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Age and petrology of the Kaapinsalmi sanukitoid intrusion in Suomussalmi, Eastern Finland

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Short Communication

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1. Introduction

Sanukitoids (high Mg-granitoids) are a group of distinctive Neoarchean granitoids, which differ in chemical composition from the voluminous tonalite-trondhjemite-granodiorite (TTG) suite. Shirey and Hanson (1984) first introduced the term sanukitoid to refer to mantle-derived rocks, which resemble high-Mg andesites, known as sanukites in the Miocene Setouchi belt of Japan. Stern et al. (1989) defined sanukitoid geochemistry as SiO_2 = 55 – 60 %, MgO > 6 %, Mg# > 60, Sr > 600 – 1800 ppm, Ba > 600 – 1800 ppm, Cr > 100 ppm, Ni > 100 ppm and LREE enriched compared to HREE. The term sanukitoid series has been introduced for granitoids with relatively high Mg#, MgO, Sr, Ba, Cr and Ni at any given silica level (Lobach-Zhuchenko et al., 2005). Sanukitoids composition shows some similarities to adakites (Martin, 1999) and to recently described Neoarchean Closepet-granites (Moyen et al., 2001).

Interpretation of the geochemistry of sanukitoids is controversial. High Mg#, MgO, Ni and Cr implies that sanukitoids are mantle-derived rocks, but high Sr, Ba and LREE suggest crustal origin (Stern & Hanson, 1991). These aspects of sanukitoid geochemistry have been explained with a two-stage process, which includes Archean subduction. In the first stage, melts and/or fluids derived from a subducting basaltic slab enriched the overlying mantle wedge with Sr, Ba and LREE. Later melting of the enriched mantle generated sanukitoid magmas (Stern & Hanson, 1991; Kovalenko et al., 2005). Pb isotopic studies indicate that subducted sediments may also have played an important role in the sanukitoid petrogenesis (Halla, 2005). Sanukitoids might thus be the first sign of existence of an enriched mantle wedge and the beginning of the modern style of plate tectonics (Martin & Moyen, 2005).

Sanukitoids have been found in many Archean cratons and most of them are ~2.7 Ga in age (Rollinson & Martin, 2005). The ~3.0 Ga sanukitoids from the Ukrainian Shield (Artemenko et al., 2003), the

Fig. 1. Geological map of the Karelian craton and sanukitoid intrusions. Sanukitoid zones and Russian sanukitoids are from Lobach-Zhuchenko et al. (2005); Loso, Arola and Siikalahti sanukitoids are from Käpyaho et al. (2006); and Koitere and Nilsiä sanukitoids are from Halla (2005). General features of the map according to Koistinen et al. (2001) and Sorjonen-Ward & Luukkonen (2005).

~2.9 Ga sanukitoids from the Pilbara craton (Smithies & Champion, 2000), and the ~2.89 Ga sanukitoids from the Amazonian craton (Oliveira et al., 2006) are the only sanukitoid intrusions known to be older than ~2.7 Ga.

More than 20 sanukitoid intrusions have been found in the Karelian craton. Sanukitoid intrusions in the Russian part of the Karelian craton are divided into Eastern and Western sanukitoid zones, which differ in composition and age (Lobach-Zhuchenko et al., 2005; Bibikova et al., 2005). Seven sanukitoid intrusions located in Finland have been described: Kuittila (O'Brien et al., 1993), Nilsiä, Koitere (Halla, 2005), Arola, Loso, Siikalahti (Käpyaho et al., 2006; Käpyaho 2006) and the recently recognised Kaapinsalmi sanukitoid intrusion (Heilimo, 2006a; 2006b) (Fig. 1). This paper describes in more detail the petrology of the Kaapinsalmi sanukitoid intrusion.

2. Geological setting

The Kaapinsalmi sanukitoid intrusion is located in Suomussalmi, in the Kianta terrain on the western margin of the Archean Karelian craton (Fig. 1). The

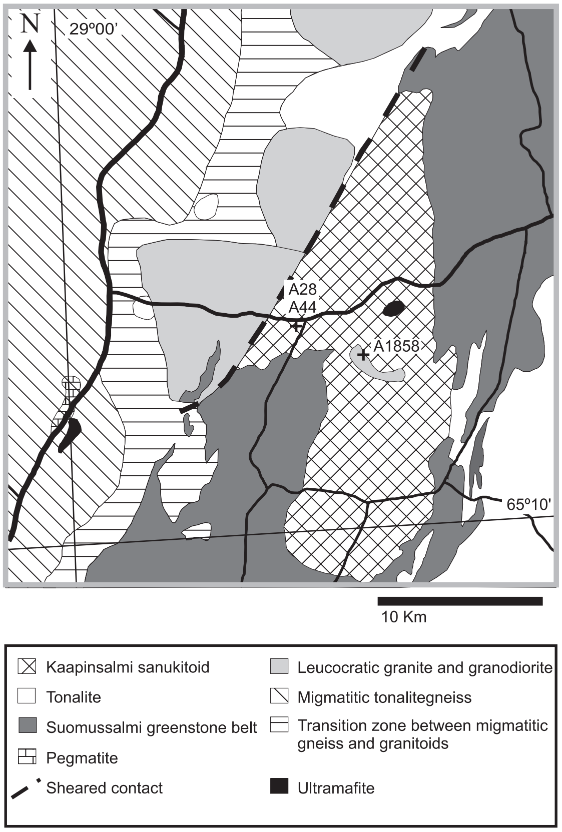

Fig. 2. Geological map of the Kaapinsalmi area, showing the locations of the dated samples. The greenstone belt is modified from Sorjonen-Ward & Luukkonen (2005).

Kianta terrain is a granite-greenstone terrain consisting mostly of migmatitic gneisses, greenstone belts, paragneisses and granitoids (Sorjonen-Ward & Luukkonen, 2005). Migmatitic Päivärinta gneiss in the vicinity of Kaapinsalmi has mesosome aged 2.83 – 2.84 Ga and leucosome aged between 2.70 – 2.67 Ga (Käpyaho et al., 2007). Greenstone belts in the Kianta terrain have been tectonically segregated into Tipasjärvi, Kuhmo, and Suomussalmi greenstone belts. The ages of the greenstone belts are between ~2.80 – 2.83 Ga (Luukkonen, 1992). Nurmes-type paragneisses in the Kianta terrain evidently have protolith ages as young as ~2.71 – 2.69 Ga (Kontinen et al., 2007). Granitoids of the Kianta terrain are metamorphosed, but they have preserved their magmatic texture. Käpyaho et al. (2006) and Käpyaho (2006) have divided the Kianta granitoids into three magmatic episodes: 1) TTG-granitoids 2.83 – 2.74 Ga, 2) sanukitoids 2.74 – 2.70 Ga and 3) leucocratic granites and granodiorites 2.70 – 2.68 Ga.

The Kaapinsalmi sanukitoid lies adjacent to the western margin of the Suomussalmi greenstone belt (Fig. 2). It has intrusive contacts with the greenstone belt and contains greenstone xenoliths, contacts with granitoids are sheared and no contact has been observed with migmatitic gneisses. Within the Kaapinsalmi sanukitoid there is a small, brecciating intrusion of leucogranodiorite called Kivilahti. The Kaapinsalmi sanukitoid is mineralogically tonalite and also contains melatonalite inclusions. The texture of the Kaapinsalmi sanukitoid is granular and mortar. The major minerals are plagioclase, quartz, hornblende and biotite, while accessory minerals include microcline, sphene, allanite, apatite, zircon and opaque minerals. The secondary minerals are biotite, epidote, sericite, saussurite, chlorite and carbonate.

3. Geochemistry

The Kaapinsalmi sanukitoid and melatonalite inclusions display distinct sanukitoid characteristics: low SiO_2 and high Mg#, MgO, Ni, Cr (Fig. 3). The Kaapinsalmi sanukitoid is intermediate (SiO_2 56.0 – 66.8 %) and has high Mg# (51.3 – 64.2). There is a 2.8 – 7.4 % variation in MgO, while Ni and Cr abundances are greater compared to eastern Finland TTGs. The K_2O content of the Kaapinsalmi sanukitoid is 0.8 – 2.7 %, while Sr varies between 206 ppm and 643 ppm and Ba from 316 ppm to 1366 ppm. Melatonalite inclusions of the Kaapinsalmi sanukitoid have slightly higher Mg# and higher contents of MgO, Ni and Cr than the Kaapinsalmi sanukitoid, with Cr abundances of up to 626 ppm and Ni abundances of up to 221 ppm; respective numbers for the Kaapinsalmi sanukitoid are 408 ppm and 207 ppm. The Kaapinsalmi sanukitoid and inclusions both have fractioned REE patterns with higher HREE than average eastern Finland TTG. Average $(La/Lu)_n$ for the Kaapinsalmi sanukitoid is 21.2 and for the melatonalite inclusions 12.2 (Fig. 4).

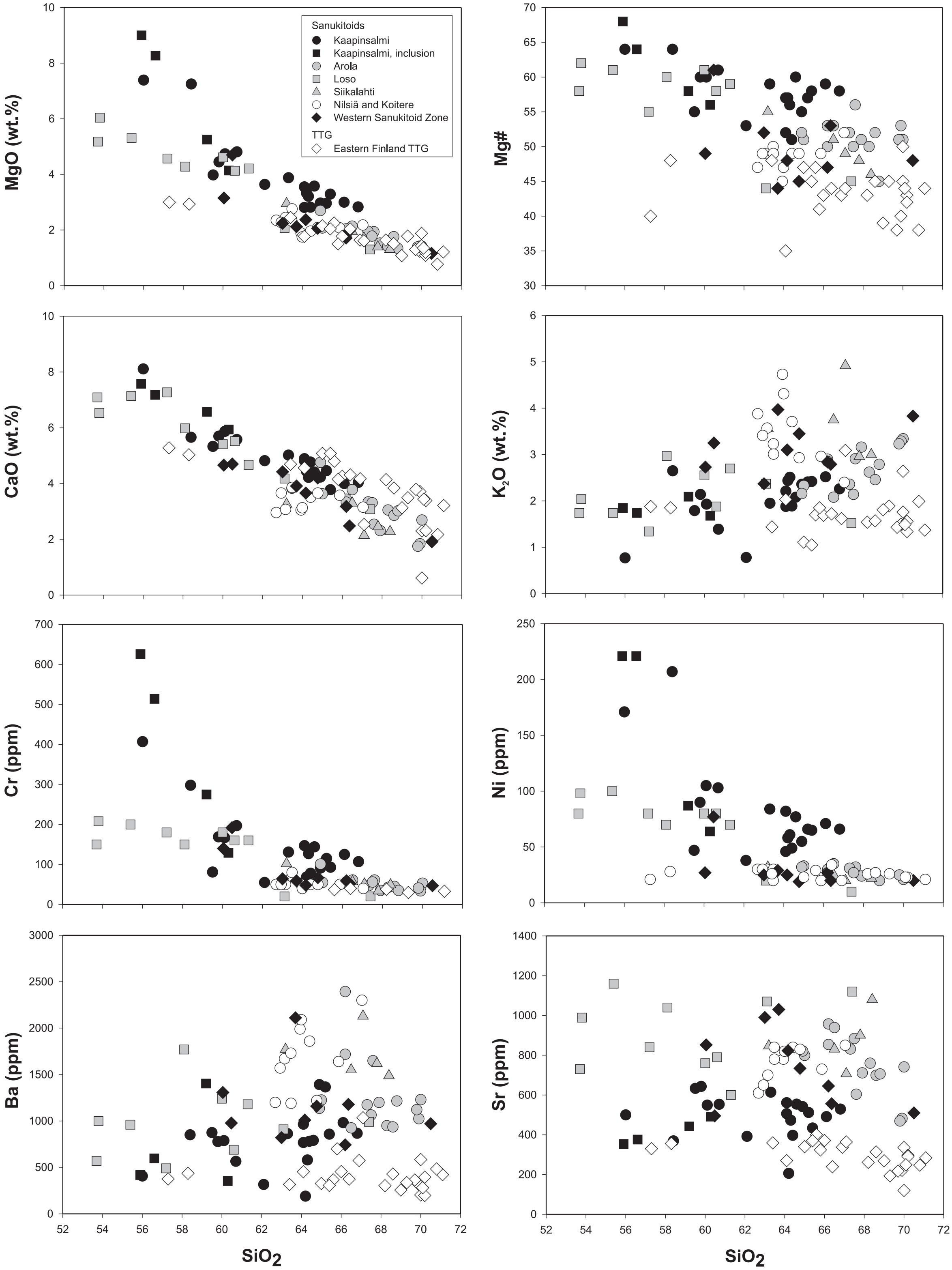

Fig. 3. Selected Harker diagrams illustrating geochemistry of West Karelian craton sanukitoids and TTGs. Data for Kaapinsalmi sanukitoid is from Heilimo (2006b); Arola, Loso, Siikalahti sanukitoids and Eastern Finland TTG data from Käpyaho (2006); data for Nilsiä and Koitere sanukitoids from Halla (2005) and that for Western sanukitoid zone is from Lobach-Zhuchenko et al. (2005).

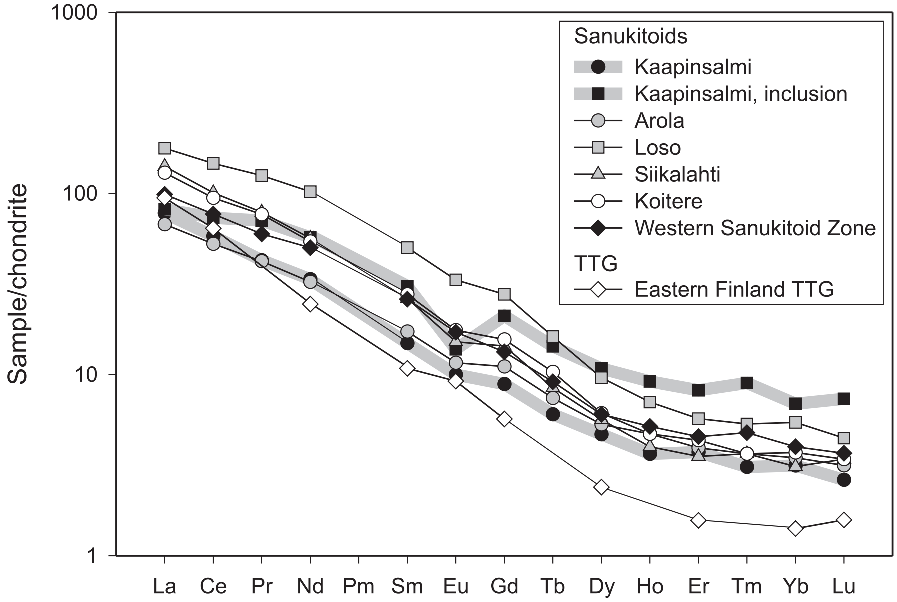

Fig. 4. Representative chondrite normalised REE-patterns of West Karelian craton sanukitoids and Eastern Finland TTG (normalisation values from Taylor & McLennan, 1985). Kaapinsalmi sanukitoid data from Heilimo (2006b); Arola, Loso, Siikalahti sanukitoids analyses after Käpyaho (2006); Nilsiä and Koitere data from Halla (2005); Western sanukitoid zone data from Lobach-Zhuchenko et al. (2005) and Eastern Finland TTG patterns after Martin (1987).

4. U-Pb dating methods

Two samples from the Kaapinsalmi sanukitoid were collected for U-Pb dating (A28 by Eero Pehkonen and A44 by Erkki Luukkonen, see Fig. 2). U-Pb samples were treated with methods described by Vaasjoki (2001) in 1978 and 1981 by Olavi Kouvo and staff of the isotopic laboratory of Geological Survey of Finland. Samples were washed, crushed and sorted on a wet shaking table and then treated with heavy liquids (bromofrom and Clerici™) and a Frantz magnetic separator. Zircon and sphene grains were selected for analysis by handpicking. U and Pb multigrain analyses were done using Krogh's method (1973). ^{235}U-^{208}Pb -spiked and unspiked isotopic rations were measured using thermal ionisation single collector mass spectrometer (TIMS) at the isotopic laboratory of Geological Survey of Finland, Espoo. U-Pb calculations were done with PbDat (Ludwig, 1991) and IsoPlot/Ex (Ludwig, 2003) programs.

5. U-Pb dating results

Zircons from the Kaapinsalmi sanukitoid were light brown and translucent in the heavy fraction. Crystal shapes were pyramidic and prismatic from subhedral to euhedral. Sample A28A was originally analysed by Kouvo & Tilton (1966) using old borax method and the resulting $^{207}Pb/^{206}Pb$ age was 2681 Ma. Afterwards, three discordant zircon fractions from sample A28 were analysed producing an upper intersect at 2718 ± 6 Ma. Additional sample A44 gave an upper intersect at 2719 ± 4 Ma, with two discordant zircon fractions and an almost concordant sphene fraction. Both ages are same within the error limits. A combined age of 2716 ± 9 Ma from both samples (A28 & A44) is thus a relatively good estimate of the Kaapinsalmi sanukitoid intrusion age (Fig. 5, Table 1).

Kivilahti leucogranodiorite located inside the Kaapinsalmi sanukitoid was also sampled (A1858) (see Fig. 2) for U-Pb dating. However, separation did not produce enough zircon or monazite for TIMS analysis.

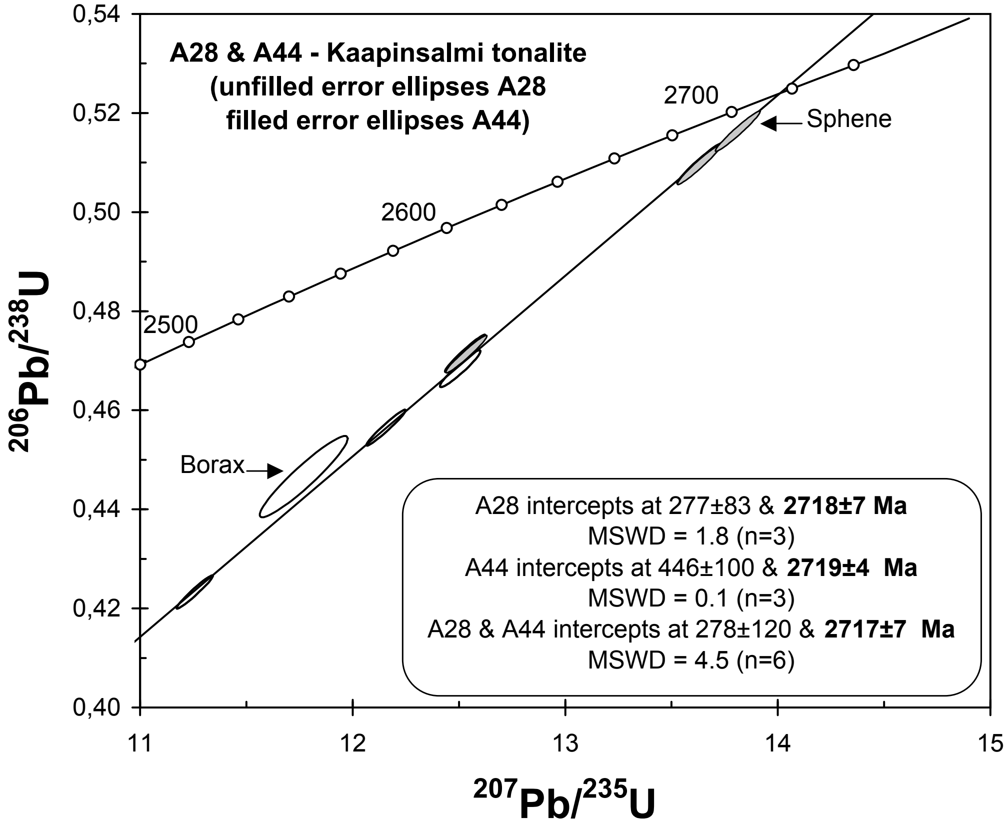

Fig. 5. Concordia diagram showing U-Pb isotopic data for the Kaapinsalmi sanukitoid. A28 fractions are unfilled error ellipses and A44 fractions are filled error ellipses. A44C sphene U-Pb isotopic data is included and A28A borax U-Pb isotopic data is excluded from the geochron (Kouvo and Tilton, 1966).

6. Discussion

In the Karelian craton, sanukitoids are younger than the surrounding TTG, implying that sanukitoids are not directly linked to the subduction processes that might have produced TTGs (Bibikova et al., 2005). The sanukitoid intrusions of the Russian part of the Karelian craton are divided into Eastern and Western sanukitoid zones (Lobach-Zhuchenko et al., 2005; Bibikova et al., 2005). The sanukitoid intrusions in the Eastern sanukitoid zone were formed 2.730 – 2.745 Ga ago. They are more mafic in composition, with higher MgO, Ni, Cr and lower Ba, Sr compared to the Western sanukitoid zone intrusions. The Eastern sanukitoid zone also shows more heterogeneity and a larger mantle-derived component than the Western sanukitoid zone. The Western sanukitoid zone is younger, with intrusions in the age range 2.700 – 2.720 Ga.

Location, age (~2.72 Ga) and composition of the Kaapinsalmi sanukitoid all show certain similarities to the Western sanukitoid zone (Figs. 1, 3 & 4), although the Mg#, MgO, Ni and Cr contents of the Kaapinsalmi sanukitoid are higher at their respective SiO_2 level than in the other west Karelian sanukitoids (Fig. 4). The Kaapinsalmi sanukitoid also has relatively low Ba and Sr contents when compared to those of the Western sanukitoid zone and other Finnish sanukitoids. Comparatively low K_2O, Ba, Sr and

Table 1. TIMS U-Pb data from the Kaapinsalmi tonalite (A28 & A44).

Sample information density	Sample weight/mg	U	Pb	^{206}Pb/^{204}Pb	^{208}Pb/^{206}Pb	Isotopic ratios*						Rho**	Apparent ages / Ma		
		ppm		measured	radiogenic	^{206}Pb/^{238}U	2σ%	^{207}Pb/^{235}U	2σ%	^{207}Pb/^{206}Pb	2σ%		^{206}Pb/^{238}U	^{207}Pb/^{235}U	^{207}Pb/^{206}Pb
A28-Kaapinsalmi tonalite															
A28A. Total (borax)	611.6	345	184	1588	0.168	0.4466	1.3	11.270	1.5	0.1831	0.5	0.94	2380	2546	2681
A28B. +4.6	23.6	270	153	2322	0.194	0.4684	0.7	12.006	0.7	0.1859	0.2	0.96	2476	2604	2706
A28C. 4.2-4.6	21.8	411	220	2158	0.147	0.4565	0.7	11.657	0.7	0.1852	0.2	0.97	2424	2577	2700
A28D. 3.8-4.0	5.9	638	307	2265	0.113	0.4233	0.7	10.757	0.7	0.1843	0.2	0.97	2275	2502	2692
A44-Kaapinsalmi tonalite															
A44A. +4.6/+200	24.2	170	106	12411	0.234	0.5098	0.7	13.131	0.7	0.1868	0.2	0.97	2655	2689	2714
A44B. 4.2-4.6	20.8	240	137	5746	0.210	0.4715	0.7	12.029	0.7	0.1850	0.2	0.97	2490	2606	2698
A44C. Sphene	31.2	57	40	499	0.257	0.5166	0.7	13.318	0.7	0.1870	0.3	0.91	2684	2702	2716

*) Isotopic ratios corrected for fractionation. blank and age related common lead (Stacey and Kramers. 1975).

**) Error correlation for ^{207}Pb/^{235}U vs. ^{206}Pb/^{238}U ratios.

A28A from Kouvo and Tilton (1966)

high MgO, Ni, Cr contents make the Kaapinsalmi sanukitoid a distinct sanukitoid in western part of the Karelian craton. The Rio Maria sanukitoid, located in the Amazonian craton in Brazil (Oliveira et al., 2006), is similar in composition to the Kaapinsalmi sanukitoid.

Current models for the petrogenesis of sanukitoids propose that fluids and/or melts from subducted basaltic slab and possible sediments enriched the overlying mantle wedge. Subsequent melting of the enriched mantle wedge then formed the sanukitoid magmas. Sanukitoids thus might contain material from three different sources: basaltic slab, sediments and mantle wedge (Stern & Hanson, 1991; Kovalenko et al., 2005; Halla, 2005). A probable source of MgO, Ni and Cr is the mantle wedge; and of K_2O, Ba and Sr the slab melts and/or fluids from a crustal component, possibly subducted sediments.

There are two possible explanations for the distinct composition of the Kaapinsalmi type sanukitoid: 1) Less involvement of recycled crust in the petrogenesis of the Kaapinsalmi type sanukitoid. This could explain the lower K_2O, Sr and Ba contents and higher MgO, Ni and Cr content. 2) Heterogeneity in the enrichment of the mantle wedge could also explain the composition of Kaapinsalmi type sanukitoid. If fluids and/or melts from the basaltic slab and possible sediments infiltrated the mantle wedge in an irregular manner, then partial melting of the less enriched parts of the wedge would have caused Kaapinsalmi type sanukitoid magmas. These two explanations are not mutually exclusive and could occur simultaneously.

7. Conclusions

The newly-recognised Kaapinsalmi intrusion has chemical composition similar to sanukitoid. Its age, location and certain compositional similarities indicate that it forms the northern extension of the Western sanukitoid zone of the Karelian craton. However, there are two important geochemical differences between the Kaapinsalmi sanukitoid and with other West Karelian sanukitoids:

1. The Kaapinsalmi sanukitoid has lower SiO_2 and higher MgO, Ni, and Cr contents compared to those of the other west Karelian sanukitoids, indicating that the primary source of the Kaapinsalmi sanukitoid was mantle peridotite.

2. The Kaapinsalmi sanukitoid has relatively low K_2O, Ba, and Sr concentrations. This might indicate smaller recycled crustal sediment component in the source of the Kaapinsalmi sanukitoid than in more felsic sanukitoids and/or mantle heterogeneity.

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