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Whole-rock geochemistry of some tonalite and high Mg/Fe gabbro, diorite, and granodiorite plutons (sanukitoid suites) in the Kuhmo district, eastern Finland

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Abstract

New whole-rock geochemical analyses (major and trace elements) of three tonalite plutons and high Mg/Fe granodiorites and diorites, termed sanukitoid suites, are presented from Neoarchaean Kuhmo district, eastern Finland. The 2.83 Ga and 2.78 Ga tonalites display only moderate fractionation of LREE/HREE thus demanding only minor or no residual garnet in their respective source regions. However, the more prominent HREE depletion in the 2.75 Ga tonalites requires more significant garnet residue. The relatively wide compositional variation in the tonalites implies that Archaean TTG (tonalite-trondhjemite-granodiorite) magmatism was derived in general from sources that exhibited considerable mineralogical heterogeneity. The ~2.70 – 2.74 Ga high-Mg/Fe granodiorites and diorites are characterised by strong fractionation of LREE/HREE, relatively high Ba and Sr, and elevated abundances of Cr and Ni as well systematic depletions in P and Ti, which are all typical features of Archaean sanukitoid suites. Some of the granodiorite plutons contain compositionally intermediate high-K enclaves, which share these geochemical characteristics, implying a contribution of mafic-intermediate LILE- and LREE- enriched source for the magma. The geochemical characteristics of the studied plutonic rocks demonstrate the role of contrasting sources for the tonalites and sanukitoid suites in the Kuhmo district.

Key words: plutonic rocks, tonalite, granodiorites, diorites, geochemistry, trace elements, Neoarchaean, Kuhmo, Finland

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1. Introduction

Most of the bedrock of the Neoarchaean Kuhmo district, in eastern Finland, belongs to a classical Archaean tonalite-trondhjemite-granodiorite (TTG) association. During the last few decades the plutonic rocks in the area have been the subject of various geochemical, geochronological, and structural studies (e.g. Martin, 1989; Hyppönen, 1983; Vaasjoki et al., 1999; Luukkonen, 1992; Luukkonen, 2001; Käpyaho et al., 2006). Based on geochemical analysis of granitoid rocks from the Kuhmo district, Martin (1987) proposed a general mechanism for the formation of TTG magmas, through melting of hydrated basaltic rocks (amphibolites) at pressures high enough to stabilise garnet; retention of garnet in the source region then accounts for some of the characteristic geochemical properties of the TTG granitoid

series. This petrogenetic model for Archaean TTGs is also supported by experimental petrology (e.g. Rapp & Watson, 1995), although the tectonic setting in which such melting occurs, and its geodynamic significance remain controversial; some researchers advocate partial melting of the subducted oceanic slab (e.g. Martin, 1999; Foley et al., 2002), whereas others favour partial melting of over-thickened crust under eclogite facies conditions (e.g. Rapp et al., 2003).

Comparisons have often been made between the genesis of TTGs and modern adakites (e.g. Martin, 1999). Adakites are rocks formed in a supra-subduction zone environment where the young and hot subducting oceanic slab melts, leaving a garnet and amphibole-bearing residue. However, during the ascent of the magma, interaction with the overlying mantle wedge is expected to produce elevated Mg/Fe, Ni, and Cr abundances, which is seldom observed in Archaean TTGs (Smithies, 2000). However, enrichments in these elements are typical of a distinct class of Archaean high Mg/Fe plutonic rocks suites, which have been described from several Archaean cratons. High Mg/Fe monzodiorites and trachyandesites from the Superior Province, Canada, were demonstrated to have a mantle origin and were termed sanukitoids by Shirey and Hanson (1984) (see also Stevenson et al., 1999). The name sanukitoid is derived from sanukites (Tatsumi & Ishizaka, 1982), which refers to high-Mg andesites within a Miocene volcanic sequence in Japan.

The sanukitoid suite covers a compositional range from diorite to granodiorites and is characterised by high Mg-numbers [Mg^{2+} / (Mg^{2+} + Fe_{tot})×100 = {43 – 62}, with Fe_{tot} as Fe^{2+}; Stern & Hanson (1991)], enrichments in LILE, elevated contents of P_2O_5 and Cr, and fractionated rare earth element (REE) patterns, albeit with no pronounced Eu anomalies (Shirey & Hanson, 1984). The geochemical data presented by Querré (1985) for the Arola granodiorite pluton from the Kuhmo district (described as the Koivulehto granodiorite in Hyppönen, 1983) demonstrated all of these characteristics. Querré (1985) attributed these features to parental magma interaction with komatiites, whereas Moyen et al. (2001) proposed that the Arola granodiorite may be considered as a sanukitoid intrusion. Furthermore, Käpyaho et al. (2006) reiterated the sanukitoid affinity of the pluton.

In this paper, new whole-rock major and trace element geochemical data are presented for 59 samples of plutonic rocks from the Kuhmo district. The purpose of the study is to characterise the time-integrated evolution of the plutonism, to demonstrate contrasting sources of the TTGs and sanukitoid suites, compare and contrast their compositions to modern adakites and, finally, to discuss the petrogenetic implications.

2. Geological background

The bedrock of the Kuhmo district has been previously mapped and described at regional scale (Hyppönen, 1983; Luukkonen, 1988; Luukkonen, 2001), as well as in numerous papers dealing with both greenstone belt volcanism (e.g., Jahn et al., 1980; Taipale, 1983; Querré 1985; Luukkonen 1988; Papunen et al., 1998; Gruau et al., 1992; Halkoaho et al., 2000) and granitoid rocks (e.g., Martin, 1985; Martin et al., 1983a, b; Halliday et al., 1988; Martin, 1987; Martin, 1989; Luukkonen, 1985, Vaasjoki et al., 1999). An overview of regional rock units and proposed relationships is given by Sorjonen-Ward & Luukkonen (2005)

The most distinct feature in the bedrock of the Kuhmo district is the linear, over 200 km long, NS-trending Tipasjärvi-Kuhmo-Suomussalmi greenstone belt (Figs. 1 and 2), for which a volcanic island-arc setting (Taipale 1983, 1988; Piirainen, 1988), and continental rift origin (Martin et al., 1984; Luukkonen, 1992, 2001) have been proposed. The belt consists of mafic, ultramafic and felsic metavolcanic rocks as well as chemical and clastic metasedimentary rocks (Piirainen, 1988; Luukkonen, 1988). Conventional U-Pb zircon ages of felsic volcanic rocks vary from ca 2.95 Ga to 2.79 Ga (Hyppönen, 1983; Luukkonen et al., 2002; Vaasjoki et al. 1999).

Granitoid rocks, which include discrete plutons, as well as somewhat gneissose bodies and complex migmatites, surround the Tipasjärvi-Kuhmo-

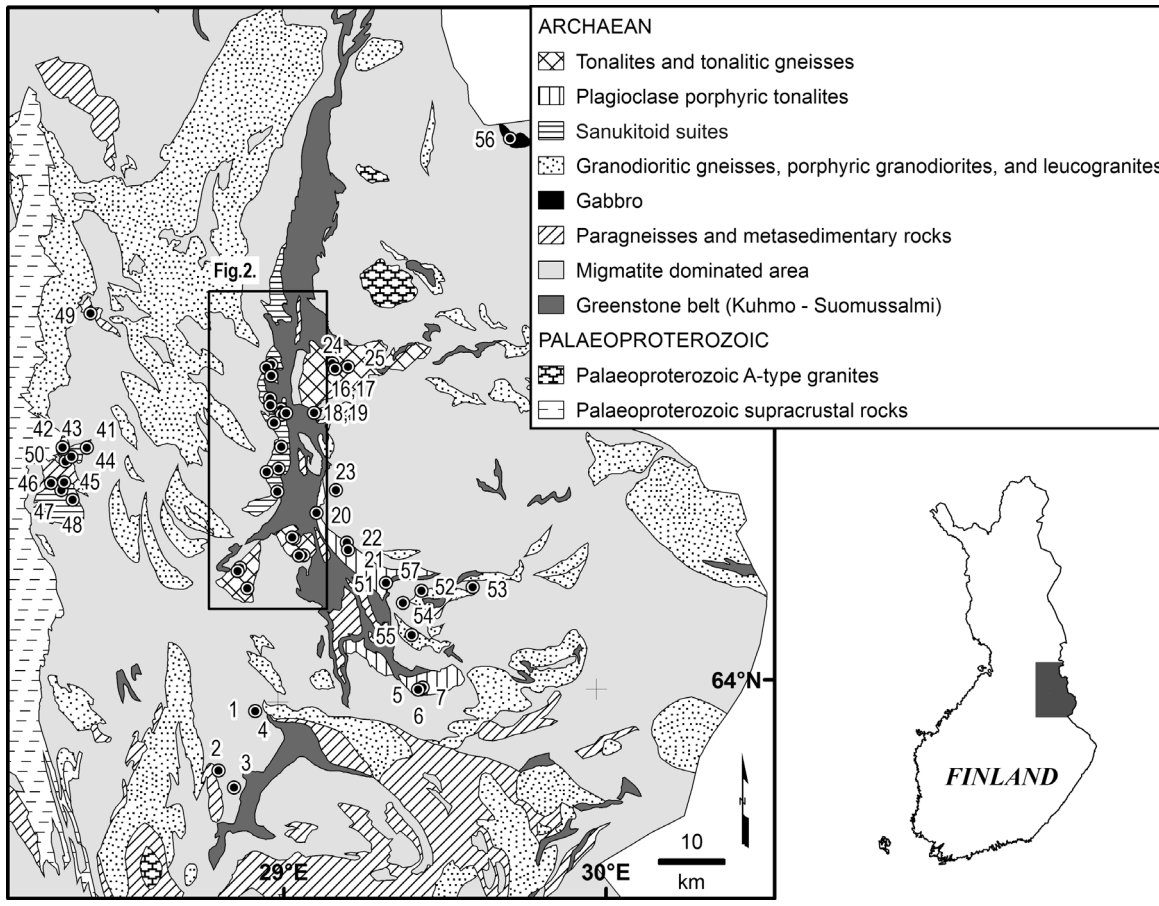

Fig. 1. Generalised bedrock map of the Kuhmo district showing the sampling locations. The map is modified after Korsman et al. (1997).

Suomussalmi greenstone belt (Fig. 1). The western side of the greenstone belt is characterised by metatexitic and diatexitic migmatites with mainly biotite-plagioclase gneiss mesosomes and leucotonalite-granodiorite leucosomes, leucocratic granodiorites and granites. In contrast, migmatites with mafic mesosomes and gneissic tonalite plutons are dominant to the east of the greenstone belt. A conventional multigrain U-Pb zircon age of 2843 ± 18 Ma from a mafic migmatite mesosome at Lylyvaara (Luukkonen, 1985) and 2830 ± 2 Ma for the unmigmatised but gneissic Haasiavaara tonalite (Vaasjoki et al., 1999; Horneman, 1990) represent the oldest reported plutonic activity in the district. Subsequently, tonalitic crust was generated at 2.78 Ga and 2.75 Ga (Vaasjoki et al., 1999; Käpyaho et al., 2006). The ages of porphyritic granodiorite from Arola and a quartz diorite/granodiorite dike of sanukitoid affinity cross-cutting the greenstone belt have U-Pb zircon ages of 2734 ± 2 Ma and 2739 ± 7 Ma, respectively (Hyppönen, 1983). The ages of the late leucogranites and leucocratic granodiorites in the Kuhmo district and adjacent areas vary between 2.70 Ga and 2.68 Ga, and most of them appear to represent recycled pre-existing crust (Luukkonen, 1988; Lauri et al., 2006; Käpyaho et al., 2006). The first plutonic episodes after the Archaean cratonisation were rift-related anorogenic magmatism at 2435 ± 12 Ma (Luukkonen, 1988) followed by several Palaeoproterozoic dolerite dyke swarms and mafic layered intrusions (Huhma et al., 1990; Vuollo, 1994).

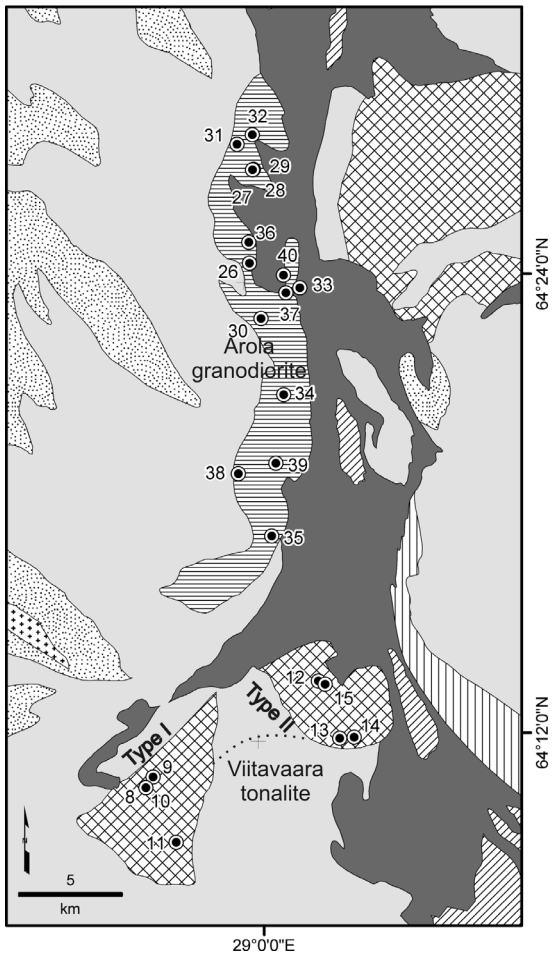

Fig. 2. Detailed map showing Viitavaara and Arola granodiorite intrusions. Map is modified after Korsman et al. (1997).

3. Sampling, field relations and previous studies

The tonalites and high Mg/Fe granitoid rocks (sanukitoid suite) of this study are separated into seven plutons based on their field relations and geochemical and U-Pb age data. A summary of the main petrographical features and ages is presented in Table 1. The tonalites comprise the Haasiavaara tonalite, the Viitavaara tonalite, and the Purnu tonalite. The Haasiavaara tonalite is described and geochemically characterised by Horneman (1990). The gneissic Purnu tonalite was studied by Martin (1987), who referred to this gneissic rock type as the "Kuusamonkylä grey gneisses".

Rocks belonging to the sanukitoid suites are sampled from four separate plutons; Arola granodiorite, Siikalahti granodiorite, Loso diorite, and Kaartojärvet gabbro (Figs. 1 and 2). Detailed description, major element and some trace element geochemistry for the Arola granodiorite is presented by Querré (1985) and the Kaartojärvet gabbro is described by Luukkonen (1988). The Loso pluton was mapped by Kontinen & Meriläinen (2004) and dated by A. Kontinen (pers. comm., 2006).

4. Analytical methods

Whole-rock samples (1 – 4 kg) were crushed using a manganese-steel jaw crusher and were pulverised in a carbon steel bowl. The major elements (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, and P) and some of the trace elements (Ba, Sr, S, Cl, Cr, Ni, Cu, Zn, Ga, As, Mo, Sn, Sb, Pb, and Bi) were determined by the X-ray fluorescence (XRF) method on pressed powder pellets. Other trace elements (Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm, Yb, Sc, Y, U, Th, Co, Hf, Nb, Rb, Ta, V, and Zr) were analysed using an inductively coupled plasma mass spectrometer (ICP-MS). Total C was determined in some samples by using Leco™ C-analyser. The analyses were performed in the geochemical laboratory of the Geological Survey of Finland at Espoo, except for the Loso pluton, which was analysed by Rautaruukki Steel Oy by XRF on pressed pellets and REE was determined by INAA at VTT in Espoo. Results are given in Table 2.

5. Whole rock geochemistry

5.1. Tonalites

5.1.1. Haasiavaara tonalite

The samples of the Haasiavaara tonalite have SiO_2 contents from 65.6 to 69.9 wt. % and rather high contents of CaO (Fig. 3). All the samples are metaluminous (Table 2). Mg# varies from 38.5 to 46.8 and the REE patterns are moderately fractionated; $(La/Yb)_N$ varies between 9.9 and 12.6 and minor negative

Table 1. Summary on the ages, mineralogy and main petrographical features of the tonalites and high-Mg/Fe granitoid rocks from the Kuhmo district.

Rock suite	U-Pb zircon Age (Ma)*	Petrography	Mineralogy§	Comments and references*
Tonalites				
Haasiavaara tonalite	2830 ± 2 (1)	Foliated, medium grained, and granoblastic with mafic and tonalitic enclaves. Often weakly plg-porphyric. Crosscut by aplitic felsic dykes.	Olig, Bt, Qz, *Zr, Ap, Tit, Ep,*	Described in (1);(2);(3)
Viitavaara tonalite	2785 ± 7 (9)	Foliated, medium grained, granoblastic, and weakly plg-porphyric. Typically contain Bt-rich mafic enclaves.	Olig/And, Fe-Mg Hbl, Fe-tscherm, Hbl, Qz, Bt, *Zr, Tit, Ap*	
Purnu tonalite	2747 ± 3 (9)	Foliated, medium and even grained to plg-porph., folded, with Bt (1-3 cm) and mica gneiss enclaves (>1 m in diameter).	Olig, Bt, Qz, *Kfs, Tit, Zr, Ap, Ep, Ser, All*	(4) "Kuusamonkylä grey gneiss"; (12) "D3 granitoid"
High Mg/Fe suites (sanukitoid suites)				
Arola granodiorite	2734 ± 3 (10)	Foliated and coarsely Kfs-porphyric and occasionally bluish Qz-porphyric, with abundant mafic or intermediate fine grained magmatic enclaves and mica gneiss enclaves. Locally Qz diorite. Croscutted by leucogranite dykes.	Alb/Olig/And, Kfs, Bt, Qz, *Zr, Tit, All, Cal, Ser, Ep*	(5);(6) "Arola augen gneisses" was considered as partial melts of pre-existing crust contaminated by komatii tes.
Siikalahti granodiorite	~2680 (9)	Coarsely Kfs-porphyric with medium grained groundmass and mafic/intermediate magmatic enclaves	Olig/And, Kfs, Bt, Qz, *Zr, Tit, Ser, Ep*	
Loso diorite	2706 ± 17 (11)	Even grained or plg-porphyric. Foliated and folded.	Olig, Qz, Bt, Hbl, *Tit, Zirc, Ap*	Mapped by (13)
Kaartojärvet gabbro	2722 ± 14 (8)	Even grained, medium grained. Folded and overthrusted.	And, Hbl, Bt, *Zr, Tit, Kfs, Ep*	Described in (7)

§ Accessories in italics

* Reference: 1) Vaasjoki et al. (1999); 2) Horneman (1990); 3) Horneman & Hyvärinen (1989); 4) Martin (1987); 5) Martin & Querré (1984); 6) Querré (1985); 7) Luukkonen (1988); 8) Luukkonen & Huhma (unpublished); 9) Käpyaho et al. (2006); 10) Hyppönen (1983); 11) Kontinen et al. (in review); 12) Luukkonen (2001); 13) Kontinen & Meriläinen (2004)

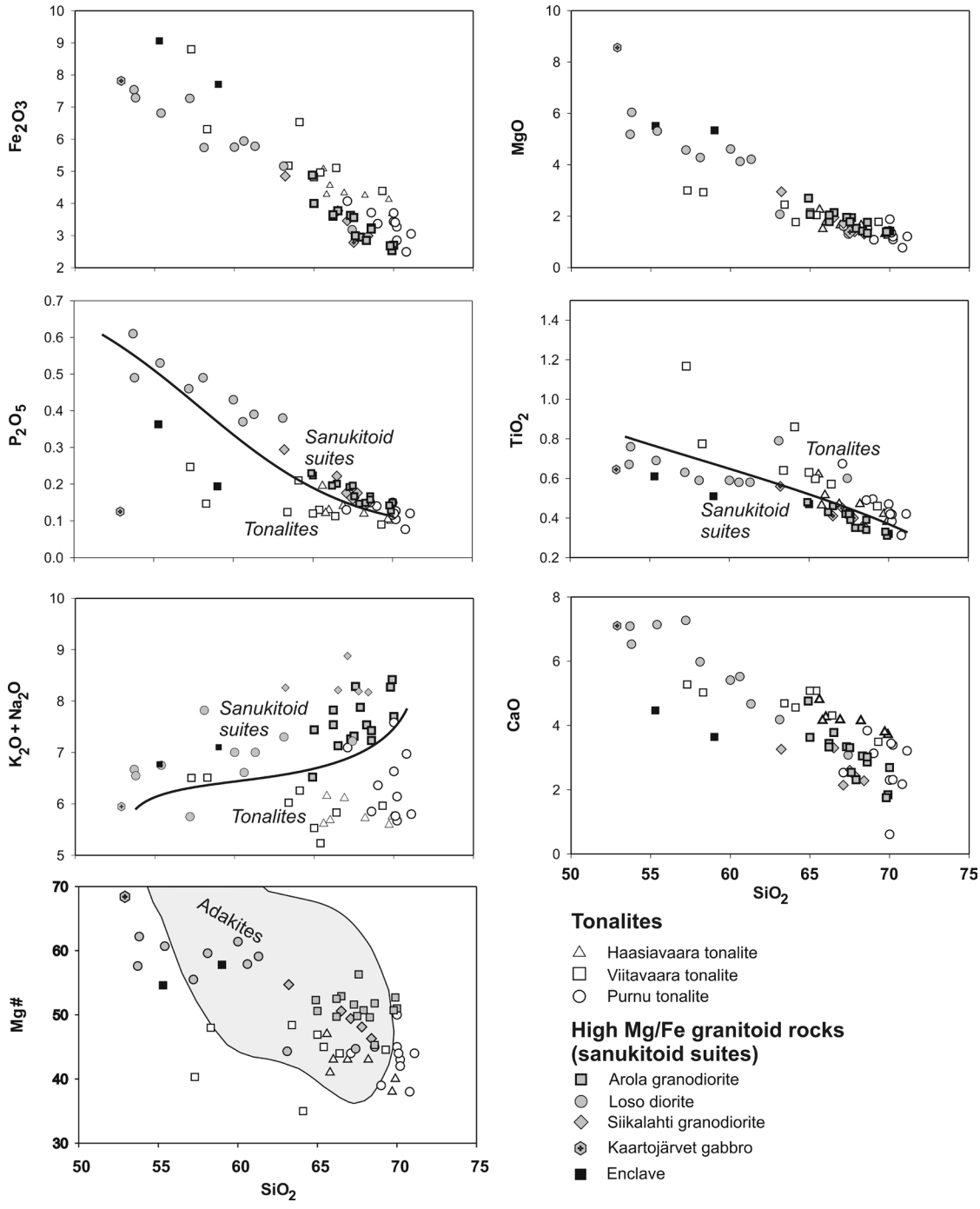

Fig. 3. Selected Harker diagrams illustrating the geochemical characteristics of granitoid rocks of the Kuhmo district. Borderline divides the fields between the sanukitoid suites and tonalites of the Kuhmo district. Field for adakites after Smithies (2000).

Eu anomalies are present (Fig. 4a). The mantle-normalised spider diagrams exhibit gently sloping curves with negative Ta, Nb, P, and Ti anomalies (Fig. 5a).

5.1.2. Viitavaara tonalite

Viitavaara tonalite comprises two types, which are here termed type I and type II (Fig. 2; Table 2). The SiO_2 contents of the type I and II Viitavaara tonalites vary from 58.3 to 65.4 wt. % and from 57.3 to 69.3 wt. %, respectively (Table 2; Fig. 3). All the samples are metaluminous. The Mg# is < 48.4 and the samples are generally rich in Fe. In the type II samples, REE levels are higher and negative Eu anomalies are more pronounced than in the type I samples (Fig. 4b). The REE patterns are invariably weakly fractionated; $(La/Yb)_N$ varies from 6.1 to 17.4. The gently descending trends on spider diagrams display negative Ta, Nb, P, and Ti anomalies, and two samples show negative Th and U anomalies (Fig. 5b).

5.1.3. Purnu tonalite

The SiO_2 content of Purnu tonalite samples varies from 67.1 to 71.1 wt. % (Fig. 3). Samples are peraluminous or metaluminous, the Mg# varies from 38.0 to 50.1, and the REE patterns are more depleted in HREE compared to the Viitavaara and Haasiavaara tonalites (Fig. 4c). The $(La/Yb)_N$ varies from 18.8. to 73.9. The mantle-normalised spider diagrams show

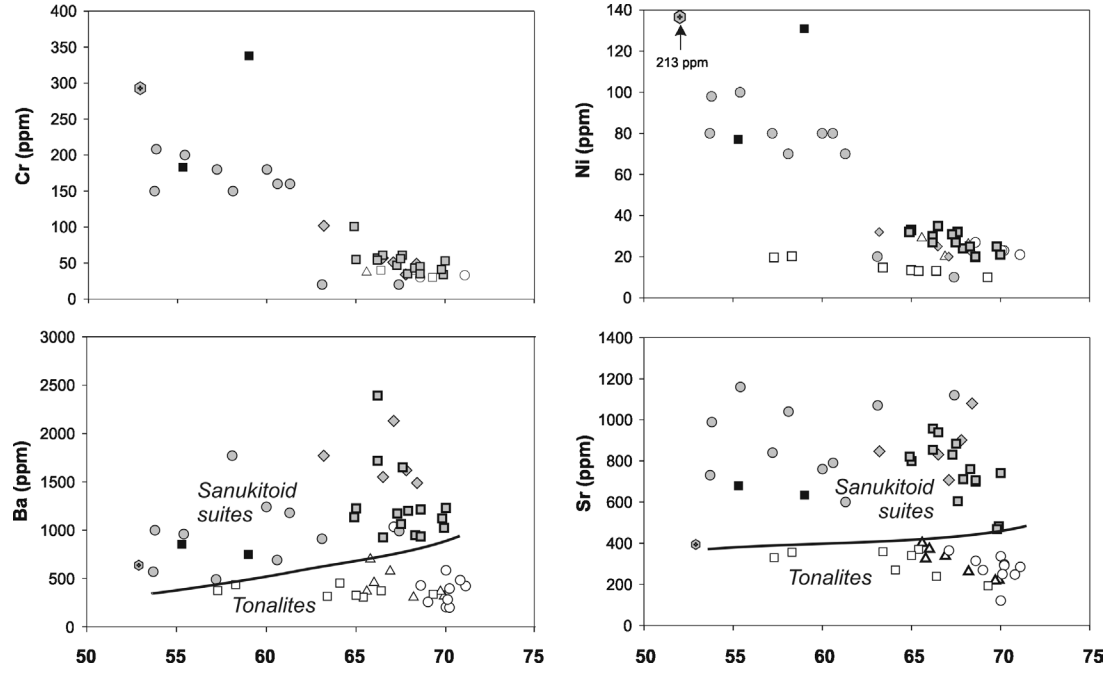

Fig. 3. Cont.

negative Ba, U, Ta, Nb, P, and Ti anomalies and a positive Th anomaly (Fig. 5c).

5.2. High Mg/Fe rocks (sanukitoid suites)

High Mg/Fe rocks show approximately linear trends on the TiO_2, P_2O_3, and MgO vs. SiO_2 diagrams (Fig. 3). The SiO_2 content varies from 53.7 to 67.4 wt. % in the Loso pluton, whereas the Arola and Siikalahti plutons are more felsic. The Mg# varies from 45.3 to 56.3 in the Arola granodiorite, from 44.3 to 62.2 in the Loso diorite, and from 46.3 to 54.7 in the Siikalahti granodiorite. All these high Mg/Fe rocks have generally higher contents of Cr and Ni than the tonalites of the same area (Fig. 3). In addition, these rocks are enriched in Ba and Sr and weakly enriched in light rare earth elements (LREE) (Fig. 4d, e). In the mantle-normalised spider diagrams the majority of the samples show positive Ba, Sr, and Nd anomalies and negative Ta, Nb, P, and Ti anomalies (Fig. 5d, e, f). Both negative and positive U anomalies are present.

Two fine-grained dark-coloured enclaves of the high Mg/Fe granodiorites were analysed: AAK-02-53B from the Arola granodiorite and AAK-02-177B from the Siikalahti granodiorite. According to total alkali silica (TAS) classification (after LeMaitre et al., 2002) these samples correspond to latite and shoshonite in composition, respectively. Their REE patterns are similar to high Mg/Fe rocks and samples are enriched in Ba, Sr, Ni, and Cr, as well (Fig. 4d, e; Table 2).

6. Petrogenetic constraints

6.1. Garnet and/or plagioclase residue?

Fractionation of the LREE from the heavy rare earth elements (HREE) may be a consequence of preferential retention of the latter in pyroxene, olivine, or garnet. However, of these minerals, only garnet is able to produce significant fractionation between these elements (e.g., Rollinson, 1993). The HREE and Y are strongly partitioned into garnet during partial melting and therefore the melt is depleted in these elements if garnet remains in the residue. Negative Eu anomalies in REE patterns are predominantly due to feldspar fractionation and similarly, the Sr budget is largely controlled by plagioclase (e.g., Rollinson, 1993). Therefore, the Sr/Y vs Y. and $(La/Yb)_N$ vs. Yb_N -digrams (Fig. 6a, b) are commonly used for demonstrating the influence of residual garnet and plagioclase during partial melting (e.g. Drummond & Defant, 1990; Defant & Drummond, 1990; Martin, 1999). Accordingly, in the following chapters the petrogenetic constraints on the Kuhmo tonalites and sanukitoid suites are evaluated using these diagrams.

6.1.1. Haasiavaara tonalite

The Haasiavara samples display generally low Sr/Y and $(La/Yb)_N$ associated with moderate Y and Yb_N contents (Fig. 6). This indicates that garnet was not a significant equilibrium phase in the source during partial melting. Some samples show negative Eu anomalies, indicating that plagioclase fractionation could have occurred or that plagioclase has remained in the residue.

6.1.2 Viitavaara tonalite

Some of the Viitavaara samples have moderate Y and Yb contents, and show linear behaviour in the Sr/Y vs. Y and $(La/Yb)_N$ vs. Yb_N –digrams (Fig. 6a, b). This feature could be related to variable amounts of partial melting or, more probably, fractional crystallisation of plagioclase, which is also suggested by the negative Eu anomalies. Samples generally show low Sr/Y and $(La/Yb)_N$, which may be attributed to low abundance of garnet in the residue.

The Sr/Y vs. Y behavior of type II tonalite is rather similar to that in the low-Al TTD (tonalite-trondhjemite-dacite) group reported by Drummond et al. (1996). They concluded that the high Y associated with low Sr/Y is a consequence of plagioclase and pyroxene extraction during partial melting and/or differentiation at low pressures. This suggests that the source for the Viitavaara tonalite could have been at a shallow crustal level, above the stability regime of

Table 2. Major and trace-element analytical data of granitoid rocks in Kuhmo district

	Haasivaara tonalite							Viitavaara tonalite				Viitavaara tonalite				Purnu tonalite					
								Type I				Type II									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
wt.%	94003584	AAK-02-166	94003579	A1086	AAK-02-100	AAK-02-106	94002606	A1705	AAK-02-70	AAK-02-71	AAK-03- 9	94003244	AAK-03- 10	96-ASM-03	AAK-03-79	94003249	AAK-02-28	94002640	AAK-02-155	AAK-02-66	AAK-02-78
SiO_2	69.9	68.2	65.6	69.7	66.0	65.8	66.9	63.4	65	58.3	65.4	64.1	66.4	69.3	57.3	70.0	70.2	71.1	70.2	69.0	70.8
TiO_2	0.38	0.47	0.62	0.42	0.52	0.46	0.47	0.64	0.63	0.78	0.60	0.86	0.57	0.46	1.17	0.47	0.38	0.42	0.42	0.50	0.31
Al_2O_3	15.0	14.6	15.5	14.5	15.3	15.2	15.9	17.1	16.2	18.0	16.1	15.2	15.1	14.1	16.8	15.3	14.7	14.8	14.6	15.1	15.0
Fe_2O_3	3.68	4.25	5.07	4.12	4.56	4.28	4.33	5.18	4.82	6.31	4.96	6.53	5.11	4.39	8.80	3.43	2.85	3.05	3.27	3.37	2.49
MnO	0.07	0.07	0.08	0.07	0.06	0.08	0.08	0.09	0.09	0.09	0.08	0.12	0.08	0.06	0.14	0.04	0.04	0.05	0.04	0.05	0.04
MgO	1.24	1.64	2.25	1.30	1.77	1.50	1.64	2.45	2.15	2.93	2.04	1.77	2.04	1.78	3.00	1.43	1.09	1.21	1.20	1.08	0.77
CaO	3.71	4.14	4.80	3.79	4.26	4.15	4.17	4.69	5.08	5.03	5.08	4.56	4.31	3.49	5.28	2.30	3.39	3.21	2.31	3.13	2.17
Na_2O	4.25	4.18	3.91	4.16	3.99	4.30	4.49	4.58	4.42	4.66	4.19	4.23	4.11	4.07	4.63	4.87	4.33	4.43	4.58	4.55	4.98
K_2O	1.50	1.54	1.70	1.43	1.69	1.85	1.62	1.44	1.11	1.85	1.05	2.03	1.72	1.89	1.88	1.76	1.34	1.37	1.56	1.81	1.99
P_2O_5	0.100	0.119	0.195	0.104	0.129	0.121	0.140	0.124	0.120	0.147	0.127	0.205	0.113	0.090	0.247	0.150	0.104	0.120	0.127	0.140	0.077
C	n.a.	n.a.	n.a.	0.05	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Tot	99.83	99.21	99.73	99.64	98.28	97.75	99.74	99.69	99.61	98.09	99.62	99.62	99.55	99.62	99.24	99.75	98.43	99.76	98.30	98.72	98.63
Mg #	40.0	43.3	46.8	38.5	43.5	41.0	42.8	48.4	46.9	47.9	44.9	34.9	44.2	44.6	40.3	45.2	43.1	44.0	42.1	38.8	38.0
A/CNK	0.98	0.91	0.91	0.95	0.95	0.91	0.95	0.97	0.92	0.96	0.93	0.87	0.92	0.93	0.87	1.09	1.00	1.01	1.09	1.00	1.05
ppm																					
Ba	316	303	366	364	455	700	574	316	326	436	306	453	373	336	375	203	395	421	198	256	483
Rb	41.8	42.4	73.8	45.0	62.7	66.1	48.7	40.1	27	53.9	37.9	58.0	53.5	47.9	51.2	105	66.1	78.3	97.5	77.7	98.8
Sr	221	261	400	217	371	324	337	359	340	356	370	270	239	193	330	336	297	284	291	269	247
Pb	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Th	3.12	5.59	4.24	2.89	0.99	1.21	2.73	1.10	2.22	1.90	3.04	3.83	4.29	7.55	3.58	7.66	5.34	3.98	8.18	7.74	10.5
U	0.78	1.02	0.96	0.60	0.23	0.21	b.d.l.	0.34	0.50	0.52	0.54	0.71	1.08	1.48	0.93	0.95	0.60	1.05	0.57	1.16	0.81
Hf	2.70	3.76	4.78	3.39	3.09	2.92	3.00	2.32	2.85	3.95	3.90	5.18	4.02	4.32	5.30	4.28	3.67	2.95	3.96	4.54	3.07
Zr	141	143	190	135	132	121	163	105	124	159	170	273	148	179	246	209	154	166	165	181	125
Nb	4.33	7.41	5.96	4.62	3.70	5.59	5.28	3.93	4.35	5.67	4.54	9.47	6.03	7.42	11.50	4.87	3.87	4.48	4.40	6.00	5.72
Ta	0.41	0.64	0.49	0.39	0.24	0.32	0.24	0.27	0.26	0.37	0.35	0.65	0.50	0.72	0.76	0.46	0.33	0.46	0.38	0.79	0.62
Y	10.8	15.9	14.3	11.4	9.56	16.5	15.6	10.2	11.5	14.1	11.6	30.9	18.7	22.7	34.7	10.1	5.14	5.62	8.31	8.09	3.88
Sc	b.d.l.	7.22	b.d.l.	8.23	9.84	12.0	b.d.l.	8.86	8.53	14.6	9.94	b.d.l.	9.14	7.12	13.4	b.d.l.	3.2	b.d.l.	6.73	3.5	3.2
V	45.1	47.9	66.6	53.1	59.5	56.1	53.6	71.9	65.5	97.5	70.3	58.3	54.6	36.6	91.6	36.9	30.4	31.9	35	35.4	21.1
Cr	b.d.l.	38	37	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	40	30	b.d.l.	b.d.l.	b.d.l.	33	b.d.l.	b.d.l.	b.d.l.
Co	b.d.l.	10.1	b.d.l.	9.47	17.0	10.6	b.d.l.	14.8	13.4	20.2	12.9	b.d.l.	13.2	9.9	19.7	b.d.l.	6.95	b.d.l.	7.70	7.04	11
Ni	b.d.l.	26	29	b.d.l.	b.d.l.	b.d.l.	20	26	23	28	b.d.l.	b.d.l.	34	26	21	b.d.l.	23	21	b.d.l.	b.d.l.	b.d.l.
Cu	b.d.l.	24	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	37	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	23
Zn	63	62	71	59	67	72	70	85	76	104	69	96	68	33	101	40	58	60	33	65	27
Ga	b.d.l.	25	b.d.l.	22	21	26	b.d.l.	27	25	29	27	b.d.l.	24	24	25	b.d.l.	26	b.d.l.	25	23	24
La	17.7	22.8	27.6	16.3	10.6	11.3	17.5	13.7	16.3	16.3	12.7	25.3	17.8	24.4	23.2	27.3	22.5	18.6	24.5	21.2	12.4
Ce	34.4	40.6	56.2	32.8	20.8	23.4	35.0	28.3	35.40	37.9	28.9	55.2	37.3	49.8	58.1	48.7	41.8	33.2	47.3	39.5	24.7
Pr	3.81	4.48	6.41	3.70	2.42	3.05	4.36	3.14	4.00	4.33	3.26	7.04	4.30	5.61	7.71	5.26	4.17	3.32	4.65	3.90	2.18
Nd	13.2	16.1	23.8	13.9	10.1	13.7	17.0	12.5	15.8	17.7	13.1	28.8	17.0	19.8	31.3	18.0	14.4	11.5	16.7	13.7	7.22
Sm	2.38	3.02	4.08	2.53	2.17	3.35	3.50	2.40	2.73	3.37	2.43	5.84	3.33	3.75	6.58	3.15	1.92	1.88	2.49	2.13	1.00
Eu	0.68	0.79	0.98	0.66	0.76	0.78	0.90	0.75	0.70	0.97	0.77	1.39	0.79	0.78	1.35	0.77	0.58	0.51	0.65	0.70	0.34
Gd	2.14	3.16	3.59	2.38	2.27	3.90	3.33	2.37	2.64	3.52	2.63	5.84	3.54	3.87	6.61	2.73	1.91	1.56	2.56	2.22	1.05
Tb	0.32	0.44	0.52	0.34	0.31	0.57	0.49	0.35	0.40	0.48	0.35	0.88	0.52	0.63	1.00	0.37	0.22	0.19	0.31	0.25	0.13
Dy	1.89	2.59	2.35	2.02	1.64	3.16	2.60	1.84	2.01	2.78	2.12	5.07	3.12	3.83	5.75	1.95	0.98	0.94	1.59	1.37	0.68
Ho	0.34	0.51	0.48	0.36	0.31	0.57	0.54	0.37	0.38	0.44	0.40	0.98	0.66	0.77	1.15	0.38	0.18	0.17	0.29	0.24	0.13
Er	0.96	1.41	1.33	1.17	0.96	1.55	1.43	0.93	1.16	1.33	1.11	2.70	1.84	2.29	3.31	0.90	0.48	0.47	0.78	0.74	0.30
Tm	0.14	0.22	0.18	0.15	0.13	0.21	0.19	0.13	0.14	0.21	0.15	0.41	0.25	0.39	0.50	0.13	b.d.l.	b.d.l.	b.d.l.	0.12	b.d.l.
Yb	1.01	1.52	1.26	1.18	0.80	1.29	1.21	0.92	0.98	1.24	1.08	2.80	1.72	2.53	3.26	0.81	0.45	0.52	0.67	0.81	0.37
Lu	0.14	0.23	0.20	0.18	0.12	0.20	0.17	0.14	0.15	0.18	0.17	0.41	0.26	0.38	0.48	0.11	b.d.l.	b.d.l.	b.d.l.	0.12	b.d.l.

* = Analysed only by XRF (data from courtesy of A. Kontinen)
§ = XRF data from Käpyaho et al.. (accepted)
b.d.l. = below detection limit
n.a. = not analysed
$Mg\# = Mg^{2+} / (Mg2+ + Fe_{tot})*100$
$A/CNK = Al_2O_3 / (CaO+Na_2O+K_2O)$. molar ratio

Table 2. cont. Major and trace-element analytical data of granitoid rocks in Kuhmo district

	Purnu tonalite				High Mg/Fe granitoid rocks (sanukitoid suites)								High Mg/Fe granitoid rocks (sanukitoid suites)						
					Arola suite								Arola suite						
	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
wt.%	94002618	AAK-02-43	AAK-03-13A	AAK-03-49	AAK-02-81	AAK-02-57	A572	94003258	AAK-02-87	AAK-03- 5	AAK-03- 6	AAK-03- 17	AAK-02-85	103-ASM-03	107-ASM-03	113-ASM-03	130-ASM-03	AAK-02-77	A402
SiO_2	68.6	67.1	70.0	70.1	65.0	67.9	68.3	70.0	66.2	69.9	69.8	68.6	68.6	67.6	66.5	67.3	66.2	67.5	64.9
TiO_2	0.49	0.67	0.43	0.42	0.47	0.35	0.35	0.32	0.43	0.31	0.33	0.39	0.34	0.39	0.46	0.42	0.43	0.42	0.48
Al_2O_3	15.5	15.6	14.9	15.0	15.3	14.9	14.7	14.5	15.7	14.9	15.1	14.9	14.8	15.5	15.5	15.3	15.7	14.9	15.0
Fe_2O_3	3.71	4.07	3.70	3.41	4.00	2.95	2.85	2.70	3.60	2.53	2.68	3.24	3.20	2.99	3.77	3.63	3.65	3.56	4.88
MnO	0.06	0.04	0.05	0.05	0.07	0.05	0.06	0.05	0.06	0.05	0.04	0.06	0.04	0.06	0.06	0.06	0.07	0.06	0.08
MgO	1.51	1.61	1.88	1.35	2.07	1.53	1.42	1.42	1.79	1.42	1.39	1.76	1.34	1.94	2.14	1.95	2.04	1.78	2.70
CaO	3.84	2.53	0.61	3.44	3.63	2.31	3.05	2.69	3.44	1.84	1.75	2.86	3.02	2.54	3.78	3.34	3.33	3.31	4.76
Na_2O	4.28	4.00	4.94	4.27	5.11	4.72	4.91	4.36	4.64	5.13	5.04	4.97	4.44	5.38	5.05	4.90	4.98	5.18	4.36
K_2O	1.57	3.09	2.64	1.49	2.33	3.16	2.62	3.34	2.90	3.29	3.23	2.46	2.79	2.91	2.08	2.36	2.85	2.14	2.16
P_2O_5	0.150	0.130	0.116	0.120	0.224	0.147	0.149	0.150	0.197	0.128	0.142	0.167	0.158	0.167	0.201	0.192	0.196	0.196	0.230
C	n.a.	0.03	n.a.	n.a.	n.a.	n.a.	0.26	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.16	n.a.
Tot	99.71	98.85	99.27	99.65	98.20	98.01	98.44	99.53	98.94	99.49	99.51	99.40	98.78	99.47	99.54	99.45	99.45	99.04	99.55
Mg #	44.6	44.0	50.1	43.9	50.6	50.7	49.6	51.0	49.7	52.7	50.7	51.8	45.3	56.3	52.9	51.6	52.5	49.8	52.3
A/CNK	0.99	1.07	1.23	1.01	0.87	0.97	0.90	0.92	0.92	0.97	1.01	0.93	0.94	0.93	0.89	0.92	0.91	0.88	0.83
ppm																			
Ba	428	1035	584	281	1225	1200	949	1230	2394	1024	1122	936	1215	1649	925	1174	1718	1064	1135
Rb	58.2	129	93.5	57.0	59.0	106	93.8	93.0	60.8	83.7	94.4	63.1	65.4	56.8	45.6	56.3	53.7	59	61.7
Sr	314	364	120	249	799	711	760	741	957	482	469	699	706	604	939	831	854	884	821
Pb	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	31	33	b.d.l.	33	b.d.l.	b.d.l.	b.d.l.	32	b.d.l.	b.d.l.	34	b.d.l.	b.d.l.	32
Th	8.52	20.3	7.58	4.92	4.41	14.20	7.44	10.00	5.56	5.53	8.87	9.61	10.80	5.74	4.47	5.78	3.01	4.96	6.02
U	0.57	1.84	1.75	0.95	1.01	1.09	2.01	1.35	1.30	1.75	1.82	2.01	2.98	1.60	1.35	1.87	0.94	1.28	1.91
Hf	4.50	4.21	4.71	3.11	3.87	4.12	3.24	3.18	3.84	3.40	3.28	4.03	3.35	3.42	3.91	3.69	2.90	2.93	2.86
Zr	212	169	187	161	157	144	113	135	132	117	114	146	131	146	160	157	124	136	105
Nb	3.73	6.38	5.27	3.97	5.39	4.10	4.17	4.16	4.68	3.74	4.23	5.04	5.32	4.74	4.41	5.01	4.10	4.62	3.82
Ta	0.29	0.43	0.43	<0.2	0.42	0.29	0.32	0.29	0.38	0.30	0.35	0.44	0.44	0.38	0.32	0.39	0.26	0.36	0.25
Y	8.40	5.33	7.35	5.91	13.5	9.67	8.53	8.95	13.2	7.91	9.14	11.0	9.81	9.30	10.3	9.31	9.52	11.50	11.0
Sc	b.d.l.	5.32	5.43	4.90	9.90	7.16	6.57	b.d.l.	7.06	4.48	4.59	6.74	6.22	5.98	6.59	6.68	6.19	0.50	8.92
V	40.1	39.0	35.5	32.5	66.8	51.0	44.8	41.4	55.6	35.3	40.4	51.5	43.0	48.5	58.0	56.9	54.6	56.6	75.1
Cr	b.d.l.	b.d.l.	b.d.l.	b.d.l.	55	35	43	53	57	34	41	45	35	61	61	47	54	56	101
Co	b.d.l.	11.6	8.24	8.01	11.4	13.6	7.00	b.d.l.	11.5	7.44	9.77	9.96	8.42	8.19	11.4	11.0	9.10	11	12.7
Ni	27	b.d.l.	b.d.l.	23	33	24	25	21	30	b.d.l.	25	b.d.l.	20	32	35	31	27	27	32
Cu	b.d.l.	40	b.d.l.	b.d.l.	b.d.l.	24	b.d.l.	b.d.l.	36	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
Zn	65	34	35	60	64	56	61	58	58	50	51	61	30	39	70	67	69	61	72
Ga	b.d.l.	25	23	25	29	27	27	b.d.l.	26	25	24	27	30	30	26	27	23	23	27
La	36.3	27.8	30.0	15.3	31.7	32.3	30.7	27.4	32.3	23.3	27.2	25.5	28.4	33.6	28.9	27.7	21.4	29.1	24.8
Ce	62.4	54.2	56.9	30.0	71.8	61.6	55.7	51.3	69.5	45.6	55.2	55.2	57.5	67.4	60.8	58.1	48.7	63.2	50.4
Pr	6.32	4.37	5.79	3.00	8.86	7.23	6.24	6.11	8.20	5.34	6.31	6.39	6.56	7.73	7.09	6.77	5.98	7.42	5.79
Nd	20.6	13.3	19.4	10.5	36.0	28.7	25.1	23.2	32.9	21.0	23.9	25.7	25.6	28.6	29.2	25.5	24.9	29.4	23.1
Sm	2.96	1.51	2.83	2.00	6.15	4.65	3.92	3.83	5.62	3.52	4.03	4.22	4.33	4.83	4.54	4.46	4.21	5.10	3.99
Eu	0.70	0.56	0.64	0.58	1.40	1.16	1.00	0.84	1.03	0.77	0.92	1.03	0.95	1.11	1.25	1.08	1.05	1.27	1.01
Gd	2.47	1.46	2.76	1.53	5.14	3.84	3.47	2.86	4.99	2.75	3.35	3.81	3.74	3.95	3.69	3.75	3.29	4.05	3.39
Tb	0.30	0.16	0.28	0.22	0.60	0.47	0.37	0.36	0.56	0.32	0.39	0.48	0.42	0.44	0.47	0.44	0.40	0.50	0.43
Dy	1.63	0.91	1.29	1.11	2.85	1.81	1.73	1.67	2.46	1.31	1.74	2.10	1.97	1.90	2.00	1.89	1.79	2.19	2.02
Ho	0.27	0.12	0.24	0.21	0.44	0.34	0.31	0.28	0.46	0.25	0.27	0.39	0.32	0.31	0.32	0.32	0.30	0.38	0.40
Er	0.72	0.30	0.70	0.48	1.17	0.90	0.75	0.71	1.01	0.63	0.74	1.05	0.88	0.89	0.87	0.79	0.76	0.90	0.98
Tm	0.10	b.d.l.	b.d.l.	b.d.l.	0.16	0.14	0.12	0.10	0.15	0.10	0.11	0.13	0.11	0.10	0.12	0.13	0.11	0.13	0.13
Yb	0.64	0.27	0.64	0.51	1.07	0.82	0.76	0.68	0.92	0.65	0.68	0.95	0.77	0.73	0.86	0.87	0.75	0.91	0.86
Lu	0.11	b.d.l.	0.10	b.d.l.	0.14	0.12	0.10	0.10	0.14	b.d.l.	0.10	0.14	0.11	0.10	0.12	0.12	0.10	0.12	0.12

Table 2. cont. Major and trace-element analytical data of granitoid rocks in Kuhmo district

	High Mg/Fe granitoid rocks (sanukitoid suites)																	
	Loso (qz-) diorite										Siikalahti granodiorite					Kaartoj. gb	Eclaves	
	41*	42*	43*	44*	45*	46*	47*	48*	49*	50§	51	52	53	54	55	56§	57	58
wt.%	26-AML-87	68-2-AML-87	72-AML-87	223-AML-87	209-TMB-87	225-TMB-87	280-TMB-87	299-TMB-87	397-ATK-83	61-1-ATK-86	AAK-02-177A	94002610	AAK-03- 8	AAK-03- 12	AAK-02-137	A1146	AAK-02-177B	AAK-02-57B
SiO_2	60.6	63.1	58.1	55.4	67.4	57.2	61.3	60	53.7	53.8	67.8	63.2	66.5	67.1	68.4	52.9	55.3	59
TiO_2	0.58	0.79	0.59	0.69	0.6	0.63	0.58	0.59	0.67	0.76	0.40	0.56	0.41	0.45	0.36	0.65	0.61	0.51
Al_2O_3	15.8	16.6	16.4	16.8	16.6	16.3	15.6	15.8	18.1	15.8	15.5	15.8	15.0	15.4	15.2	13.6	13.9	13.7
Fe_2O_3	5.94	5.16	5.74	6.81	3.18	7.27	5.78	5.75	7.54	7.29	2.97	4.85	3.77	3.46	2.99	7.82	9.06	7.71
MnO	0.10	0.07	0.10	0.11	0.04	0.13	0.11	0.09	0.12	0.12	0.04	0.07	0.07	0.05	0.05	0.12	0.148	0.13
MgO	4.13	2.07	4.28	5.31	1.3	4.57	4.21	4.61	5.18	6.04	1.39	2.95	1.95	1.71	1.30	8.56	5.51	5.34
CaO	5.52	4.18	5.98	7.14	3.08	7.27	4.67	5.41	7.09	6.53	2.45	3.26	3.30	2.14	2.28	7.10	4.47	3.64
Na_2O	4.73	4.93	4.85	5.01	5.7	4.41	4.3	4.45	4.93	4.50	5.23	4.70	4.46	3.96	5.17	3.36	3.21	2.61
K_2O	1.88	2.37	2.97	1.74	1.52	1.34	2.7	2.55	1.74	2.04	2.96	3.56	3.75	4.92	3.00	2.59	3.56	4.49
P_2O_5	0.370	0.380	0.490	0.530	0.000	0.460	0.390	0.430	0.610	0.490	0.176	0.294	0.222	0.176	0.147	0.125	0.363	0.194
C	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.03	n.a.	n.a.	n.a.	n.a.	0.030	0.25	n.a.	0.26
Tot	99.65	99.65	99.50	99.54	99.42	99.58	99.64	99.68	99.68	97.41	98.92	99.24	99.44	99.37	98.93	96.81	96.13	97.59
Mg #	57.9	44.3	59.6	60.7	44.7	55.5	59.1	61.4	57.6	62.2	48.1	54.7	50.6	49.4	46.3	68.4	54.6	57.8
A/CNK	0.80	0.91	0.74	0.73	1.00	0.74	0.84	0.79	0.79	0.73	0.95	0.90	0.86	0.98	0.96	0.64	0.81	0.87
ppm																		
Ba	690	910	1770	960	990	490	1180	1240	570	999	1619	1771	1550	2130	1488	638	855	750
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	57.6	71.4	91.0	85.8	129	75.1	116	130	258
Sr	790	1070	1040	1160	1120	840	600	760	730	989	901	847	831	707	1080	394	679	634
Pb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	b.d.l.	42	b.d.l.	48	53	46	b.d.l.	35	32
Th	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3.71	9.86	9.89	15.90	16.00	7.80	7.17	15.3	4.17
U	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.66	1.96	1.57	2.78	8.36	2.20	2.01	2.06	1.87
Hf	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3.47	3.72	3.89	3.98	3.79	3.08	2.48	4.14	2.24
Zr	170	210	200	230	200	210	170	200	180	147	145	172	143	154	122	108	179	110
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4.23	3.59	4.01	5.28	5.07	2.89	6.99	4.2	2.24
Ta	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	b.d.l.	0.28	0.27	0.51	0.49	<0.2	0.4	<0.2	<0.2
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	20.6	7.41	10.7	11.1	8.84	6.46	10.7	11.4	8.15
Sc	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	22.4	5.99	b.d.l.	7.78	6.83	5.60	0.4	20	0.35
V	110	80	110	140	40	110	100	110	120	155.0	46.6	78.4	53.3	51.9	44.2	102	122	115
Cr	160	20	150	200	20	180	160	180	150	208	34	102	57	51	49	293	183	338
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	33.8	7.45	b.d.l.	9.27	10.0	7.83	36.6	23.5	22.8
Ni	80	20	70	100	10	80	70	80	80	98	b.d.l.	32	25	20	22	213	77	131
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	45	b.d.l.	54	b.d.l.
Zn	100	100	100	130	50	130	100	90	140	113	66	105	79	73	65	109	248	215
Ga	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	23	27	b.d.l.	24	27	27	21	28	36
La	n.a.	n.a.	65.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	58.3	43.2	51.8	47.2	49.7	26.6	21.9	53.3	36.8
Ce	n.a.	n.a.	140	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	134	85.0	96.5	96.2	95.0	60.3	47.1	99.7	58.8
Pr	n.a.	n.a.	17.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	17.3	9.43	10.80	10.90	10.30	6.68	5.61	11.3	6.53
Nd	n.a.	n.a.	72.7	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	73.3	35.0	40.2	41.1	37.6	25.2	21.6	42.6	23.7
Sm	n.a.	n.a.	11.6	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	12.10	5.27	6.08	6.29	5.34	3.93	3.82	6.55	3.7
Eu	n.a.	n.a.	2.9	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	3.05	1.27	1.32	1.40	1.19	0.91	0.94	1.55	0.78
Gd	n.a.	n.a.	8.49	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	9.67	3.94	4.40	5.03	4.06	2.89	3.2	5.34	2.87
Tb	n.a.	n.a.	0.94	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.03	0.42	0.49	0.55	0.46	0.31	0.4	0.56	0.35
Dy	n.a.	n.a.	3.66	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4.34	1.61	2.15	2.12	1.97	1.20	2.08	2.31	1.62
Ho	n.a.	n.a.	0.6	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.71	0.25	0.34	0.38	0.33	0.18	0.35	0.38	0.3
Er	n.a.	n.a.	1.42	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.88	0.62	0.88	0.88	0.68	0.30	0.98	0.91	0.68
Tm	n.a.	n.a.	0.19	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.23	b.d.l.	0.13	0.12	0.11	b.d.l.	0.14	0.13	0.1
Yb	n.a.	n.a.	1.35	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	1.56	0.56	0.77	0.86	0.71	0.15	0.87	0.86	0.67
Lu	n.a.	n.a.	0.17	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	0.22	b.d.l.	0.13	0.12	0.10	b.d.l.	0.11	0.14	b.d.l.

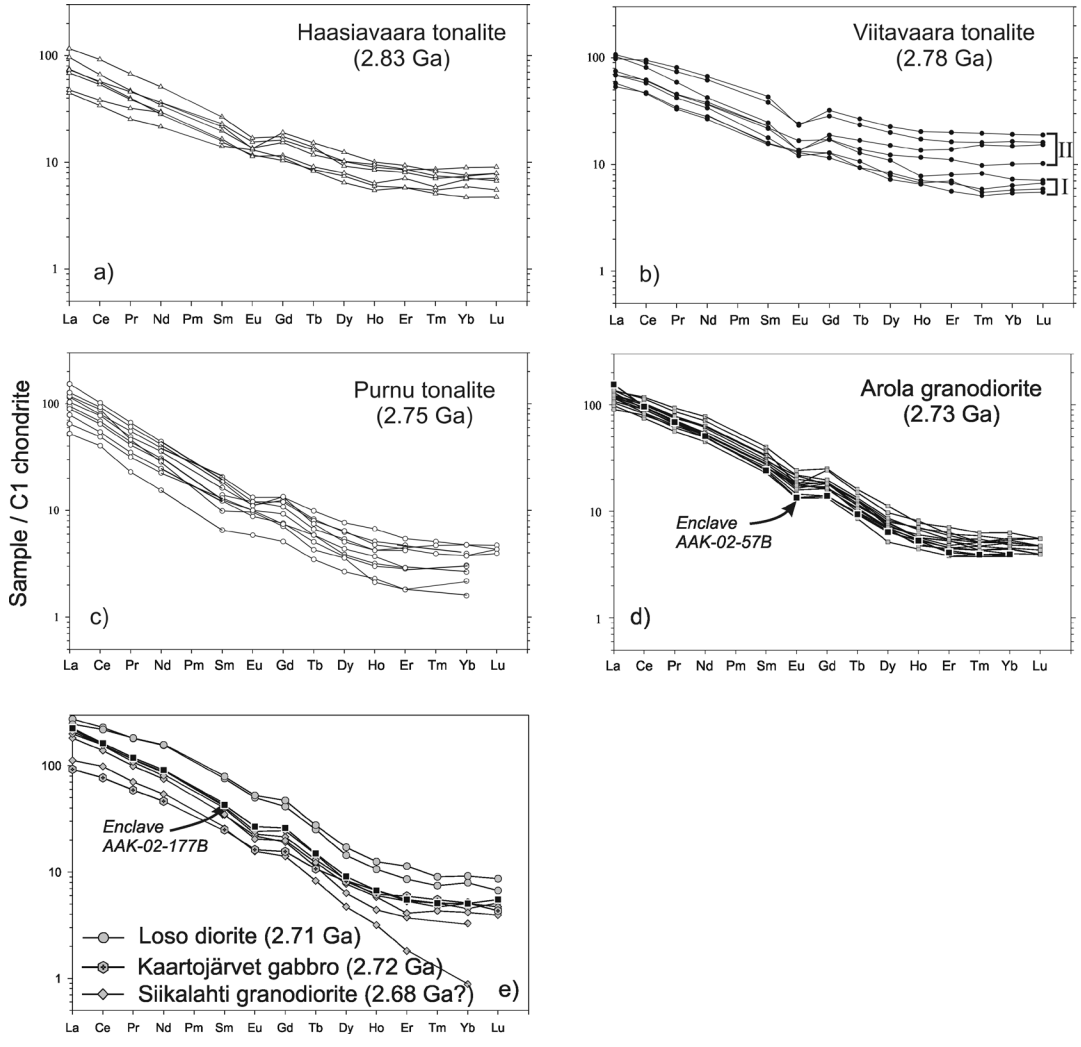

Fig. 4. C1 chondrite-normalised REE patterns for a) Haasiavaara tonalite, b) Viitavaara tonalite (types I and II), c) Purnu tonalite, d) Arola granodiorite, e) Loso diorite, Siikalahti granodiorite, and Kaartojärvet gabbro. C1 chondrite-normalising values after Sun & McDonough (1989).

garnet. Negative Eu anomalies suggests either residual retention or fractionation of plagioclase, which is also consistent with the low Al and Sr observed in the Viitavaara samples.

6.1.3. Purnu tonalite

The Purnu tonalites exhibit more depleted HREE and Y (Fig. 7a, b) than the Haasiavaara and Viitavaara tonalites. As modelled by Martin (1987), similar depletion of HREE could be achieved by partial melting of tholeiitic amphibolite leaving 25 % garnet residue. The Purnu tonalites have higher Al_2O_3/(CaO + K_2O + Na_2O) than the Viitavaara and Haasiavaara suites and the average REE pattern of the Purnu tonalite overlaps with the high-Al TTD trend (Fig. 7a) reported in Drummond et al. (1996). These high-Al TTDs were attributed to partial melting of a basaltic source leaving garnet, clinopyroxene, and amphibolite residue.

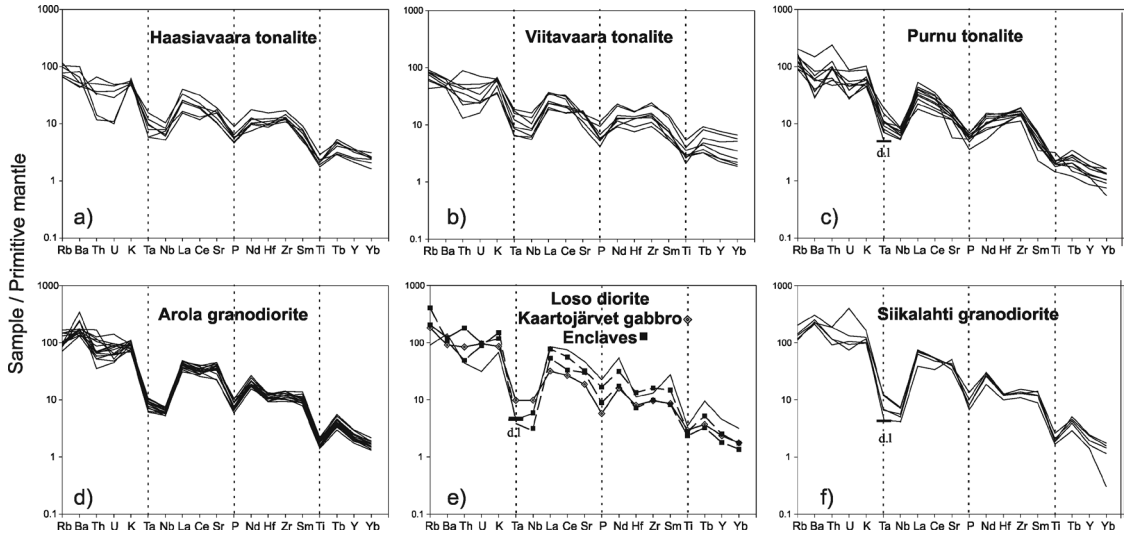

Fig. 5. Primordial mantle-normalised values for a) Haasiavaara tonalite, b) Viitavaara tonalite, c) Purnu tonalite, d) Arola granodiorite, e) Loso diorite, and f) Siikalahti granodiorite. The term d.l. denotes the detection limit. Primitive mantle values are after Sun & McDonough (1989).

6.1.4. High Mg/Fe rocks (sanukitoid suites)

Sanukitoid suites and the two mafic enclaves from the Kuhmo district show weak negative Eu anomalies (Figs. 4 d,e). As concluded earlier, this feature is most probably related to plagioclase fractionation or retention in the source region. Sanukitoid suites from the Kuhmo district are also more enriched in LREE than the tonalites and have Sr/Y vs. Y and $(La/Yb)_N$ vs. Yb_N –distributions comparable with modern adakites and other Archaean sanukitoids, based on data reported in the literature (Fig. 6) (see Rapp et al., 2003 and references therein).

7. Discussion

7.1. Variable sources of TTGs of the Kuhmo district

Debate concerning the origin of Archaean TTGs has focussed mainly on whether garnet amphibolites or, alternatively, hornblende eclogites could account for the observed geochemical characteristics (e.g. Martin, 1999; Foley et. al., 2002; Rapp et al., 2003). Although most Archaean TTGs are depleted in HREE, which is consistent with partial melting of either of those sources, there are also some Archaean tonalites that do not require either garnet amphibolite nor eclogite residue. As shown in Figures 4b and 6a the type II Viitavaara tonalite samples lack significant LREE/HREE fractionation and therefore do not necessarily demand a complementary garnet-bearing residue. In fact, some of the Viitavaara tonalites have Sr/Y vs. Y and $(La/Yb)_N$ vs. Yb_N –distributions similar to mid ocean ridge basalts (MORB) (Fig. 6). Furthermore, low-Al (high-Yb) TTDs presented in Drummond et al. (1996) share similar geochemical characteristics, but are slightly richer in HREE (Fig. 7). Similar weakly fractionated REE patterns for Archaean tonalites have previously been documented from the Superior Province in Canada (e.g., Feng & Kerrich, 1992, Whalen et al., 2004).

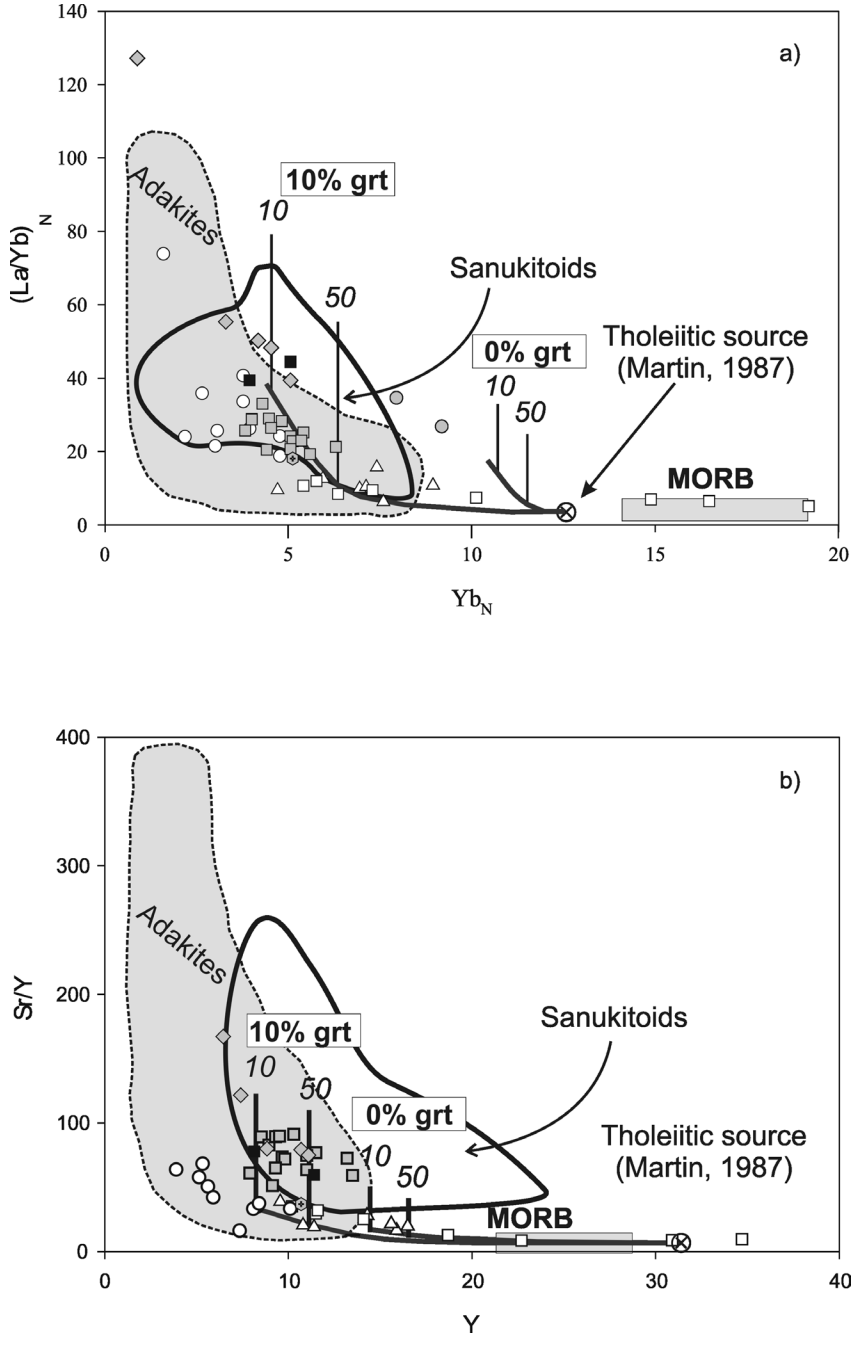

Fig. 6. a) Sr/Y vs. Y (ppm) and b) $(La/Yb)_N$ vs. Yb_N diagrams illustrating the influence of garnet and plagioclase residue in the plutonic suites from the Kuhmo district. Solid line denotes partial melts of the tholeiitic source (circled x) after Martin (1987). Numbers in italics show the amount of partial melts. The fields for adakites and sanukitoids are re-drawn after Rapp et al. (2003). MORB-field combines the E-MORB and N-MORB after Sun & McDonough (1989). Symbols are like in Fig. 3.

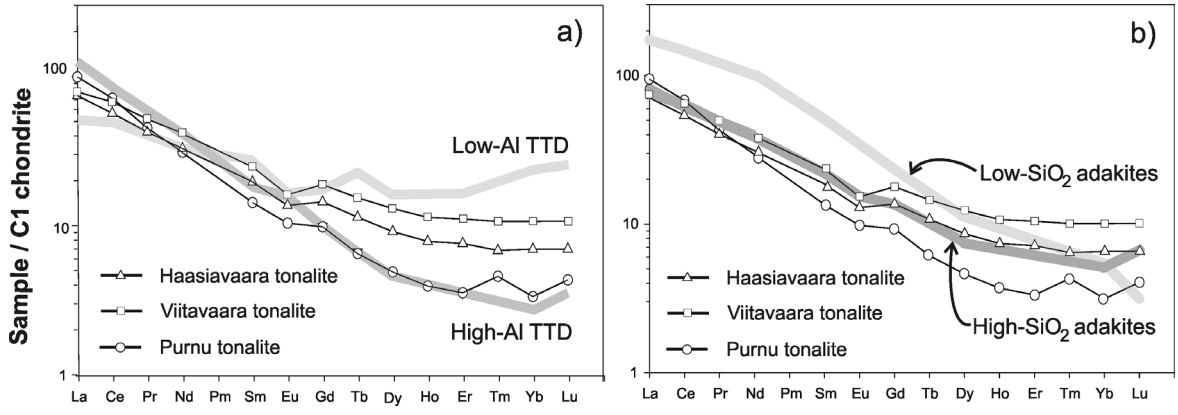

Fig 7. C1 chondrite-normalised REE patterns for a) showing the average REE patterns of High-Al TTD and Low-Al TTD suites after Drummond et al. (1996) and b) average REE behaviour of adakites after (Martin, 2005), compared to tonalites from the Kuhmo district. C1 chondrite normalising values after Sun & McDonough (1989).

If the REE patterns of the Viitavara tonalite (type II) are compared to REE patterns of low SiO_2 adakites and high SiO_2 adakites (after Martin et al., 2005), it appears that LREE/HREE fractionation in both these types of adakites is stronger than in the samples of Viitavaara tonalite (Fig. 7b). In addition, Figure 6a further indicates that Sr/Y vs. Y -distributions in most samples of the Viitavaara tonalite are not consistent with adakites (see also Fig. 3). The trace element behaviour of the Purnu tonalite, nevertheless, corresponds rather well with the modern adakites (Figs. 6 and 7) (cf. Drummond et al., 1996). It thus seems obvious that both garnet bearing and non-garnet amphibolitic residues may be acceptable sources for different tonalite plutons in the Kuhmo district, a feature which is also seen in the other Archaean cratons (e.g., Condie, 2003; Whalen et al., 2004).

7.2. Sources of the Kuhmo sanukitoid suites and comparison to TTGs

In general, sanukitoid suites are enriched in large ion lithophile elements (LILE), LREE, Cr, and Ni with respect to tonalites. In addition, on spider diagrams normalised against primitive mantle, the sanukitoid suites show deeper negative Nb-Ta, P, and Ti anomalies than TTGs (Fig. 5). On the basis of the Harker diagrams and trace element distributions, it seems unlikely that simple fractional crystallisation of a common parental magma could account for the differences between sanukitoid and tonalite suites, because the elevated Mg#, Ni, and Cr contents of sanukitoid suites clearly call for a more mafic source. Querré (1985) considered that in the case of the Arola granodiorite, these characteristics could be a result of komatiite contamination of the parental TTG magmas. This model, however, cannot easily explain the elevated LREE and LILE. Instead, a mafic/intermediate source component enriched in LILE, HREE, Cr and Ni in the Arola granodiorite is supported by the presence of the latitic enclave. Correspondingly, a LREE-enriched shoshonitic enclave with elevated Ni, Cr, and LILE was observed in the Siikalahti pluton, also suggesting multiple source components for that pluton (Table 2). More mafic Loso suite and Kaartojärvet gabbro have even higher contents of Cr, Ni, and LREE, thus calling for a primitive, yet LILE enriched source. The enclaves indicate that the Cr, Ni, LREE, and LILE enrichment of the Siikalahti and Arola granodiorites could be due to the mafic-inter-

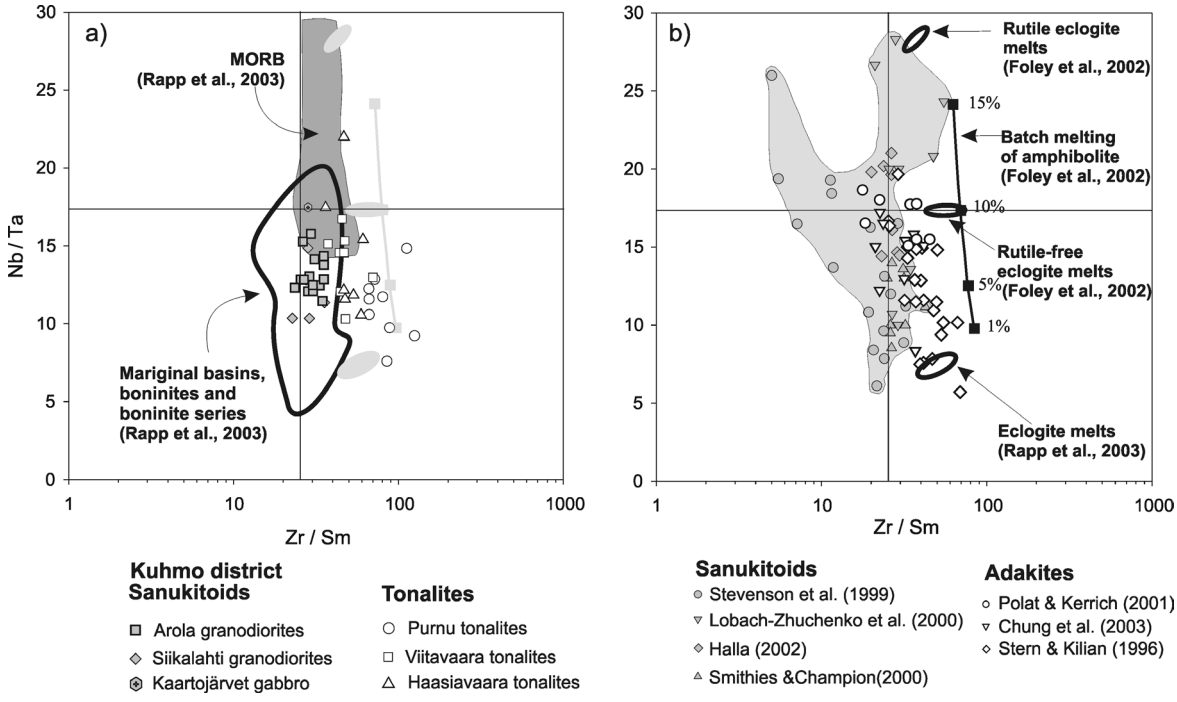

Fig. 8. Diagram adapted from Foley et al. (2002) showing Nb/Ta vs. Zr/Sm distribution a) for tonalites and sanukitoids of the Kuhmo district and b) for some reported sanukitoids and adakites. Modelled eclogite and amphibole melts are after Rapp et al. (2003) and Foley et al. (2002). Intersection of the horizontal and vertical lines denotes the composition of primordial mantle.

mediate source component. The generally felsic nature of the Arola granodiorite and Siikalahti granodiorite may be related to fractional crystallisation of this parental mafic-intermediate source and/or contribution of the more felsic (perhaps TTG-like) source component (cf. Stern & Hanson, 1992). However, more detailed petrogenetic modelling is required to test this hypothesis.

The LILE- and LREE-enriched mafic source component associated with sanukitoids is often attributed to a melting of subduction-metasomatised (enriched) mantle (Shirey & Hanson, 1984; Stern & Hanson, 1991), which would also explain the elevated Ni, Cr, and Mg#. Direct evidence for the presence of Archaean metasomatised mantle in the Fennoscandian shield is provided by Archaean zircon xenocrysts (up to 3.1 Ga) reported from the Palaeoproterozoic Jormua ophiolite (Peltonen et al., 2003). The Kaartojärvet gabbro (A1146) with 52.9 wt.% SiO_2 and Mg# of 68.4 shows Ba and Sr contents of 638 ppm and 394 ppm, respectively (Table 2). These contents correspond with the 3.0 Ga gabbros from the Mallina basin, NW Australia, which are considered as one of the oldest examples derived from a LREE-enriched mantle resulting from subduction of oceanic crust and sediments (Smithies et al., 2004).

Archaean TTGs, in general, have lower Nb/Ta and higher Zr/Sm than modern oceanic basalts and mantle-derived rocks, which is considered to reflect partial melting of low-Mg amphibolite in a subduction setting (Foley et al., 2002; Tiepolo et al. 2001). According to Foley et al. (2002), low-magnesium amphibolite may produce the low Nb/Ta and high Zr/Sm, thus precluding rutile-bearing eclogites in the

lower parts of thick oceanic crust as potential sources. However, Rapp et al. (2003) presented experimental evidence of partial melting of hydrous basalt under eclogite facies conditions, which yields Nb/Ta and Zr/Sm distribution similar to those observed in Archaean TTGs.

On the Nb/Ta vs. Zr/Sm -diagram adapted from Foley et al. (2002) most of the tonalites from the Kuhmo district are situated in the lower right quadrant, whereas the sanukitoid suites from Kuhmo lie close to, but still mostly on the right side of the Zr/Sm –line defined by primitive mantle (Fig. 8a). The Kuhmo sanukitoid suites have generally lower Zr/Sm than the Kuhmo tonalites and TTGs reported in the literature (cf. Rapp et al., 2003 and, references therein). The distribution of Zr/Sm and Nb/Ta in the Kuhmo sanukitoid suites is similar to modern boninites, boninite series and rocks from mariginal basins as they all lie in the vicinity of the Zr/Sm line for primitive mantle and have mainly sub-chondritic Nb/Ta values (for references see Rapp et al., 2003). Although sanukitoid suites share many geochemical features with adakites (elevated Mg# and enrichment of LILE) (Fig. 3; Fig. 6), which are attributed to direct melting of a subducted oceanic slab (Defant & Drummond, 1990), they differ in being lower in Zr/Sm than adakites (Fig. 6b). The higher Zr/Sm of the eclogite-derived melts (Foley et al., 2002; Rapp et al., 2003) compared to the sanukitoid suites from Kuhmo makes an eclogitic source improbable, whereas the mantle source component is in accordance with observed chemical characteristics.

7.3. Time-integrated evolution of the plutons

As noticed by Martin (1985) there appear to be some systematic trends in the geochemical characteristics of the plutonic rocks from the Kuhmo district. Firstly, the 2.83 Ga and 2.78 Ga tonalites seem to have lower $(La/Yb)_N$ and Sr/Y than the > 2.75 Ga plutonic suites, which could be related to a progressive increase in the amount of residual garnet with time. However, confirmation of this would demand detailed petrogenetic modeling to estimate the role of fractional crystallisation and contamination. Such task is, however, beyond the scope of this study.

Secondly, the < 2.74 Ga sanukitoid suites show deeper negative Nb-Ta anomalies than the preceding tonalites. Negative Nb-Ta is often attributed to the presence of a subduction component, due to preferential retention of Nb and Ta in the descending slab instead of being released to the slab-derived fluid-phase (e.g. Pearce, 1982). However, as noticed in several papers the generation of sanukitoid suites is not necessarily related to the subduction event itself, but may also be a result of subsequent melting of subduction-modified enriched mantle (e.g., Stevenson et al., 1999).

In general, the geochemistry together with available U-Pb age data on plutonic rocks probably reflect a transition in tectonic conditions at around 2.74 Ga, which is marked the appearance of the LILE- and LREE-enriched mafic source component of the magmas. This phenomenon appears to be regional rather than local as it has been recently demonstrated that the period between 2.74 Ga and 2.70 Ga has been a significant period of sanukitoid magmatism over a large part of the Karelia craton (e.g., Samsonov et al., 2004; Bibikova et al., 2005; Halla, 2005).

8. Summary

Whole rock geochemical data on the studied Neoarchaean tonalites from the Kuhmo district indicate variable sources. The 2.83 Ga *Haasiavaara* tonalites, which are metaluminous, slightly depleted in HREE with minor negative Eu anomalies, were probably derived from a source, in which garnet was a stable, though relatively minor phase. The 2.78 Ga *Viitavaara* tonalite comprise two types (I and II). The type II does not necessarily demand derivation via processes involving residual garnet fractionation, however, pronounced negative Eu anomalies are indicative of plagioclase fractionation, or retention in the source region. The type I have only slightly lower contents of HREE than the type II. The 2.75 Ga peraluminous *Purnu* tonalite shows strong fractionation of LREE/HREE, thus requiring that a substantial

amount of garnet remained in the source, as originally suggested by the geochemical modelling by Martin (1987). Variable compositions of the tonalites imply that the sources of Archaean TTGs have a wide mineralogical compositional variation and tonalites with low $(La/Yb)_N$, such as type II of the Viitavara tonalite, differ from Cenozoic adakites (cf. Martin, 1999; Smithies, 2000). The type II is rather similar to the low-Al TTDs, which are considered to represent low pressure partial melts of a basaltic source (e.g. Drummond et al., 1996). The Purnu tonalite has many geochemical charateristics similar to adakites.

The high Mg/Fe granitoid rocks from the Kuhmo district range from diorites and quartz diorites to granodiorites. The geochemical characteristics of these high Mg/Fe granitoid rocks differ from the tonalites in that they are enriched in LREE, Ba, Sr, Cr, and Ni. Thus, these high Mg/Fe rocks are geochemically similar to the other Archaean rocks belonging to sanukitoid suites. The geochemical characteristics of the sanukitoid suites could be attributed to contribution of an enriched mantle source component (cf. Stern & Hanson, 1991; Halla, 2005). LREE and LILE enriched sources for the Kuhmo sanukitoid suites are supported by the presence of LREE- and LILE-enriched latitic and shoshonitic enclaves of the *Arola* and *Siikalahti* granodiorite plutons. Nb/Ta and Zr/Sm distributions of the sanukitoid suites correspond to rocks from mariginal basins, including boninites (cf. Rapp et al., 2003), thus being different from the tonalites of this study.

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