonic setting. Also, A-type volcanic rocks and granites are associated with some mafic layered intrusions, like the Bushveld complex in South Africa (e.g., Walraven, 1985; Kleemann & Twist, 1989; Hill et al., 1996). In Bushveld, the silicic volcanic rocks predate the intrusion of the mafic magma and the granites represent the latest phase of the extensional magmatic cycle. The A-type geochemical character of the Sirniö Group and the close association with the Koillismaa layered igneous complex suggest a tectonic setting comparable to Bushveld. It is probable that the rocks of the Sirniö Group were generated in an extensional environment, although some of the characteristics like the negative Nb anomaly (Fig. 10) may indicate that the source for the Sirniö Group had been modified by earlier subduction processes.

6. Discussion and conclusions

Granophyres have been described from many different igneous suites (e.g., Hughes, 1971; Irvine, 1975; Pankhurst et al., 1978; Agron & Bentor, 1981; Dickin & Exley, 1981; Walraven, 1985; Bloxam & Dirk, 1988; Hirschmann, 1992; Lipman et al., 1997; Lowenstern et al., 1997) and have been interpreted to have formed in volcanic, subvolcanic and plutonic settings. Most of the granophyres described as intrusive (plutonic and subvolcanic) have common characteristics such as small areal extent, clearly discernible intrusive contacts and medium to coarse grain size. Other textural phenomena such as miarolitic cavities, plumose alkali feldspars, compositional and mineralogical layering and orbicular and pegmatitic zones are also quite common (e.g., Hughes, 1971; Smith, 1974). Volcanic granophyres are commonly associated with non-granophyric volcanic rocks and often show indications of some hydrothermal or metamorphic processes (e.g., Agron and Bentor, 1981; Walraven, 1985).

Alapieti (1982) suggested that the Koillismaa western intrusion is a sill-like body that intruded a subhorizontal uncorfomity between the Archean basement and overlying volcanic rocks the age of which is uncertain. According to him, intrusion of the mafic magmas into the unconformity resulted in the crystallization of the mafic layered sequence and the granophyre, but he did not discuss the genesis of the granophyre in detail. Based on U–Pb isotope analyses, the emplacement age of the Koillismaa layered igneous complex is 2436±5 Ma and one zircon fraction analyzed from the granophyre in the Porttivaara block falls into the same discordia line as the gabbroic rocks (Alapieti, 1982). Field evidence suggests that the Sirniö Group is slightly older than the layered intrusion and thus probably forms the original roof of the gabbros. The fine grain size, the absence of the typical plutonic features and the presence of shattered plagioclase phenocrysts, breccia interlayers and possible amygdules suggest that the Sirniövaara Formation is volcanic in origin. Although the later hydrothermal, deformational and metamorphic processes have disturbed the original geochemistry, the granophyric rhyodacite seems to be mineralogically and geochemically quite similar to the felsic volcanic rocks of the Unijoki Formation. We consider the granophyric rhyodacite to be a crystal-rich volcanic rock, possibly ignimbritic in origin, that formed slightly before the emplacement of the Koillismaa western intrusion. The granophyric texture was probably formed later as a consequence of reheating, hydrothermal alteration and small scale partial melting caused by the emplacement of the Koillismaa layered igneous complex, although some of it may be derived from primary devitrification of glassy volcanic components in the unit.

Evidence for ~2.44 Ga volcanic activity is common in northern Finland and adjacent Russia and farther southeast in Russian Karelia (Fig. 1). Most of the volcanic rocks of this age are described as rift-related (e.g., Lehtonen et al., 1998), although they commonly show both tholeiitic and calc-alkaline geochemical character (e.g., Manninen, 1991). In northern Finland the ~2.44 Ga felsic and intermediate volcanic rocks are combined into the Salla Group (Lehtonen et al., 1998), in Russia they are commonly referred to as the Sumi Group in Karelia or the Strelna Group in the Kola Peninsula (Zagorodny et al., 1982; Gorbunov et al., 1985). The Salla Group extends from central Lapland to the Kuusamo area and is, in many places, the lowermost volcanic formation lying unconformably on the Archean basement (Lehtonen et al., 1998; Räsänen, 1999). The roofs of the ~2.44 Ga Koitelainen and Akanvaara layered intrusions in northern Finland (Mutanen, 1997) consist of felsic volcanic rocks of the Salla Group dated at 2.48–2.44 Ga (Manninen et al., 2001; Mutanen & Huhma, 2001; Räsänen & Huhma, 2001). Further south is the Salla greenstone belt, the lowermost parts of which consist of basaltic andesites and rhyolites of the Salla Formation that are separated from the overlying basalts of the Mäntyvaara Formation by an erosional surface (Manninen, 1991). The absolute age of the Salla and Mäntyvaara Formations is not known but they both are cut by a 2383±33 Ma diabase dike (Manninen & Huhma, 2001). In the Kuusamo area and the adjacent Paanajärvi area in Russia felsic volcanic rocks commonly occur as the lowermost formation above the Archean basement but little published data exist on these rocks. In the Kola Peninsula, the 2.44 Ga felsic volcanic rocks and a subvolcanic granophyre belonging to the Seidorechca formation of the Strelna Group are associated with the Imandra lopolith, another 2.44 Ga mafic layered intrusion (Amelin et al., 1995). The ~2.44 Ga Vetreny belt in Russian Karelia is an extensive volcanic system that contains some felsic rocks in association with voluminous komatiites (Puchtel et al., 1997).

The ~2.44 Ga layered intrusions of the Fennoscandian Shield are suggested to have formed during the early Paleoproterozoic rifting of the Fennoscandian Archean craton, the rifting being caused possibly by mantle plume activity (e.g., Huhma et al., 1990; Amelin et al., 1995; Heaman, 1997; Puchtel et al., 1997). The amount of mafic magma in the layered intrusions is so large that it can be expected to partially melt the pre-existing Archean crust, creating silicic melts (e.g., Huppert & Sparks, 1988). As the crust extended, some of these magmas may have been able to extrude through the rift zone faults. It seems probable that some silicic volcanic activity preceeded the formation of the layered intrusion in the Koillismaa area. Most of these volcanic rocks may have been eroded soon after extrusion as a consequence of rapid erosion in response to the updoming of the crust. The Sirniövaara Formation and the Unijoki Formation are thus probably the remains of a much thicker volcanic pile. The presumably ~2.44 Ga volcanism in the Koillismaa area is comparable to other occurrences in northern Finland and adjacent Russia. We suggest that the Sirniö Group can be tentatively correlated with the Salla Group in northern Finland. Thus the ~2.44 Ga rift-related volcanism seems to extend from Koillismaa area all the way through Salla to the central Lapland, comparably with the distribution of the mafic layered intrusions.

Acknowledgements

We wish to acknowledge the following people. Markku Iljina worked as the project leader in the Geological Survey of Finland (GTK). Lassi Pakkanen and Bo Johanson from the mineralogical laboratory of the GTK made the microprobe analyses and provided the thin section photos. Prof. Ilmari Haapala, the project leader at the University of Helsinki, and Tapani Rämö both gave useful comments on the manuscript. The thorough reviews of Kauko Laajoki and Wolfgang Maier greatly improved the manuscript. This work was funded by the Academy of Finland (project #47690) and the GTK.

Editorial handling: Petri Peltonen

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