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Growth of Archaean crust in the Kuhmo district, eastern Finland: U–Pb and Sm–Nd isotope constraints on plutonic rocks

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Abstract

Neoarchaean plutonism in the Kuhmo district in eastern Finland, Karelia, includes tonalites, sanukitoids, leucocratic granodiorites, and leucogranites. A U–Pb (SIMS and TIMS) study of zircons and titanites places age constraints on this plutonic activity, and whole-rock Sm–Nd isotopes are used to characterise source variation. U–Pb results indicate that the tonalites were emplaced during at least three separate periods; >2.81, ∼2.78, and 2.76–2.74 Ga. The initial ε_{Nd} values vary from +0.3 to +2.2, and suggest no major involvement of significantly older crust in the genesis of tonalites. The tonalites were followed by 2.74–2.70 Ga (possibly also 2.68 Ga) sanukitoids with initial ε_{Nd} values of −0.7 to 1.2. Close temporal relations between the ∼2.74 Ga tonalites and sanukitoids indicate that their genesis may be linked. Subsequent leucocratic granodiorites and leucogranites were emplaced at 2.70–2.68 Ga and commonly contain inherited zircons. The initial ε_{Nd} values of these granodiorites and granites vary from +1.1 to −3.4, indicative of multiple magma sources. The general decrease in initial ε_{Nd} values with decreasing age demonstrate progressive recycling of pre-existing crust, thus stressing the importance of crustal recycling as a process in forming the leucocratic granitoid rocks. Overall, the Archaean plutonic rocks of the Kuhmo district are temporally similar to those in the adjacent Russian Karelia, suggesting that 2.83–2.68 Ga was one of the most extensive periods of crustal growth throughout the Karelia craton.

Keywords: Archaean; Magmatism; TTG; Sanukitoid; U–Pb; Sm–Nd; Granite

1. Introduction

The first Archaean U–Pb zircon ages from the eastern Finland, Karelia craton (hereinafter Karelia), were published by Kouvo (1958) and initiated an ongoing geochronological program in the area (Fig. 1). The Kuhmo district in eastern Finland is regarded as a classic example of a Neoarchean granite–greenstone terrain and it is an ideal area for studying the temporal relationships and source histories of the plutonic rocks (see Martin, 1989). Moyen et al. (2003) divided Archaean plutonic rocks into six gategories: tonalite–trondhjemite–granodiorite (TTG) association, sanukitoids, Closepet-like plutons, biotite granites, two-mica granites, and peralkaline plutons. Archaean TTGs are often considered to represent partial melts derived from subducted slabs or, alternatively, as the products of partial melting of oceanic plateaus or root zones of volcanic arcs (see Martin et al., 2005; Condie, 2005). Similarly, sanukitoids, so named by Shirey and Hanson (1984), because of their chemical similarity to Japanese Miocene high-Mg andesites (sanukite, cf. Tatsumi and Ishizaka, 1982), are also commonly assigned a subduction-related origin (e.g. Stern and Hanson, 1991; Halla, 2005), although plume-related uplift or delamination and decompression melting have also been invoked (e.g., Stevenson et al., 1999; Whalen

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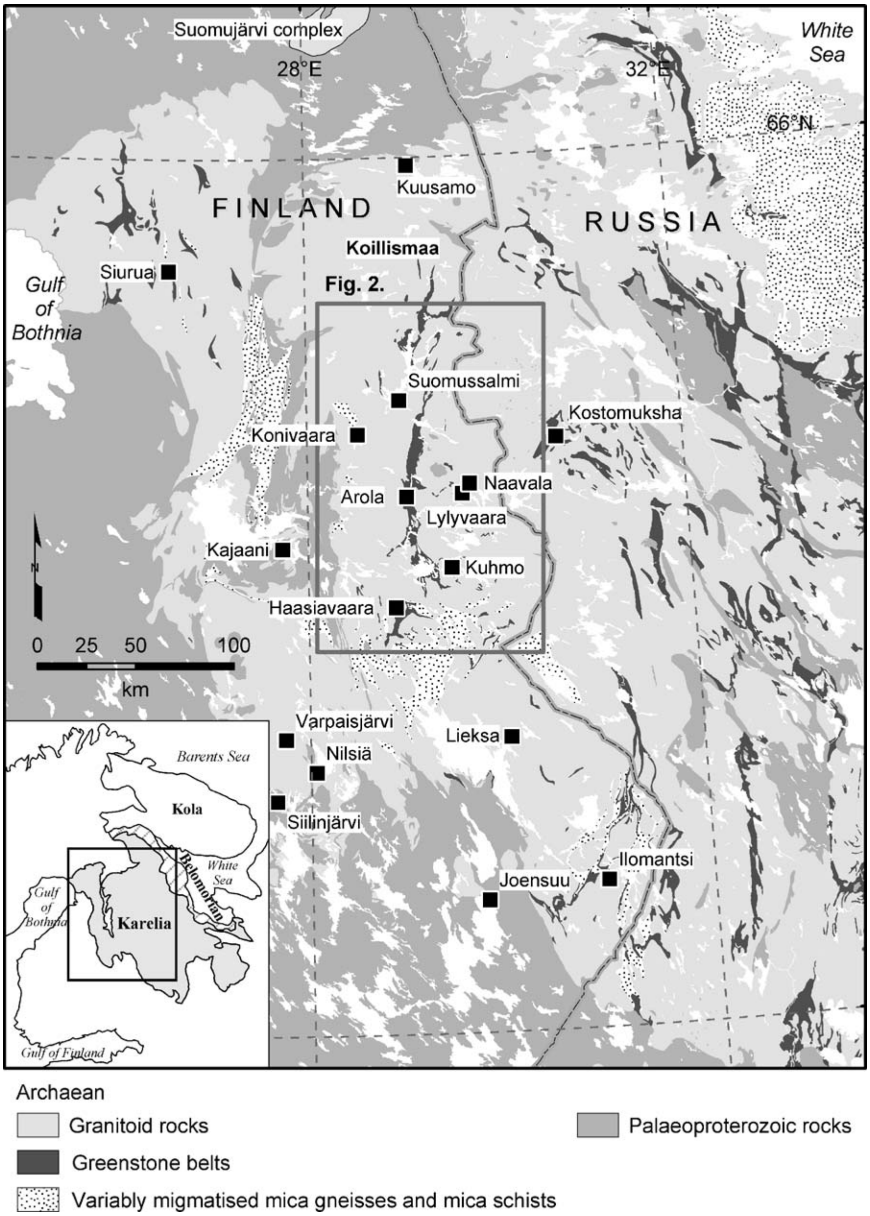

Fig. 1. Generalised bedrock map of the Fennoscandian shield (modified after Koistinen et al., 2001). Key locations and the main municipalities are indicated.

et al., 2004; Kovalenko et al., 2005). According to Shirey and Hanson (1984), the most mafic (primitive) sanukitoids are associated with greater volumes of compositionally more evolved plutons (e.g., granodiorites and monzogranites). In addition to Superior Province, Archean sanukitoids with varying SiO_2 contents are known, e.g. from Australia (Smithies and Champion, 2000), Russia (Lobach-Zhuchenko et al., 2000b; Bibikova et al., 2005; Kovalenko et al., 2005), India (Balakrishnan and Rajamani, 1987), and Finland (Halla, 2002, 2005). In this paper, the term sanukitoid is also assigned to more felsic varieties (e.g., granodiorites) that have a high Mg# (generally over 50), notably elevated Ba and Sr contents, and elevated Ni and Cr compared to TTGs in general (see Le Maitre et al., 2002; Halla, 2005; Kovalenko et al., 2005).

Archaean K-rich granitoids have commonly been interpreted to represent remelting of older crust (e.g., Sylvester, 1994). In the Kuhmo district, the genesis of certain leucogranites (Querré, 1985) and leucocratic granodiorites (Luukkonen, 1988) has been explained in this manner. Moyen et al. (2001, 2003), however, suggested that some Neoarchaean K-rich plutons (in addition to sanukitoids) could be mantle derived and advocated a comprehensive re-evaluation of the origin of K-rich plutons worldwide. Moyen et al. (2001) also proposed that sanukitoid and K-rich granite magmatism share a unique temporal relationship in all Archaean cratons, the latter occurring shortly after the former. Similarly, a genetic link was inferred between the sanukitoid suite and monzogranite-granodiorite magmatism within the central Wabigon Province, Superior Province (Whalen et al., 2004). Furthermore, Moyen et al. (2003) concluded that, because of the close temporal association between TTG magmatism and sanukitoids, a subduction setting is demanded for both. Bibikova et al. (2005), however, indicated that the tonalites from Russian Karelia are ∼60–100 Ma younger than the spatially associated sanukitoids, thus implying a separate origin (or at least melting event) for sanukitoids and tonalites.

In this paper, we present new U–Pb age data (zircon and titanite) on the tonalites, sanukitoids, and K-rich granitoid rocks from the Kuhmo district. By using these data we will discuss the temporal relationship of these plutons in the context of concept outlined above. We will also evaluate the significance of crustal recycling in the Kuhmo district using Nd isotopes. Finally, we compare these results to the other Archaean plutonic suites with special reference to Karelia.

2. Regional geology

The Arcahaean domain in the Fennoscandian Shield is classically divided into Kola province, Belomorian province, and Karelian province (hereinafter Karelia) (Gaál and Gorbatschev, 1987) (Fig. 1). In the north and north-east, Karelia is bordered by Belomorian province (belt), which constitute of Neoarchaean plutonic and supracrustal rocks that have been strongly reworked in the Palaeoproterozoic (Bibikova et al., 1999). Karelia is composed of Archaean greenstone belts, TTG gneisses and migmatites, calc-alkaline plutons, and paragneisses and their migmatitic counterparts (Figs. 1 and 2). In eastern Finland (Karelia), a conspicuous feature in the bedrock is the 200 km long, discontinuous Kuhmo–Suomussalmi greenstone belt. It consists of mafic and ultramafic metavolcanic rocks, felsic pyroclastic rocks, metaconglomerates, metaphyllites, metapelites, quartzites, and banded iron formations (Luukkonen, 1988). Conventional U–Pb zircon ages of felsic volcanic rocks vary from 2966 ± 9 to 2790 ± 3 Ma (Vaasjoki et al., 1999). Two different tectonic settings have been suggested for the Kuhmo–Suomussalmi greenstone belt: a volcanic island-arc setting (Taipale, 1983, 1988; Piirainen, 1988) and a continental rift (Martin et al., 1984; Luukkonen, 1992, 2001).

The Kuhmo–Suomussalmi greenstone belt is surrounded by migmatitic tonalitic gneisses, partially migmatised gneisses of sedimentary origin and discrete TTG, Archaean sanukitoid, and granite plutons (Martin, 1987; Luukkonen, 1992; Kontinen, 1991). In the Kuhmo district, the oldest plutonic TIMS U–Pb multi-grain zircon ages come from the mesosome of a migmatitic tonalitic gneiss at Lylyvaara (Fig. 1) and from tonalite not associated with migmatites, at Haasiavaara (A1086; Fig. 2). These rocks have yielded ages of 2843 ± 18 Ma (Luukkonen, 1985) and 2830 ± 2 Ma (Vaasjoki et al., 1999), respectively. Both these rocks are broadly coeval with the oldest TTG gneisses from the Suomujärvi complex (Fig. 1), which was interpreted by Evins et al. (2002) as the southwestern margin of the Belomorian belt. These TTGs are, however, markedly younger than 3.5 Ga trondhjemite gneisses from Siurua (Fig. 1) situated ∼150 km NW of Kuhmo within the Pudasjärvi granulite belt (Mutanen and Huhma, 2003) and 3.2 Ga migmatite protoliths from the Varpaisjärvi granulites (Hölttä et al., 2000; Mänttäri and Hölttä, 2002), which are the oldest reported rocks in Karelia.

In the Kuhmo district, Martin (1987, 1989) and Martin et al. (1983) divided the TTG gneisses into two groups based on Rb–Sr geochronology: migmatitic Kivijärvi gneisses (3.0–2.8 Ga) and locally migmatised Naavala gneisses (2.69–2.65 Ga). The Kivijärvi data are consistent with U–Pb zircon ages from Lylyvaara, but U–Pb dating on zircon and monazite from Naavala tonalitic gneisses (Fig. 1) give ages of 2752 ± 8 Ma and 2700 ± 2 Ma, respectively (Luukkonen, 2001). Re-equilibration of the Rb–Sr system during younger events is considered as an explanation for the contradictory ages by Halliday et al. (1988) (see also Barbey and Martin, 1987; Vaasjoki, 1988).

The tonalites are temporally followed by the K-feldspar porphyritic Arola granodiorite, which has been dated at 2734 ± 2 Ma (Hyppönen, 1983; A572 in Fig. 2). Nearly concordant titanite fractions give an average age of 2707 Ma, apparently related to metamorphism. This granodiorite is situated at the western margin of the Kuhmo greenstone belt, which is one of the major fault zones in the area (cf. Luukkonen, 1992). The Arola granodiorite shows high Mg#, elevated Ba and Sr contents, and higher contents of Ni and Cr than the preceding tonalites, thus resembling felsic members of Archaean sanukitoid suites (hereinafter sanukitoid) (Table 1; cf. Moyen et al., 2001; Querré, 1985).

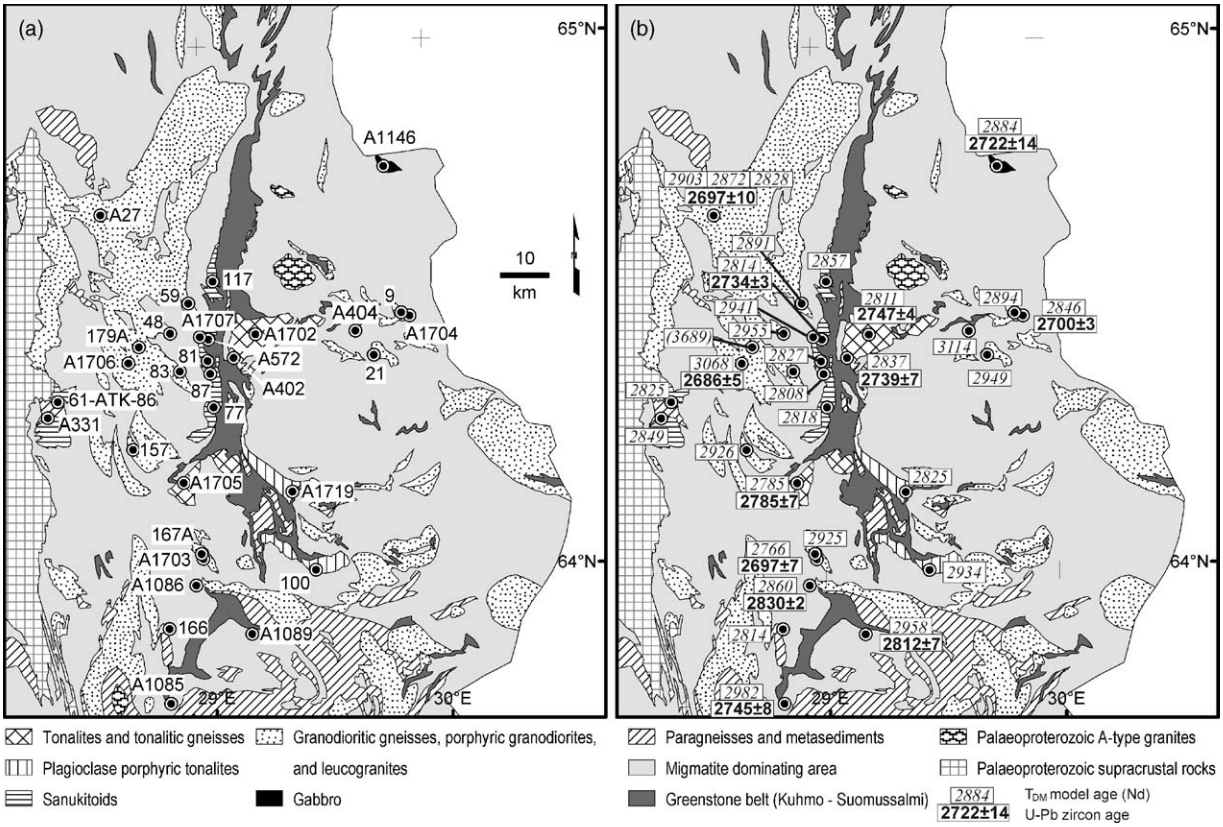

Fig. 2. Bedrock map of the Kuhmo district (modified after Korsman et al., 1997) showing (a) sampling sites (only the last digits are given for AAK-02- samples; see Table 4) and (b) T_{DM} model ages in italics (calculated after DePaolo, 1981) and U–Pb age results ± 2σ errors.

The youngest Archaean plutonic activity reported from Kuhmo district includes the 2697 ± 10 Ma porphyritic granodiorite from Konivaara (sample A27 in Fig. 2; Luukkonen, 1988), and pink, fine-grained leucogranite from Pohjajärvi (Table 1), which has a minimum age of 2600 Ma, determined on the basis of two discordant zircon fractions (Hyppönen, 1983). This granite demonstrably intruded older gneisses, greenstones and the porphyritic Arola granodiorite (Martin and Querré, 1984; Querré, 1985).

The final stage of cratonisation of this area is considered to have taken place ca. 2.67–2.64 Ga (Luukkonen, 1992). A-type granitic plutons and mafic intrusions were subsequently emplaced into the Archaean crust at 2.44 Ga (Luukkonen, 1988; Alapieti, 1982), related to widespread Palaeoproterozoic rifting of Karelia (Huhma et al., 1990; Vuollo, 1994). Thermal overprinting of the Archaean basement at 1.8–1.9 Ga is also demonstrated by Proterozoic K–Ar ages for biotite and hornblende from eastern Finland (Kontinen et al., 1992). Proterozoic deformation of the Archaean rocks appears to be absent at least in the eastern side of the Kuhmo greenstone belt, but in the south, there are documented examples of ductile to semi-brittle deformation zones of Proterozoic age (Pajunen and Putiainen, 1999).

3. Analytical methods

3.1. U–Pb geochronology

Samples weighing 8–15 kg were washed, crushed, washed over a wet concentraing table, and treated with methylene-diodide and Clerici® solutions for separation of the heavy minerals. Non-magnetic heavy fractions were separated with a Frantz isodynamic separator. Zircons and titanites were selected by hand-picking for analyses. Some of the fractions were air-abraded (Krogh, 1982) for TIMS (thermal ionization multicollector mass spectrometer) U–Pb analyses (Table 2). The dissolution of zircons and titanites and extraction of U and Pb for multigrain TIMS analyses mainly followed the procedure described by Krogh (1973). ^{235}U–^{208}Pb-spiked and unspiked isotopic ratios were measured using a VG Sector 54 TIMS in the Geological Survey of Finland, Espoo. The measured lead and uranium isotopic ratios were normalized to the accepted values for SRM 981 and U500

Table 1
Geochemical analyses of rock suites from the Kuhmo district

	Tonalites			High Mg/Fe granitoid rocks – Sanukitoids				Leucocratic granites and granodiorites		
	Average of Haasiavaara tonalite[a]	Viitavaara tonalite[b]	Average of Purnu tonalite[c]	Average of Arola granodiorite[d]	Average of Siikalahti pluton[e]	Loso diorite[f]	Kaartojärvet gabbro[g]	Pohjajärvi leucogranite[h]	Average of leucogranites[i]	Vartius granodiorite[j]
SiO_2	71.27	62.02	70.83	67.62	61.35	53.8	52.90	75.64	75.38	71.85
TiO_2	0.4	0.55	0.37	0.36	0.59	0.76	0.65	0.14	0.12	0.13
Al_2O_3	14.6	16.46	14.87	15.30	15.62	15.8	13.60	12.57	13.43	15.2
Fe_2O_3	3.72	4.68	2.7	2.99	5.07	7.29	7.82	1.02	0.91	0.99
MnO	0.06	0.08	0.04	0.06	0.08	0.12	0.12	0.00	0.02	0.01
MgO	1.22	2.07	1.16	1.68	3.06	6.04	8.56	0.35	0.19	0.43
CaO	3.24	4.6	2.76	2.91	3.63	6.53	7.10	0.55	0.67	1.73
Na_2O	3.92	4.44	4.43	4.77	5.23	4.50	3.36	3.17	3.93	5.08
K_2O	1.71	0.97	1.72	3.10	2.88	2.04	2.59	4.82	4.5	3.19
P_2O_5	0.08	0.12	0.37	0.14	0.26	0.49	0.13	0.04	0.06	0.07
Mg#	39	47	46	53	54	62	68	40	29	46
Ba	432	–	–	1295	1565	999	638	–	620	2212
Rb	50	–	75	93	72	58	116	–	182	53
Sr	220	–	278	694	918	989	397	–	129	1197
Zr	126	–	134	125	136	147	108	–	138	99
Cr	–	–	–	68	124	208	293	–	15	0
Ni	–	–	12	20	27	98	213	–	–	4

$Mg\# = Mg^{2+}/(Mg^{2+} + Fe_{tot}) \times 100$.

[a] Average reported by Horneman (1990).

[b] Analysis no. 21 in Hyppönen (1983).

[c] Average of the Kuusamonkylä grey gneisses from Martin (1987). Sample collected in the vicinity of Purnu dating location.

[d] Average of the analyses G3, G6, G154, G155, G156, G159, G181, G224 in Querré (1985).

[e] Average of analyses G214 and G215 in Querré (1985).

[f] Sample from the Loso intrusion (Käpyaho, unpublished).

[g] Sample from the Kaartojärvet gabbro dating location (Käpyaho, unpublished).

[h] Analysis no. 29 from the Pohjajärvi dating location reported by Hyppönen (1983).

[i] Average of leucogranites reported by Querré (1985).

[j] Analysis no. 83 reported by Luukkonen (2001). Sample collected from the vicinity of Vartius dating sample.

Table 2
TIMS U–Pb isotopic data for zircons and titanites from samples A1089 (Huuskonvaara tonalite) and A1702 (Purnu tonalite), and A1719 (Siikalahti granodiorite)

Sample information	Sample (weight/mg)	U (ppm)	Pb (ppm)	$^{206}Pb/^{204}Pb$ (measured)	Isotopic ratios[a,b]			Apparent ages (Ma) ± 2σ		
					$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
A1089 Huuskonvaara tonalite										
(D) Zr $\rho > 4.5\ g\ cm^{-3}$, long prismatic, transparent, abraded 16 h	0.26	153	92	1545	0.5216	14.180	0.1972	2706	2762	2803
(E) Zr $\rho > 4.5\ g\ cm^{-3}$, long prismatic, transparent	0.26	178	99	786	0.4755	12.684	0.1935	2508	2657	2772
A1702 Purnu tonalite										
(A) titanite, abraded 20 min	1.95	167	113	417	0.5238	13.507	0.1870	2715	2716	2716
A1719 Siikalahti granodiorite										
(A) Zr $\rho > 4.3\ g\ cm^{-3}$, <75 μm, long prismatic, transparent, abraded 3 h	0.17	414	216	2703	0.4678	11.689	0.1812	2474	2580	2664
(B) Zr $\rho > 4.3\ g\ cm^{-3}$, <75 μm, prismatic, transparent	0.28	469	233	2164	0.4436	11.015	0.18011	2367	2524	2654
(C) zr $\rho > 4.3\ g\ cm^{-3}$, >75 μm, traslucent, short prismatic, abraded 24 h	0.28	563	302	2031	0.4734	11.891	0.18218	2498	2596	2673
(D) Zr $\rho = 4.2–3.6\ g\ cm^{-3}$, prismatic, translucent, abraded 2 h	0.16	540	259	2371	0.4283	10.543	0.1785	2298	2484	2639

Zr: zircon.

[a] Isotopic ratios corrected for fractionation, blank (50 pg), and age related common lead (Stacey and Kramers, 1975; $^{206}Pb/^{204}Pb \pm 0.2$; $^{207}Pb/^{204}Pb \pm 0.1$; $^{208}Pb/^{204}Pb \pm 0.2$).

[b] 2σ errors for Pb/U ratios are 0.65% and for $^{207}Pb/^{206}Pb$ ratios 0.15%. Error correlation between $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ ratios are 0.97.

standards. The U–Pb age calculations were done using the PbDat-program (Ludwig, 1991) and the fitting of the discordia lines was performed using the Isoplot/Ex program 3.0 (Ludwig, 2003). See Table 2 for further details.

Secondary ion mass spectrometry (SIMS) U–Pb analyses of zircons from seven samples were performed on the Nordic Cameca IMS 1270 at the Swedish Museum of Natural History, Stockholm (NORDSIM facility). The spot diameter for the 4 nA primary O_2^- ion beam was 30 μm and oxygen flooding in the sample chamber was used to increase the production of Pb^+ ions. Three counting blocks, each including four cycles of the Zr, Pb, Th, and U species of interest, were measured from each spot. The mass resolution ($M/\Delta M$) was 5400 (10%). The raw data were calibrated against a zircon standard (91500; Wiedenbeck et al., 1995) and corrected for modern common lead ($T = 0$; Stacey and Kramers, 1975). For the detailed analytical procedure see Whitehouse et al. (1997, 1999). All the age errors reported in the text and figures are at 2σ confidence level.

3.2. Sm–Nd isotope geochemistry

For whole-rock Sm–Nd analysis, 150–200 mg of powdered sample was spiked with a ^{149}Sm–^{150}Nd tracer. The sample-spike mixture was dissolved in HF-HNO_3 in sealed Teflon bombs for 48 h at 180 °C. Prior to dissolving the residue in 6.2 N HCl, the fluorides were evaporated using HNO_3. Conventional cation exchange chromatography was used for separation of the light rare earth elements, while Sm and Nd were separated by Teflon-HDEHP (hydrogen di-ethylhexyl phospate) method modified from Richard et al. (1976). Total procedural blank was <0.5 ng for Nd. Isotope ratios were measured on a VG Sector 54 TIMS using Ta–Re triple filaments. Nd isotope ratios were measured in dynamic mode and Sm isotopes in static mode. Based on the duplicate analyses, the accuracy of the ^{147}Sm/^{144}Nd is estimated to be better than 0.4%. Average ^{143}Nd/^{144}Nd for the La Jolla standard is 0.511850 ± 0.000008 (standard deviation for 105 measurements during years 1995–2003). The ε_{Nd} was calculated using $\lambda^{147}\mathrm{Sm} = 6.54 \times 10^{-12}\ \mathrm{a}^{-1}$, $^{147}\mathrm{Sm}/^{144}\mathrm{Nd} = 0.1966$, and $^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.512640$ for the present CHUR. T_{DM} was calculated according to DePaolo (1981).

4. U–Pb geochronology: samples and results

In order to establish the age distribution of the main plutonic phases we sampled two tonalites (A1702 and A1705), two leucocratic granodiorites (A1704 and A1706), two leucogranites (A1707 and A1703), and one granodiorite with Archaean sanukitoid affinity (A1719; Siikalahti in Table 1). For sample locations see Fig. 2. These samples were dated by SIMS (Table 3). Two additional zircon fractions previously analysed from the Huuskonvaara tonalite (A1089; Vaasjoki et al., 1999), four zircon fractions from A1719, and one titanite fraction from A1702 were dated by the multi-grain TIMS method (Table 2). Average major element compositions and some representative analyses of these plutons are reported in Table 1.

4.1. Tonalite (A1089) – Huuskonvaara

Three previously dated zircon fractions yield an upper intercept age of 2808 ± 14 Ma for the Huuskonvaara biotite tonalite (Vaasjoki et al., 1999). In order to better constrain the upper intercept age, two additional zircon fractions were analysed (Table 2; Fig. 3). The zircons were long prismatic, transparent and slightly brown. A discordia line drawn through all five fractions gives an upper intercept age of 2813 ± 8 Ma (MSWD = 4.2); and if the, most discordant fraction C comprising zircons from the lightest density fraction is excluded, the upper intercept age is 2814 ± 3 Ma (MSWD = 1.3). This is interpreted as the emplacement age of the pluton.

4.2. Tonalite (A1705) – Viitavaara

The Viitavaara tonalite (45% quartz, 30% plagioclase, 1% microcline, 5% hornblende and 15 % biotite with accessory epidote, apatite, and zircon) is medium-grained, plagioclase–phyric, and contains a northwest-

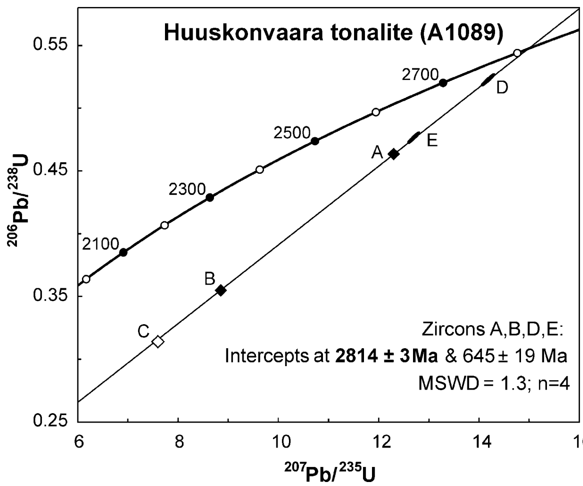

Fig. 3. Concordia diagram showing zircon U–Pb isotopic data for the Huuskonvaara tonalite. Zircon fractions A, B, and C are from Vaasjoki et al., 1999 and E and D are from this study. See text for details. Error ellipses are at 2σ.

Table 3
SIMS U–Pb age data for zircons

Sample/ spot #	Spot site[a] (Zircon type)	Derived ages						Corrected ratios						r	Disc. % 2s lim.	Elemental data				
		$^{207}Pb/^{206}Pb$	±s	$^{207}Pb/^{235}U$	±s	$^{206}Pb/^{238}U$	±s	$^{207}Pb/^{206}Pb$	±s (%)	$^{207}Pb/^{235}U$	±s (%)	$^{206}Pb/^{238}U$	±s (%)			[U] (ppm)	[Th] (ppm)	[Pb] (ppm)	$^{206}Pb/^{204}Pb$ (measured)	Th/U (measured)
A1705 Viitavaara tonalite (n1208)																				
01ab	Zoned (short prismatic)	2794	7	2755	22	2703	51	0.1961	0.41	14.08	2.3	0.5208	2.3	0.98		93	35	63	3.44E+04	0.38
02a	Zoned (short prismatic)	2785	6	2746	22	2693	51	0.1950	0.38	13.94	2.3	0.5186	2.3	0.99		108	38	72	7.27E+04	0.35
03a	Zoned (short prismatic)	2764	11	2750	23	2731	51	0.1925	0.70	14.00	2.4	0.5275	2.3	0.96		104	51	72	1.80E+04	0.49
04a	Zoned (prismatic)	2768	10	2783	23	2803	53	0.1931	0.60	14.50	2.4	0.5448	2.3	0.97		138	87	102	2.03E+03	0.63
05a	Zoned (long prismatic)	2779	8	2752	23	2715	51	0.1943	0.51	14.03	2.4	0.5237	2.3	0.98		147	71	102	1.50E+04	0.48
06a	Zoned (long prismatic)	2773	8	2748	23	2713	51	0.1936	0.49	13.97	2.4	0.5233	2.3	0.98		154	72	106	7.87E+03	0.47
07a	Unclear zoning (long prismatic)	2780	9	2780	23	2779	52	0.1945	0.58	14.45	2.4	0.5390	2.3	0.97		107	87	81	1.34E+04	0.81
08a	Zoned (prismatic)	2797	12	2770	23	2732	52	0.1965	0.73	14.30	2.4	0.5278	2.3	0.95		69	52	51	3.04E+04	0.75
09a	Zoned (prismatic)	2809	10	2771	23	2719	51	0.1979	0.63	14.32	2.4	0.5246	2.3	0.97		96	58	68	>1E6	0.60
10a	Zoned (short prismatic)	2801	7	2778	23	2747	52	0.1970	0.45	14.43	2.4	0.5314	2.3	0.98		189	100	134	2.37E+04	0.53
11a	Unclear zoning (long prismatic)	2801	16	2777	24	2744	52	0.1969	0.98	14.40	2.5	0.5305	2.3	0.92		34	19	24	2.54E+04	0.55
A1702 Purnu tonalite (n1207)																				
01a	Zoned (short prismatic)	2741	5	2717	46	2685	104	0.1899	0.31	13.53	4.7	0.5168	4.7	1.00		310	138	207	2.94E+03	0.44
02a	Zoned (prismatic)	2751	5	2760	22	2774	52	0.1910	0.33	14.16	2.3	0.5377	2.3	0.99		272	215	204	1.91E+04	0.79
03a	Zoned (prismatic)	2756	6	2913	46	3145	118	0.1917	0.35	16.62	4.7	0.6289	4.7	1.00	6.7	411	168	337	2.27E+04	0.41
04a	Zoned (long prismatic)	2752	5	2881	46	3070	116	0.1911	0.32	16.08	4.7	0.6101	4.7	1.00	3.7	356	274	301	2.40E+03	0.77
05a	Homog rim (prismatic)	2713	5	2672	45	2618	102	0.1866	0.33	12.89	4.7	0.5009	4.7	1.00		317	72	197	9.68E+03	0.23
05b	Weakly zoned inner domain (prismatic)	2762	6	2751	46	2736	106	0.1923	0.35	14.02	4.7	0.5287	4.7	1.00		374	288	275	3.89E+03	0.77
06a	Zoned (long prismatic)	2752	6	2736	46	2713	105	0.1912	0.34	13.79	4.7	0.5234	4.7	1.00		226	105	156	6.06E+03	0.46
07a	Zoned (short prismatic)	2745	4	2693	45	2624	102	0.1903	0.26	13.19	4.7	0.5024	4.7	1.00		270	100	175	1.10E+04	0.37
08a	Zoned (short prismatic)	2745	4	2692	45	2623	102	0.1903	0.26	13.18	4.7	0.5021	4.7	1.00		261	124	173	3.09E+04	0.48
09a	Zoned (short prismatic)	2742	3	2793	46	2864	110	0.1900	0.21	14.66	4.7	0.5594	4.7	1.00		563	369	428	1.10E+04	0.66
10a	Homog (rounded, metam?)	2755	7	2850	46	2987	113	0.1915	0.43	15.56	4.7	0.5895	4.7	1.00	0.0	120	70	94	9.21E+03	0.58
11a	Homog (rounded, metam?)	2737	8	2753	46	2776	107	0.1893	0.50	14.05	4.7	0.5382	4.7	0.99		178	79	125	4.11E+03	0.45
12a	Zoned (long prismatic)	2746	5	2661	45	2550	100	0.1905	0.28	12.74	4.7	0.4852	4.7	1.00		445	169	277	3.50E+03	0.38
A1704 Vartius granodiorite (n1210)																				
01a	Quite homog-weakly zoned outer domain (prismatic)	2699	4	2662	22	2614	50	0.1851	0.25	12.76	2.3	0.5000	2.3	0.99		70	20	44	6.01E+03	0.28
02a	Weakly zoned (prismatic)	2705	5	2669	18	2622	39	0.1858	0.33	12.86	1.8	0.5019	1.8	0.98	0.0	387	100	244	3.18E+03	0.26
03a	Quite homog (prismatic)	2701	5	2684	17	2660	40	0.1854	0.30	13.06	1.8	0.5109	1.8	0.99		587	206	383	2.35E+04	0.35
04a	Quite homog outer domain (prismatic)	2678	5	2662	18	2640	40	0.1828	0.32	12.76	1.9	0.5062	1.8	0.99		384	135	248	7.98E+03	0.35
04b	Weakly zoned inner domain (prismatic)	2702	7	2674	18	2638	39	0.1854	0.40	12.93	1.8	0.5057	1.8	0.98		558	219	363	2.88E+03	0.39
05a	Weakly zoned (short prismatic)	2693	6	2794	18	2935	43	0.1845	0.37	14.67	1.8	0.5768	1.8	0.98	6.9	333	96	242	2.00E+03	0.29
06a	Weakly zoned (rounded)	2686	4	2648	17	2600	39	0.1836	0.22	12.58	1.8	0.4967	1.8	0.99	−0.3	718	203	449	5.91E+03	0.28
07a	Weakly zoned, dark (prismatic)	2713	8	2707	19	2699	43	0.1866	0.47	13.38	2.0	0.5200	1.9	0.97		167	44	108	2.03E+03	0.26
08a	Weakly zoned-homog (prismatic)	2728	3	2705	17	2674	39	0.1883	0.20	13.35	1.8	0.5142	1.8	0.99		571	244	383	4.59E+04	0.43
09a	Zoned (prismatic)	2741	4	2715	17	2680	39	0.1899	0.27	13.50	1.8	0.5154	1.8	0.99		399	129	262	2.41E+04	0.32
10a	Quite homog (prismatic)	2701	4	2669	17	2626	39	0.1854	0.26	12.85	1.8	0.5029	1.8	0.99		362	101	229	1.34E+04	0.28
11a	Zoned, dark (prismatic)	2767	16	2722	20	2661	40	0.1929	0.99	13.59	2.1	0.5109	1.8	0.88		25	1	15	7.72E+03	0.06
12a	Homog (equidimensional)	2704	6	2673	17	2631	39	0.1857	0.34	12.90	1.8	0.5040	1.8	0.98		371	146	241	4.55E+03	0.39
13a	Homog (short prismatic)	2694	4	2676	17	2652	39	0.1845	0.26	12.95	1.8	0.5089	1.8	0.99		594	186	384	2.33E+04	0.31
14a	Quite homog (equidimensional)	2700	4	2698	17	2694	39	0.1853	0.27	13.25	1.8	0.5187	1.8	0.99		309	171	214	3.49E+04	0.55

16a	Homog-wide zone (prismatic)	2698	3	2686	17	2670	39	0.1850	0.20	13.09	1.8	0.5131	1.8	0.99		684	197	443	1.51E+04	0.29
17a	Homog-wide zone (prismatic)	2705	5	2644	17	2565	38	0.1858	0.30	12.52	1.8	0.4888	1.8	0.99	−2.7	335	111	208	2.69E+03	0.33
19a	Quite homogeneous (prismatic)	2675	5	2647	17	2609	38	0.1824	0.27	12.55	1.8	0.4990	1.8	0.99		551	189	351	2.80E+04	0.34
20a	Weakly zoned (prismatic)	2696	4	2645	17	2579	38	0.1847	0.23	12.53	1.8	0.4918	1.8	0.99	−1.8	685	198	426	1.87E+04	0.29
Data ignored due to low $^{206}Pb/^{204}Pb$ and/or high discordance																				
01b	Inner domain (prismatic)	2690	10	2550	18	2378	35	0.1841	0.58	11.32	1.9	0.4460	1.8	0.95	−10.1	382	100	212	9.56E+02	0.26
15a	Quite homog rim, dark (prismatic)	2666	8	2244	17	1811	28	0.1814	0.50	8.113	1.9	0.3243	1.8	0.96	−33.7	411	99	167	7.34E+02	0.24
18a	Zoned (prismatic)	2688	19	2604	20	2497	37	0.1838	1.2	11.99	2.1	0.4730	1.8	0.83	−2.9	239	36	136	6.83E+02	0.15
A1703 Katajavaara granite (n1209)																				
03a	Zoned (short prismatic)	2679	4	2646	22	2602	50	0.1829	0.23	12.54	2.3	0.4973	2.3	1.00		522	85	320	4.91E+03	0.16
04a	Homog rim-vide zone (short prismatic)	2628	2	2592	22	2547	49	0.1773	0.14	11.84	2.3	0.4844	2.3	1.00		1263	138	740	5.06E+04	0.11
05a	Zoned (prismatic)	2759	7	2696	22	2612	50	0.1920	0.43	13.22	2.3	0.4996	2.3	0.98	−1.9	195	91	129	3.81E+03	0.47
06a	Homog outer zone (long prismatic)	2699	3	2642	22	2569	49	0.1851	0.20	12.49	2.3	0.4895	2.3	1.00	−1.5	588	12	343	2.74E+04	0.02
12a	Homog (?)	2699	6	2790	17	2918	42	0.1851	0.37	14.61	1.8	0.5725	1.8	0.98	5.9	165	86	126	3.31E+04	0.52
13a	Weakly zoned (prismatic)	2690	9	2656	18	2612	38	0.1840	0.54	12.68	1.9	0.4996	1.8	0.96		91	49	61	1.72E+04	0.53
14a	Zoned (prismatic)	2711	4	2682	17	2643	39	0.1864	0.24	13.03	1.8	0.5069	1.8	0.99		461	132	296	4.25E+04	0.29
15a	Homog inner domain/wide zone(short prismatic)	2710	7	2668	18	2613	39	0.1863	0.45	12.84	1.9	0.4998	1.8	0.97	−0.5	148	120	105	2.53E+03	0.81
16a	Weakly zoned inner domain (prismatic)	2707	3	2670	17	2622	39	0.1860	0.18	12.87	1.8	0.5020	1.8	0.99	−0.3	719	522	500	1.33E+04	0.73
17a	Weakly zoned inner domain (bipyramidal)	2701	5	2646	17	2576	38	0.1853	0.31	12.55	1.8	0.4912	1.8	0.99	−2.0	227	144	152	1.84E+04	0.63
18a	Homog/weakly zoned (?)	2693	4	2700	17	2710	40	0.1844	0.26	13.28	1.8	0.5224	1.8	0.99		576	141	377	2.59E+04	0.25
19a	Zoned inner domain (prismatic)	2689	2	2790	17	2933	42	0.1839	0.15	14.61	1.8	0.5761	1.8	1.00	7.3	947	932	795	4.05E+04	0.98
20b	Homog outer domain (anhedral)	2654	2	2615	17	2563	38	0.1802	0.15	12.13	1.8	0.4883	1.8	1.00	−0.7	1114	78	652	1.94E+04	0.07
02a	Zoned outer domain (short prismatic)	2696	3	2566	22	2405	46	0.1847	0.18	11.52	2.3	0.4523	2.3	1.00	−8.8	982	427	585	3.19E+03	0.43
11a	Homog outer domain (short prismatic)	2651	3	2510	22	2340	45	0.1798	0.18	10.85	2.3	0.4375	2.3	1.00	−10.0	1001	71	525	5.49E+03	0.07
Data ignored due to low $^{206}Pb/^{204}Pb$ and/or high discordance																				
20a	Homog rim, altered (anhedral)	2029	18	1541	17	1211	20	0.1250	1.0	3.562	2.1	0.2066	1.8	0.87	−39.1	1462	105	373	2.59E+02	0.07
10a	Zoned (prismatic)	2470	15	1685	21	1129	24	0.1613	0.87	4.256	2.5	0.1914	2.4	0.94	−54.8	1383	520	380	1.81E+02	0.38
07a	Inner zone (prismatic)	2640	7	2429	22	2184	43	0.1787	0.41	9.934	2.3	0.4033	2.3	0.98	−16.3	366	60	182	1.23E+03	0.16
08a	Zoned inner domain (prismatic)	2680	7	2441	22	2164	42	0.1829	0.44	10.06	2.3	0.3990	2.3	0.98	−18.6	308	122	160	3.03E+03	0.40
09a	Homog outer domain (bipyramidal)	2590	4	2357	21	2098	41	0.1734	0.27	9.193	2.3	0.3846	2.3	0.99	−18.5	1180	150	551	3.20E+03	0.13
01a	Weakly zoned (prismatic)	2673	13	2643	23	2604	50	0.1822	0.81	12.50	2.5	0.4978	2.3	0.94		278	248	205	4.50E+02	0.89
A1706 Pieni Tuomaanjärvi (n1279)																				
02a	Zoned (long prismatic)	2708	2	2732	17	2764	41	0.1861	0.15	13.74	1.8	0.5354	1.8	1.00		1136	764	833	7.58E+04	0.67
03a	Homog outer domain (elongated)	2647	5	2625	17	2596	39	0.1794	0.27	12.26	1.8	0.4958	1.8	0.99		505	168	319	2.14E+04	0.33
04a	Zoned (prismatic)	2688	3	2659	17	2622	39	0.1838	0.21	12.72	1.8	0.5018	1.8	0.99		1142	781	775	5.30E+04	0.68
05a	Homog inner domain (prismatic)	2679	3	2668	17	2653	39	0.1829	0.19	12.84	1.8	0.5092	1.8	0.99		903	1271	721	8.83E+04	1.41
07a	Weakly zoned (short prismatic)	2690	3	2648	17	2594	38	0.1841	0.19	12.57	1.8	0.4954	1.8	0.99	−0.8	827	162	507	1.06E+05	0.20

Table 3 (*Continued*)

Sample/ spot #	Spot site[a] (Zircon type)	Derived ages						Corrected ratios						r	Disc. % 2s lim.	Elemental data				
		$^{207}Pb/^{206}Pb$	±s	$^{207}Pb/^{235}U$	±s	$^{206}Pb/^{238}U$	±s	$^{207}Pb/^{206}Pb$	±s (%)	$^{207}Pb/^{235}U$	±s (%)	$^{206}Pb/^{238}U$	±s (%)			[U] (ppm)	[Th] (ppm)	[Pb] (ppm)	$^{206}Pb/^{204}Pb$ (measured)	Th/U (measured)
08a	Weakly zoned inner domain (prismatic)	2697	4	2605	17	2488	37	0.1849	0.25	12.01	1.8	0.4711	1.8	0.99	−5.9	587	434	385	1.39E+04	0.74
09a	Zoned (long prismatic)	2802	9	2712	18	2592	38	0.1971	0.58	13.45	1.9	0.4949	1.8	0.95	−5.2	132	80	89	1.26E+03	0.61
10a	Unclear zoning (short prismatic)	2675	3	2629	17	2568	38	0.1825	0.16	12.31	1.8	0.4895	1.8	1.00	−1.4	1175	125	697	2.11E+05	0.11
11a	Zoned (long prismatic)	2668	6	2492	17	2282	34	0.1816	0.39	10.64	1.8	0.4248	1.8	0.98	−13.8	420	273	240	3.78E+03	0.65
12a	Homog inner domain (short prismatic)	2700	6	2678	17	2649	39	0.1852	0.36	12.98	1.8	0.5083	1.8	0.98		319	216	223	1.07E+05	0.68
13a	Quite homog (short prismatic)	2700	10	2764	19	2851	42	0.1852	0.63	14.21	1.9	0.5562	1.8	0.95	2.2	67	84	57	2.82E+04	1.25
16a	Homog/weakly zoned outer domain (prismatic)	2687	4	2680	17	2671	40	0.1838	0.23	13.01	1.8	0.5134	1.8	0.99		788	80	490	9.27E+04	0.10
17a	Zoned (prismatic)	2768	4	2729	17	2676	40	0.1930	0.24	13.69	1.8	0.5146	1.8	0.99	−0.5	398	345	294	7.99E+03	0.87
18a	Weakly zoned (lomg prismatic)	2683	4	2643	17	2592	38	0.1833	0.24	12.51	1.8	0.4949	1.8	0.99	−0.6	438	106	272	4.98E+04	0.24
19a	Weakly zoned inner domain (prismatic)	2698	4	2638	17	2560	38	0.1850	0.24	12.43	1.8	0.4875	1.8	0.99	−2.7	833	394	532	7.72E+03	0.47
20a	Zoned (prismatic)	2693	2	2610	17	2503	37	0.1844	0.14	12.07	1.8	0.4745	1.8	1.00	−5.2	1628	1232	1072	2.64E+04	0.76
Data ignored due to low $^{206}Pb/^{204}Pb$ and/or high discordance																				
16b	*Homog inner domain, dark (prismatic)*	*2532*	*20*	*2259*	*20*	*1970*	*30*	*0.1674*	*1.2*	*8.252*	*2.2*	*0.3575*	*1.8*	*0.83*	*−20.2*	*85*	*78*	*45*	*1.22E+03*	*0.92*
01a	*Zoned (prismatic, slightly altered)*	*2645*	*6*	*2482*	*17*	*2289*	*35*	*0.1791*	*0.39*	*10.53*	*1.8*	*0.4263*	*1.8*	*0.98*	*−12.5*	*645*	*283*	*355*	*4.59E+02*	*0.44*
06a	*Zoned (prismatic)*	*2631*	*85*	*2249*	*57*	*1853*	*49*	*0.1777*	*5.3*	*8.161*	*6.1*	*0.3331*	*3.1*	*0.50*	*−13.3*	*416*	*275*	*180*	*2.81E+02*	*0.66*
14a	*Zoned inner domain (short prismatic)*	*2619*	*3*	*2318*	*17*	*1991*	*31*	*0.1764*	*0.20*	*8.803*	*1.8*	*0.3619*	*1.8*	*0.99*	*−25.1*	*904*	*505*	*438*	*6.19E+03*	*0.56*
15a	*Zoned, few altered zones (prismatic)*	*2530*	*6*	*1523*	*14*	*907*	*15*	*0.1672*	*0.35*	*3.483*	*1.8*	*0.1510*	*1.8*	*0.98*	*−66.7*	*1165*	*240*	*220*	*1.35E+03*	*0.21*
A1707 Pohjanjärvi (n1278 and n1489)																				
1-03a	Weakly zoned (short prismatic)	2761	5	2753	18	2742	41	0.1922	0.28	14.05	1.8	0.5301	1.8	0.99		364	176	255	7.19E+03	0.48
1-01a	Weakly zoned (short prismatic)	2752	4	2747	17	2740	41	0.1911	0.25	13.96	1.8	0.5297	1.8	0.99		478	339	351	6.73E+03	0.71
2-04a	Weakly zoned (prismatic)	2751	5	2741	18	2728	42	0.1911	0.33	13.87	1.9	0.5267	1.9	0.984		207	105	145	9.79E+03	0.51
1-12a	Weakly zoned (short prismatic)	2750	6	2777	18	2815	42	0.1909	0.36	14.41	1.9	0.5475	1.8	0.98		326	148	235	9.50E+03	0.45
1-05a	Zoned (short prismatic)	2741	6	2693	18	2629	39	0.1899	0.34	13.18	1.9	0.5036	1.8	0.98	−1.3	374	330	257	4.29E+03	0.88
1-02a	Weakly zoned (prismatic)	2732	9	2719	20	2700	44	0.1888	0.56	13.55	2.1	0.5203	2.0	0.96		274	152	188	9.21E+02	0.56
1-06a	Zoned (prismatic)	2732	4	2711	17	2683	40	0.1888	0.25	13.44	1.8	0.5163	1.8	0.99		484	274	335	8.88E+03	0.57
1-16a	Quite homog/edges zoned (prismatic)	2724	4	2687	17	2637	39	0.1879	0.24	13.10	1.8	0.5055	1.8	0.99	−0.3	419	249	287	5.06E+04	0.59
2-07a	Weakly zoned (elongated)	2718	3	2677	18	2625	40	0.1872	0.16	12.97	1.9	0.5025	1.9	0.996	−0.5	1037	1097	772	1.78E+04	1.06
2-05a	Weakly zoned (prismatic)	2713	3	2721	18	2733	42	0.1866	0.18	13.58	1.9	0.5279	1.9	0.995		797	883	626	4.68E+03	1.11
2-10a	Zoned (long prismatic)	2710	5	2681	18	2642	40	0.1863	0.32	13.01	1.9	0.5065	1.9	0.986		603	571	422	1.04E+03	0.95
2-03a	Weakly zoned (short prismatic)	2701	5	2640	18	2561	39	0.1853	0.29	12.46	1.9	0.4878	1.9	0.988	−2.6	430	341	294	2.70E+03	0.79
1-08b	Homog outer domain (elongated)	2699	5	2793	18	2926	43	0.1851	0.28	14.66	1.8	0.5744	1.8	0.99	6.3	391	127	287	1.26E+04	0.32
1-08a	Homog inner domain (elongated)	2696	5	2633	17	2551	38	0.1848	0.31	12.37	1.8	0.4854	1.8	0.99	−2.9	536	220	336	2.53E+03	0.41
1-07a	Weakly zoned (short prismatic)	2692	4	2681	17	2665	40	0.1843	0.24	13.02	1.8	0.5121	1.8	0.99		640	503	456	1.16E+04	0.79

1-09a	Homog (short prismatic)	2684	5	2646	18	2597	39	0.1834	0.33	12.54	1.8	0.4961	1.8	0.98	−0.2	362	124	227	2.75E+03	0.34
1-15a	Zoned (short prismatic)	2657	5	2610	17	2550	38	0.1804	0.30	12.07	1.8	0.4851	1.8	0.99	−1.3	665	486	447	9.75E+03	0.73
Data ignored due to low $^{206}Pb/^{204}Pb$ and/or high discordance																				
1-04a	*Zoned (short prismatic)*	*2738*	*15*	*2397*	*19*	*2018*	*31*	*0.1895*	*0.93*	*9.603*	*2.0*	*0.3675*	*1.8*	*0.89*	*−26.2*	*331*	*343*	*167*	*6.30E+02*	*1.04*
1-11a	*Weakly zoned inner domain (prismatic)*	*2749*	*9*	*2590*	*18*	*2391*	*36*	*0.1908*	*0.57*	*11.81*	*1.9*	*0.4490*	*1.8*	*0.95*	*−11.8*	*300*	*184*	*181*	*1.78E+03*	*0.61*
2-02a	*Zoned (prismatic)*	*2647*	*5*	*2382*	*17*	*2085*	*33*	*0.1794*	*0.31*	*9.443*	*1.9*	*0.3818*	*1.9*	*0.99*	*−21.8*	*450*	*892*	*251*	*2.00E+03*	*1.98*
2-06a	*Weakly zoned (long prismatic)*	*2685*	*12*	*2319*	*18*	*1927*	*31*	*0.1835*	*0.73*	*8.815*	*2.0*	*0.3484*	*1.9*	*0.93*	*−28.8*	*305*	*261*	*140*	*6.26E+02*	*0.85*
2-08a	*Zoned (prismatic)*	*2524*	*12*	*2198*	*18*	*1867*	*30*	*0.1666*	*0.71*	*7.716*	*2.0*	*0.3359*	*1.9*	*0.93*	*−26.1*	*445*	*1177*	*207*	*2.34E+02*	*2.64*
2-09a	*Zoned (elongated)*	*2594*	*15*	*2449*	*19*	*2278*	*36*	*0.1738*	*0.92*	*10.15*	*2.1*	*0.4238*	*1.9*	*0.9*	*−9.6*	*227*	*297*	*133*	*1.69E+02*	*1.31*
2-11a	*Zoned (prismatic)*	*2604*	*5*	*2026*	*17*	*1509*	*25*	*0.1748*	*0.29*	*6.358*	*1.9*	*0.2637*	*1.9*	*0.99*	*−44.7*	*544*	*913*	*193*	*8.99E+03*	*1.68*
2-12a	*Zoned, partly re-crystallized? (prismatic)*	*2637*	*14*	*2488*	*19*	*2310*	*36*	*0.1783*	*0.83*	*10.60*	*2.0*	*0.4311*	*1.9*	*0.91*	*−10.1*	*170*	*599*	*100*	*2.97E+02*	*3.53*
2-13a	*Zoned (prismatic)*	*2440*	*61*	*831*	*24*	*363*	*7*	*0.1585*	*3.7*	*1.267*	*4.1*	*0.0580*	*1.9*	*0.46*	*−69.8*	*2003*	*2710*	*174*	*4.33E+01*	*1.35*
2-14a	*Zoned (prismatic)*	*2568*	*11*	*1990*	*18*	*1483*	*25*	*0.1711*	*0.68*	*6.101*	*2.0*	*0.2587*	*1.9*	*0.94*	*−43.7*	*424*	*1690*	*156*	*4.08E+02*	*3.99*
1-10a	*Zoned (prismatic)*	*2765*	*15*	*2862*	*20*	*3001*	*45*	*0.1927*	*0.92*	*15.75*	*2.1*	*0.5928*	*1.9*	*0.90*	*5.0*	*111*	*60*	*87*	*2.95E+02*	*0.54*
1-13a	*Weakly zoned (prismatic)*	*2776*	*15*	*2717*	*19*	*2638*	*40*	*0.1940*	*0.89*	*13.52*	*2.0*	*0.5056*	*1.8*	*0.90*	*−1.2*	*190*	*141*	*135*	*3.65E+02*	*0.74*
2-01a	*Zoned? (elongated)*	*2672*	*25*	*2640*	*23*	*2598*	*40*	*0.1821*	*1.5*	*12.46*	*2.4*	*0.4964*	*1.9*	*0.78*		*168*	*371*	*114*	*9.06E+01*	*2.21*
A1719 Siikalahti (n1488)																				
01a	Weakly zoned (prismatic)	2635	3	2632	18	2627	40	0.1781	0.18	12.35	1.9	0.5031	1.9	1.00		811	272	517	2.50E+04	0.34
02a	Dark inner domain (long prismatic)	2789	5	2783	18	2774	42	0.1955	0.33	14.50	1.9	0.5378	1.9	0.98		210	170	159	1.82E+04	0.81
03a	Weakly zoned (prismatic)	2694	3	2701	18	2710	41	0.1845	0.18	13.29	1.9	0.5225	1.9	1.00		721	245	481	4.82E+04	0.34
04a	Weakly zoned (prismatic)	2684	3	2714	18	2756	42	0.1834	0.19	13.49	1.9	0.5334	1.9	0.99		680	239	464	1.17E+05	0.35
05a	Dark inner domain (prismatic)	2808	7	2788	18	2761	42	0.1978	0.40	14.58	1.9	0.5346	1.9	0.98		284	219	212	3.34E+04	0.77
06a	Weakly zoned (prismatic)	2723	3	2734	18	2749	42	0.1878	0.20	13.77	1.9	0.5317	1.9	0.99		691	399	492	8.35E+04	0.58
07a	Weakly zoned (prismatic)	2657	3	2685	18	2722	41	0.1805	0.17	13.07	1.9	0.5254	1.9	1.00		860	324	579	3.27E+04	0.38
08a	Weakly zoned (prismatic)	2542	3	2524	18	2503	39	0.1684	0.20	11.01	1.9	0.4743	1.9	0.99		1391	648	850	8.63E+03	0.47
09a	Weakly zoned light outer domain (prismatic)	2674	4	2702	18	2740	42	0.1823	0.22	13.31	1.9	0.5297	1.9	0.99		654	208	439	3.52E+04	0.32
10a	Weakly zoned (prismatic)	2671	3	2666	18	2658	41	0.1820	0.17	12.81	1.9	0.5103	1.9	1.00		814	256	526	4.19E+04	0.31
11a	Weakly zoned (prismatic)	2687	3	2706	18	2732	41	0.1837	0.17	13.37	1.9	0.5277	1.9	1.00		863	310	584	4.35E+04	0.36
12a	Weakly zoned (long prismatic)	2689	3	2722	18	2767	42	0.1839	0.21	13.60	1.9	0.5362	1.9	0.99		738	309	514	3.64E+04	0.42

All errors are at 1σ level. Degree of discordance is calculated at the closest 2σ limit. Data in *italics* are ignored due to high discordance or low $^{206}Pb/^{204}Pb$.

[a] Internal structure of an analysed zircon on BSE-images: zoned: magmatic zoning; homog: quite homogeneous zircon domain.

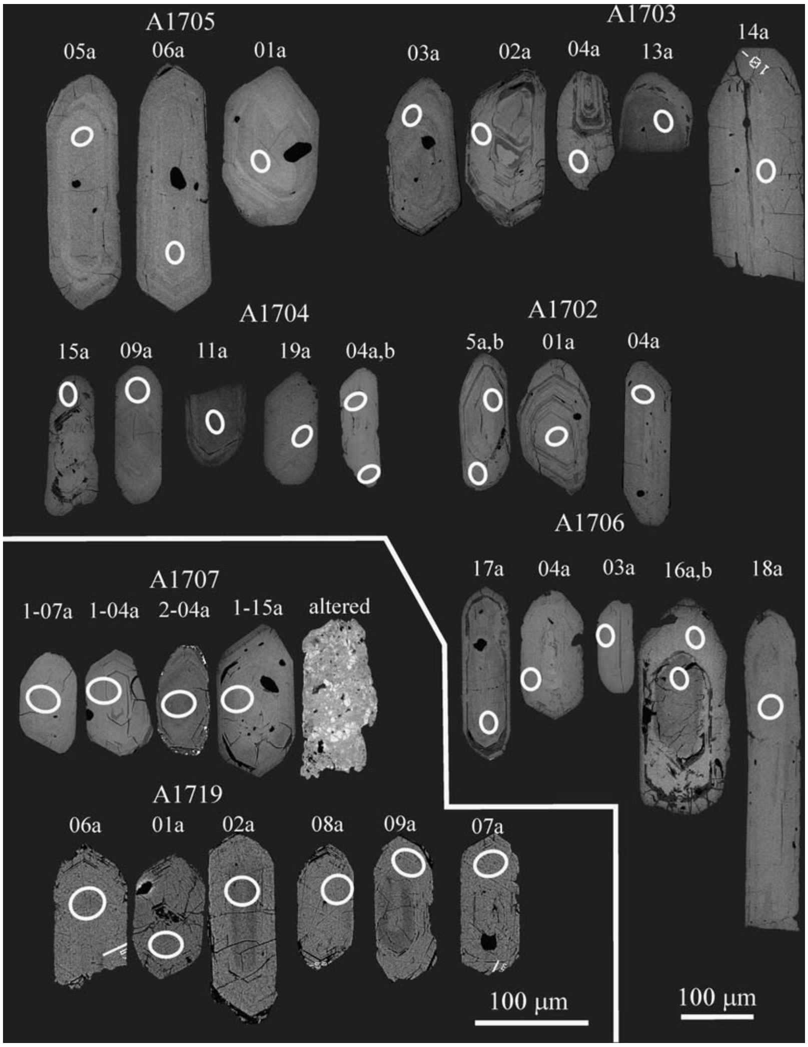

Fig. 4. BSE images showing representative zircons for samples analysed by SIMS. Analysis locations are marked with white ellipses. Note the larger scale for samples A1707 and A1719. Analysis numbers refer to Table 3.

southeast oriented foliation. Mafic inclusions up to 15 cm in diameter are also present. Zircons from the Viitavaara tonalite are bright, yellowish, and usually long and prismatic. They occasionally contain apatite and ilmenite inclusions and oscillatory zoning is evident in back-scattered electron (BSE) images (Fig. 4). All the 11 dated zircon domains define a concordia age of 2785 ± 7 Ma (Fig. 5), which is interpreted as the emplacement age of the pluton.

4.3. *Tonalite (A1702) – Purnu*

The Purnu tonalite (45% quartz, 40% plagioclase, 10% biotite, with accessory microcline, muscovite, sericite, zircon, and epidote) is medium-grained, equigranular, and leucocratic with a northwest-southeast trending foliation. It contains sporadic plagioclase phenocrysts, while biotite forms sharp edged clusters ranging from 0.1 mm to 1 cm in diameter. Zircons from the Purnu tonalite are brownish and mainly prismatic and contain apatite and K-feldspar inclusions. BSE images reveal frequent oscillatory-zoned textures and rare structureless ∼10–30 μm thick rims (Fig. 4).

A total of 13 zircon domains were analysed with the ion microprobe; 11 of them are concordant, and two are reversely discordant (Fig. 6). Ten concordant analyses give a concordia age of 2747 ± 3 Ma (MSWD = 0.38). One structurally homogenous rim domain (A1702-05a), with low Th/U, yielded a $^{207}Pb/^{206}Pb$ age of 2713 ± 10 Ma, which is consistent with the 2716 ± 3 Ma age of a dark-brown titanite of the same sample (Table 2; Fig. 6). The core domain of the same zircon has an

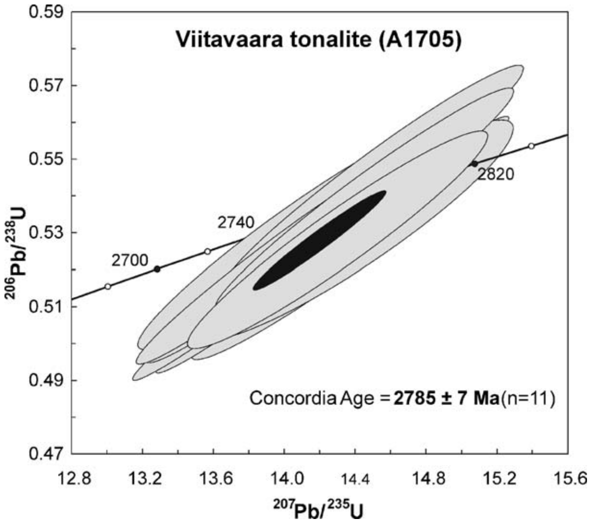

Fig. 5. Concordia diagram showing zircon U–Pb isotopic data for the Viitavaara tonalite. Error ellipses are at 2σ.

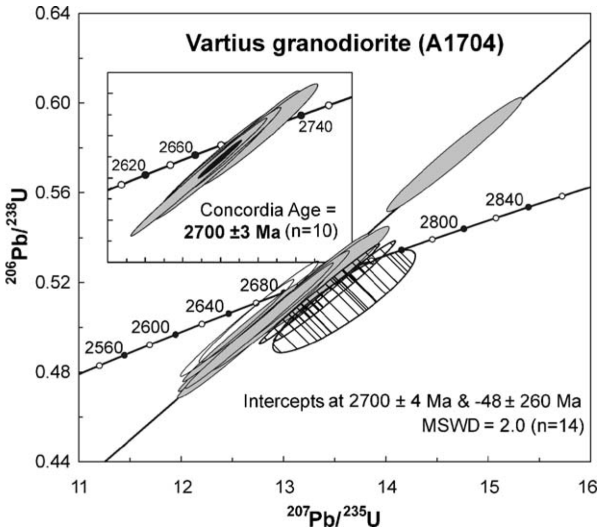

Fig. 7. Concordia diagram showing zircon U–Pb isotopic data for the Vartius granodiorite. Ruled ellipses are from inherited zircons, grey ellipses from magmatic zircons, and white ellipses represent metamorphic zircon domains. Error ellipses are at 2σ.

age of 2762 ± 12 Ma (A1702-05b). A concordia age of 2715 ± 5 Ma (n = 2) can be calculated for the rim and titanite. We interpret the age of 2747 ± 3 Ma as the emplacement age of the pluton, and the age of 2715 ± 5 Ma to represent metamorphism.

4.4. Granodiorite (A1704) – Vartius

The Vartius granodiorite (35% quartz, 30% plagioclase, 25% microcline, 3% biotite, 4% epidote, 2% muscovite with accessory sericite, titanite, and zircon) is medium-grained with K-feldspar phenocrysts. Biotite is partly replaced by epidote. The majority of the zircons are translucent, dark brown, and prismatic, only a few being pale and transparent. In BSE images, most of the zircons are quite homogeneous and show weak zoning (Fig. 4). Zircons with more evident zoning are darker in BSE images and some zircons have apparent ∼10–40 μm thick structureless rims (A1704-15a in Fig. 4).

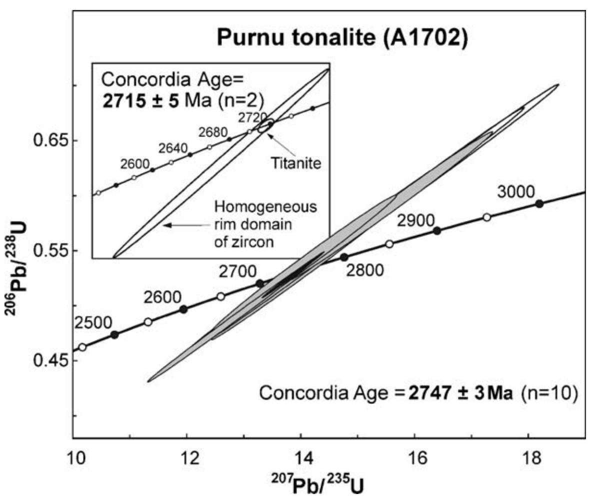

Fig. 6. Concordia diagram showing zircon and titanite U–Pb isotopic data for the Purnu tonalite. Grey ellipses denote magmatic zircons, and data for titanite and structurally homogeneous rim domain are shown as an inset. Error ellipses are at 2σ.

A total of 22 zircon domains were dated, of which three were rejected due to low $^{206}Pb/^{204}Pb$ (Table 3). One analysis plots above the concordia curve (Fig. 7). The others are concordant or slightly normally discordant. The oldest $^{207}Pb/^{206}Pb$ ages from individual spots are 2728 ± 6, 2741 ± 8, and 2767 ± 32 Ma (A1704-08a, 09a, and 11a). These ages are from BSE darker, zoned zircons. The majority of the zircons (n = 14) plot on a discordia line with an upper intercept age of 2700 ± 4 Ma (MSWD = 2.0) and using only the concordant analyses, a concordia age is calculated at 2700 ± 3 Ma. The youngest $^{207}Pb/^{206}Pb$ ages of 2675 ± 10 and 2678 ± 10 Ma (A1704-19a and 04a) are measured from a quite homogenous zircon and from a homogeneous tip-domain of a zircon, respectively. The apparently younger ages from these may indicate later homogenization and/or metamorphism. The age of 2700 ± 3 Ma is interpreted as the emplacement age of the pluton and the three older zircons are considered inherited.

4.5. Leucogranite (A1703) – Katajavaara

The Katajavaara leucogranite (35% quartz, 15% plagioclase, 45% microcline, 3% biotite with accessory epidote, muscovite, sericite, magnetite, and zircon) is red, leucocratic and shows a weak north-south trending foliation delineated by biotite. The rock is medium-grained and equigranular and contains rare magnetite crystals up to 1 cm in diameter. The sample typically contains long prismatic zircons stained with Fe-pigment. BSE images show that most of the crystals are oscillatory zoned (Fig. 4). Generally, zircons are often metamictic.

A total of 21 zircon domains were dated, of which three were excluded because of low $^{206}Pb/^{204}Pb$ (<500) and three of the most discordant data points were further excluded from the age calculation (Table 3). The oldest magmatically zoned and long zircon yields an $^{207}Pb/^{206}Pb$ age of 2759 ± 14 Ma (A1703-05a; Table 3; Fig. 8). The majority of the magmatically zoned zircons and homogeneous internal parts of the zircons ($n = 11$) define a discordia line with an upper intercept age of 2697 ± 7 Ma (MSWD = 6.4). Three homogeneous rim domains show $^{207}Pb/^{206}Pb$ ages between 2.63 and 2.65 Ga (A1703-04a, 11a, and 20b) (Fig. 4) and have low Th/U (<0.17). These rim domains are interpreted as metamorphic and the 2697 ± 7 Ma is considered as the emplacement age of the pluton.

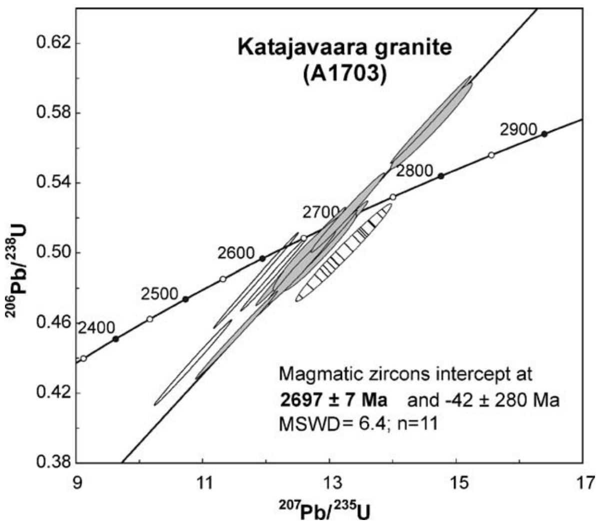

Fig. 8. Concordia diagram showing zircon U–Pb isotopic data for the Katajavaara granite. Ruled ellipse indicates inherited zircon. Analyses mostly from zoned zircon domains indicated by grey ellipses (used for age calculation). White ellipses denote structurally homogenous metamorphic rim domains with low Th/U (≤0.11). Error ellipses are at 2σ.

4.6. Leucogranodiorite (A1706) – Pieni Tuomaanjärvi

The Pieni Tuomaanjärvi granodiorite (50% quartz, 15% plagioclase, 30% microcline, 3% biotite, 2% muscovite with accessory, allanite, chlorite, and zircon) is porphyritic, reddish and medium-grained. The K-feldspar phenocrysts are from 2 to 3 cm in diameter. The rock has a variable biotite schistosity and contains gneiss inclusions up to several meters in diameter. The zircon population is heterogeneous with respect to grain size, morphology and colour. The majority of the zircons vary from short to long prismatic and translucent to turbid brown. In BSE images they show varying types of zonation (Fig. 4). Some grains show light opaque alteration.

Twenty-one zircon domains were dated. Two of the analyses were discarded because of low $^{206}Pb/^{204}Pb$ (<500) and three of the most discordant analyses were further excluded from age calculations (Table 3; Fig. 9). Two of the analysed zircons show older $^{207}Pb/^{206}Pb$ ages than the others; 2768 ± 8 Ma (A1706-17a) and 2802 ± 18 Ma (A1706-09a). The majority of the dated zircons define a discordia line with an apparent upper intercept age of 2695 ± 7 Ma (MSWD = 4.6; $n = 13$) and using the six concordant data points, a concordia age of 2686 ± 5 Ma can be calculated. The youngest analysed zircon is structurally quite homogeneous and has a $^{207}Pb/^{206}Pb$ age of 2647 ± 10 Ma (Fig. 4), which may indicate metamorphism. The concordia age of

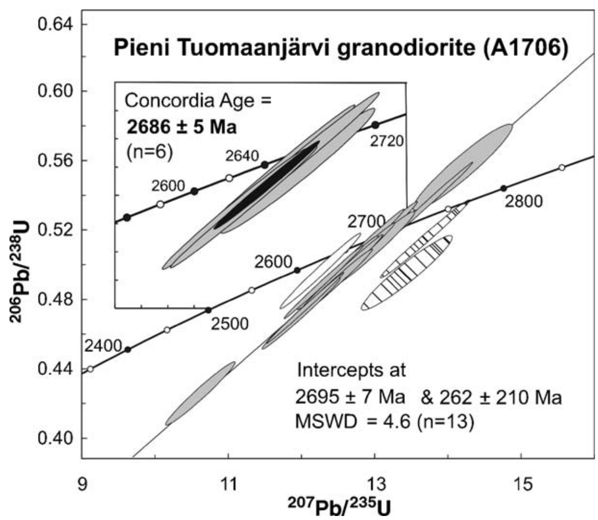

Fig. 9. Concordia diagram showing zircon U–Pb isotopic data for the Pieni Tuomaanjärvi granodiorite. Ruled ellipses indicate inherited zircons, grey ellipses denote the data points used for calulations, white ellipse indicate metamorphic zircon. Concordant data is shown as an inset. Error ellipses are at 2σ.

2686 ± 5 Ma is interpreted here as the best estimate for the crystallisation age of the pluton.

4.7. Leucogranite (A1707) – Pohjajärvi

The Pohjajärvi granite (40% quartz, 15% plagioclase, 35% microcline, 5% muscovite with accessory carbonate, zircon, rutile, and biotite) is pinkish, medium-grained and equigranular, leucocratic, and K-feldspar rich. The granite is only weakly deformed and contains rare aplitic dykes. Only a small amount of fine grained (<0.075 mm), dark brown, translucent, and short prismatic zircons were recovered. On BSE images, a large proportion of these zircons are strongly altered and corroded and these zircons were not selected for analysis (altered zircon in Fig. 4). The remaining crystals have either weak or apparently strong zoning, frequent apatite inclusions, and numerous cracks. The most prominent zoning in zircons is alteration related (see Table 3; weakly zoned versus zoned).

A total of 30 zircon analyses were made (Fig. 10). Due to low $^{206}Pb/^{204}Pb$ and/or high discordance 13 analyses were excluded from the age evaluation (Table 3). This is probably due to the beam overlapping partly with fractures or altered zones. The other data form neither distinct age groups nor is there any correlation between zircon morphology and age. Thus, the data do not allow exact determination of the crystallisation age for the granite.

Dikes of this granite crosscut the 2734 ± 2 Ma Arola granodiorite (Querré, 1985; age reported by Hyppönen, 1983), constraining a maximum age for the Pohjajärvi leucogranite intrusion. Therefore, all the >2734 ± 2 Ma zircons must be inherited (Fig. 10; e.g. A1707-2-04a in Fig. 4). The younger (<2734 Ma) age data consist mostly of analyses on oscillatory-zoned zircons (Table 3). Because the age data scatter, neither concordia age nor reasonable discordia age can be calculated. Thus, we estimate an age of 2705 ± 13 Ma for the Pohjajärvi leucogranite by calculating the weighted average of $^{207}Pb/^{206}Pb$ ages for concordant and nearly concordant data ($n = 10$), which are younger than 2732 Ma.

4.8. Granodiorite (A1719) – Siikalahti

The Siikalahti biotite granodiorite is grey, coarse grained with microcline phenocrysts. The foliation is variably orientated and the pluton often contains biotite rich mafic enclaves. This granodiorite has geochemical features typical of Archaean sanukitoids (Table 1). Zircons are mainly small (<75 μm), transparent, brownish, long and prismatic. Larger zircons are brownish, transparent and short prismatic. BSE images show darker inner domains in some zircons, with oscillatory-zoned outer domains (Fig. 4).

Twelve zircon domains from the Siikalahti granodiorite were dated using SIMS (Table 3). On the concordia diagram (Fig. 11), the majority of the data plot between 2700 and 2660 Ma. Three older and three younger data

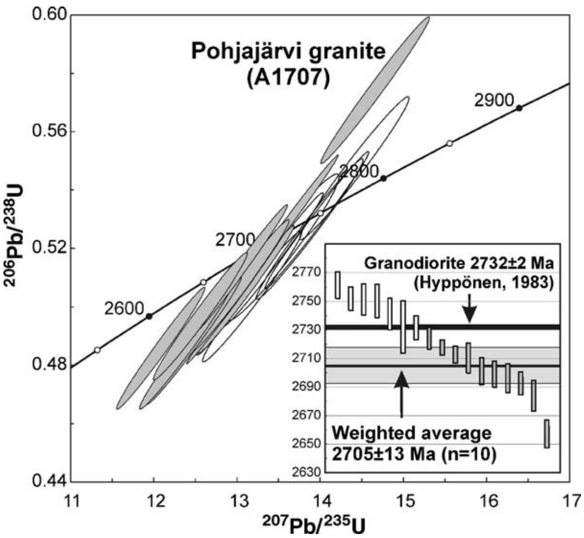

Fig. 10. Concordia diagram showing zircon U–Pb isotopic data for the Pohjajärvi granite. Inset showing the weighted average plot of $^{207}Pb/^{206}Pb$ ages from concordant and nearly concordant age data. Error ellipses and error bars are at 2σ.

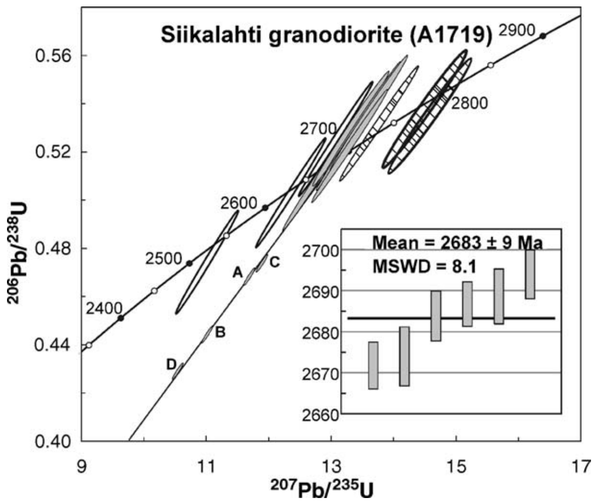

Fig. 11. Concordia diagram showing zircon U–Pb isotopic data for the Siikalahti granodiorite. The 2695 Ma discordia line is fitted trough the TIMS data (ellipses denoted by letters from A to D). Grey ellipses show the main age cluster. Ruled ellipses indicate BSE dark inner domains and an inherited zircon. White ellipses indicate the young zircons.

points plot outside of this cluster. Two BSE darker core domains (A1719-02a, 05a; Fig. 4) have $^{207}Pb/^{206}Pb$ ages of 2789 ± 11 and 2808 ± 13 Ma. Furthermore, data point A1719-06a shows a somewhat older age compared to the main age cluster. Two marginally younger zircon domains (A1719-01a and 07a) have $^{207}Pb/^{206}Pb$ ages of 2657 ± 6 Ma and 2635 ± 6 Ma and an undoubtedly younger zircon (A1719-08a) has a $^{207}Pb/^{206}Pb$ age of 2542 ± 7 Ma. The three younger zircons and the marginally older zircons do not differ morphologically or structurally from the zoned zircons in the main age cluster (Fig. 4).

Because the age data do scatter, no reasonable concordia age can be calculated when the data from the two cores and the youngest zircon are omitted. A weighted average of 2683 ± 9 Ma of the $^{207}Pb/^{206}Pb$ ages from the closest six data points (A1719 -03a, 04a, 09a, 10a, 11a, 12a; Table 3) in the main age cluster is considered as the best age estimate for the crystallisation of the Siikalahti granodiorite. This age coincides within the error limits with the upper intercept age of 2695 ± 26 Ma (MSWD = 3.6; n = 4) calculated from U–Pb TIMS data (Table 2; Fig. 11). The BSE dark core domains indicate inheritance from ca. 2.8 Ga source. The youngest zircon (A1719-08a) shows no alteration and differs from the other magmatic zircons only in having a higher U concentration. It might be that the high-U zircon was more susceptible to later U–Pb disturbance.

5. Sm–Nd whole-rock geochemistry

In order to evaluate the crustal residence time and sources of the granitoid rocks, Sm–Nd isotopes were measured on 30 whole-rock samples on dated plutons from the Kuhmo district (Table 4; Fig. 12). There are some indications that Palaeoproterozoic (1.8–1.9 Ga) metamorphism might have caused fractionation of Sm/Nd in Archaean plutonic rocks (e.g. O'Brien et al., 1993) as a result of which, an increase of Sm/Nd ratio could lead to unreasonably old T_{DM} model ages. In general, however, it appears that the Paleoproterozoic isotope fractionation of the samples analysed for this study has not been nearly extensive as in metakomatiites reported from the Kuhmo greenstone belt (Gruau et al., 1992). Therefore, we consider that Sm–Nd isotope results for most samples can be used for characterisation of the sources and crustal residence of the granitoid rocks.

The tonalites analysed have positive initial ε_{Nd} values (Fig. 12a). The 2.83–2.81 tonalites show initial ε_{Nd} values between +2.2 and +0.3. The 2.78 Ga Viitavaara tonalite (A1705) provides ε_{Nd} equivalent to the depleted mantle at that time, and the 2.75–2.74 Ga tonalites have initial ε_{Nd} values of +1.1 and +0.4.

Archaean sanukitoid samples from the Arola granodiorite pluton indicate a rather homogenous Nd isotopic composition (Tables 1 and 4; for location see Fig. 2), the average initial ε_{Nd} being +0.9 ± 0.3 (1 S.D.). A further diagnostic feature of the Archaean sanukitoids from Kuhmo is the higher Sm and Nd contents, compared to the TTGs and granites (Table 4). Sample AAK-03-21 shows negative ε_{Nd} and sample A1146 has ε_{Nd} similar to CHUR. Samples from the Loso diorite have initial ε_{Nd} values between +0.5 and +0.1.

The leucogranites and leucocratic granodiorites from Kuhmo show the most negative initial ε_{Nd} values of all the granitoid rocks analysed (Fig. 12a). Katajavaara leucogranite, however, yields an initial ε_{Nd} value of +1.1. The major clustering of ε_{Nd} values is between −2 and

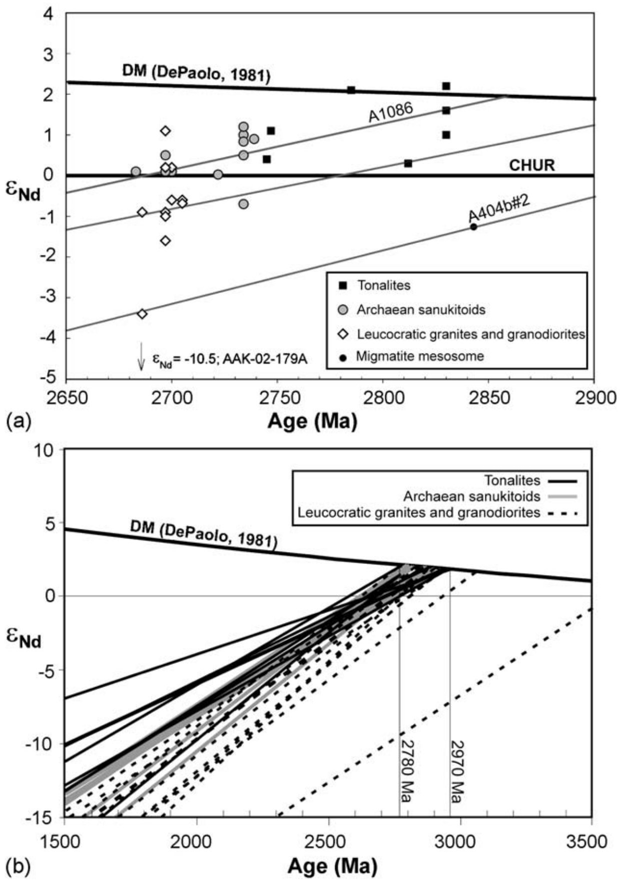

Fig. 12. (a) εNd vs. age diagram for samples from the Kuhmo district. Typical error is 0.5ε-unit. DM and CHUR denote depleted mantle (after DePaolo, 1981) and chondritic uniform reservoir (after DePaolo and Wassenburg, 1976), respectively. (b) The marked clustering of T_{DM} ages between 2780 and 2970 Ma suggests a rather short crustal prehistory for the majority of the granitoid rocks analysed.

Table 4
Sm–Nd whole-rock isotopic data

Sample	Type	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd \pm 2\sigma_m$	$\varepsilon(t)_{Ndi}$	T_{DM}	t (Ma)	Age (t) reference
2.83–2.81 Ga tonalites									
A1086	Haasiavaara tonalite	2.44	13.30	0.1108	0.511118 ± 10	1.6	2860	2830 ± 2	1
A1089	Huuskovaara tonalite	1.51	7.69	0.1188	0.511211 ± 10	0.3	2958	2812 ± 7	1
AAK-02-166	Haasiavaara tonalite	3.44	19.46	0.1067	0.511073 ± 10	2.2	2814	2830	i
AAK-02-100	Tonalite	2.25	10.28	0.1324	0.511489 ± 10	1.0	2934	2830	i
2.78 Ga tonalite									
A1705	Viitavaara tonalite	2.69	13.92	0.1166	0.511274 ± 11	2.1	2785	2785 ± 7	5
2.74 Ga tonalites									
A1702	Purnu tonalite	1.99	14.30	0.0842	0.510657 ± 9	1.1	2811	2747 ± 4	5
A1085	Halmejärvi tonalite	2.71	10.83	0.1513	0.511837 ± 10	0.4	2982	2745 ± 8	1
2.73 Ga Arola granodiorite (sanukitoids)									
A572	Granodiorite	4.14	24.61	0.1017	0.510979 ± 10	1.0	2814	2734 ± 3	2
A402	Granodioritic dike	5.05	28.24	0.1080	0.511081 ± 10	0.9	2837	2739 ± 7	2
AAK-02-77	Granodiorite	5.48	30.85	0.1074	0.511082 ± 9	1.1	2818	2734	i
AAK-02-81	Granodiorite	5.83	32.62	0.1081	0.511087 ± 9	0.9	2827	2734	i
AAK-02-117	Granodiorite	6.11	34.62	0.1066	0.511042 ± 8	0.5	2857	2734	i
AAK-02-87	Granodiorite	6.75	38.45	0.1061	0.511066 ± 9	1.2	2808	2734	i
2.70 Ga Loso diorite (sanukitoids)									
61-ATK-86	Diorite	11.90	69.10	0.1044	0.511022 ± 9	0.5	2825	2697	6
A331	Diorite	8.41	50.24	0.1011	0.510944 ± 12	0.1	2849	2697 ± 30	6
Other sanukitoids									
A1719	Granodiorite	5.08	33.18	0.0926	0.510802 ± 10	0.1	2825	2683 ± 9	5
AAK-02-21	Granodiorite	4.00	22.73	0.1064	0.510974 ± 9	−0.7	2949	2734	i
A1146	Gabbro	3.61	20.89	0.1046	0.510989 ± 10	0.1	2884	2722 ± 14	4
Vartius granodiorites									
A1704	Granodiorite	1.34	6.50	0.1015	0.510954 ± 31	0.2	2846	2700 ± 3	5
AAK-02-09	Granodiorite	1.29	8.14	0.0959	0.510812 ± 15	−0.6	2894	2700	i
Konivaara granodiorite									
A27-1	Granodiorite	1.37	9.35	0.0883	0.510661 ± 10	−1.0	2903	2697 ± 10	3
A27-2	Granodiorite	1.73	15.77	0.0662	0.510270 ± 10	−0.9	2872	2697	3
A27-4	Granodiorite	5.98	41.63	0.0869	0.510696 ± 10	0.2	2828	2697	3
Katajavaara leucogranite									
A1703	Leucogranite	2.55	17.76	0.0867	0.510739 ± 12	1.1	2766	2697 ± 7	5
AAK-02-157	Leucogranite	1.42	10.75	0.0797	0.510475 ± 10	−1.6	2926	2697	i
AAK-02-167A	Leucogranite	1.75	10.62	0.0996	0.510860 ± 9	−1.0	2925	2697	i
Pohjanjärvi leucogranite									
A1707	Leucogranite	2.17	11.16	0.1182	0.511210 ± 26	−0.6	2941	2705 ± 13	5
AAK-02-59	Leucogranite	6.90	50.59	0.0820	0.510557 ± 10	−0.7	2891	2705	i
Pieni Tuomaanjärvi granodiorite									
A1706	Granodiorite	3.04	19.07	0.0965	0.510692 ± 10	−3.4	3068	2686 ± 5	5
AAK-02-179A	Granodiorite	1.03	5.89	0.1051	0.510486 ± 7	−10.5	3629	2686	i
AAK-02-48	Granodiorite	7.80	40.59	0.1161	0.511160 ± 30	−0.9	2955	2686	i
Lylyvaara migmatitie									
A404b#2[a]	Migmatite mesosome	4.55	23.82	0.1154	0.511050 ± 10	−1.3	3114	2843 ± 18	7

$^{143}Nd/^{144}Nd$ normalized to $^{146}Nd/^{144}Nd = 0.7219$, within-run precision is $2\sigma_m$ in the last significant digits. The ε_{Ndi} was calculated using $\lambda^{147}Sm = 6.54 \times 10^{-12}\ a^{-1}$, $^{147}Sm/^{144}Nd = 0.1966$, and $^{143}Nd/^{144}Nd = 0.512640$ for the present CHUR. T_{DM} was calculated after DePaolo (1981). Age references—1: Vaasjoki et al. (1999); 2: Hyppönen (1983); 3: Luukkonen (1988); 4: Luukkonen and Huhma (unpublished data); 5: This study; 6: Kontinen and Huhma (unpublished data); 7: Luukkonen (1985); i: age inferred on the basis of field relations.

[a] Analysis from Luukkonen (2001).

+0.2. Two samples (A1706 and AAK-02-179A) are less radiogenic with ε_{Nd} of −3.4 and −10.5 and also provide T_{DM} in excess of 3.0 Ga (Fig. 12b). Sample AAK-02-179A has anomalously low Sm and Nd concentrations and therefore this sample is suspect for secondary alteration. Nd isotope evolution lines of tonalites, sanukitoids, leucocratic granodiorites and leucogranites overlap each other, and there is a conspicuous clustering of T_{DM} ages between 2.78 and 2.97 Ga (Fig. 12b).

6. Discussion

6.1. Temporal relations of the plutonic suites from the Kuhmo district

6.1.1. Tonalites (2.83–2.74 Ga)

U–Pb data presented in this study, in conjunction with previously reported data, define a sequential evolution for the plutonic rocks in the Kuhmo district (Table 5). The earliest plutonic magmatism is recorded by 2.83 and 2.81 Ga tonalites (Vaasjoki et al., 1999; this study). A subsequent tonalitic intrusive event took place at 2785 ± 7 Ma (sample A1705) and the third period of tonalite generation took place ∼40 Ma later at 2747 ± 3 Ma (A1702) and 2745 ± 8 Ma (Vaasjoki et al., 1999). It thus seems, that the growth of tonalitic crust has been episodic over a period from 2.83 to 2.74 Ga.

6.1.2. Sanukitoids (2.74–2.70 Ga)

The Arola granodiorite (A572; Hyppönen, 1983) and quartz diorite dike crosscutting the metavolcanic rocks of Kuhmo greenstone belt (A402; Hyppönen, 1983) have ages of 2734 ± 3 and 2739 ± 7 Ma, respectively. The diorite from Loso (A331; Table 5) indicates an age of 2697 ± 30 Ma and the Kaartojärvet gabbro has an age of 2722 ± 14 Ma (A1146; Tables 1 and 5). Granodiorite from Siikalahti (A1719) has an estimated of 2683 ± 9 Ma. These suites show high Mg#, elevated Ba and Sr contents, and relatively high contents of Ni and Cr (Table 1) as is typical of Archaean sanukitoids. Consequently, the ages of Archaean sanukitoids from the Kuhmo district vary from ∼2.74 to ∼2.70 Ga, and may even be as young as 2.68 Ga (A1719). Thus, the emplacement of the sanukitoids (granodiorites and diorites) took place almost immediately after the last phase of tonalitic magmatism or possibly simultaneously with it (Table 5).

Table 5
Summary of U–Pb age data for plutonic rocks from the Kuhmo district

Sample		Rock type	Age ± 2σ error[a]		Method[b]	Reference
			Zircon (Ma)	Titanite (Ga)		
A1086	Haasiavaara	Tonalite	2830 ± 2	2.69	TIMS	Vaasjoki et al. (1999)/(Titanite $^{207}Pb–^{206}Pb$-age)
A1089	Huuskovaara	Tonalite	2814 ± 3		TIMS	Vaasjoki et al. (1999); this study
A1705	Viitavaara	Tonalite	2785 ± 7		SIMS	This study
A1702	Purnu	Tonalite	2747 ± 3	2.71	SIMS	This study
A1183	Naavala	Tonalite	2752 ± 8	Discordant	TIMS	Luukkonen (2001)
A572	Arola (Koivulehto)	Granodiorite (s)	2734 ± 2	2.71	TIMS	Hyppönen, 1983
A402	Härmäjoki	Quartz diorite dike (s)	2739 ± 7	2.71	TIMS	Hyppönen, 1983
A331	Loso	Diorite (s)	2697 ± 30		TIMS	Unpublished data; Huhma and Kontinen
A1719	Siikalahti	Granodiorite (s)	(2683 ± 9)		SIMS+TIMS	This study
A1146	Kaartojärvet	Gabbro (s)	2722 ± 14		TIMS	Unpublished data; Luukkonen pers. com., 2003
A1147	Lentiira	Granite dike[c,d]	2700 ± 13	2.71 ± 0.03	TIMS	Luukkonen (2001)
A1704	Vartius	Granodiorite	2700 ± 3		SIMS	This study
A1703	Katajavaara	Granite	2697 ± 7		SIMS	This study
A1706	Pieni Tuomaanjärvi	Granodiorite	2686 ± 5		SIMS	This study
A27	Konivaara	Granodiorite	2697 ± 10		TIMS	Luukkonen (1988)
A1707	Pohjajärvi	Granite	(2705 ± 13)		SIMS	This study

(s): sanukitoid; see Table 1.
[a] Age in parenthesis is tentative.
[b] TIMS: conventional multigrain method; SIMS: single zircon dating by secondary ion mass spectrometer.
[c] A1147 is considered here as granite dike instead of microtonalite (mode—Quartz: 43%; K-feldspar: 23.2%; plagioclase: 17.2%).
[d] SiO_2: 68.8; K_2O: 5.11; Na_2O: 3.33 [analyse 64 from Luukkonen (2001)].

6.1.3. Leucocratic granitoid rocks (2.70–2.68 Ga)

The leucogranites and leucocratic granodiorites are the youngest Archaean plutonic rocks within the Kuhmo district. The zircons from the Vartius granodiorite (A1704) indicate a crystallisation age of 2700 ± 3 Ma. The emplacement age of the Katajavaara leucogranite (A1703; 2697 ± 7 Ma) corresponds to the Vartius granodiorite within the error limits. The Konivaara granodiorite, dated at 2697 ± 10 Ma (A27; Luukkonen, 1988), may have been coeval with Vartius magmatism. However, the TIMS multigrain analyses imply some heterogeneity in the zircon population and the age of the Konivaara pluton could possibly be younger than reported (cf. Luukkonen, 1988). The 2686 ± 5 Ma Pieni Tuomaanjärvi granodiorite represents the youngest Neoarchaean plutonism yet documented from the Kuhmo district. Because of the very heterogenous zircon population the actual emplacement age of the Pohjajärvi leucogranite (A1707) remains unresolved, although it is tentatively correlated with the other leucocratic granitoid rocks. In conclusion, a large propotion of the granodiorite and leucogranite plutons in the Kuhmo district were emplaced between ∼2.70 and ∼2.68 Ga. These plutons postdate tonalites and the earliest sanukitoids, but may have been coeval with some of the latest sanukitoids (Table 5).

6.1.4. Metamorphism (2.71 and 2.65–2.63 Ga)

Three samples from the Kuhmo district have zircon domains, which are significantly younger than the crystallisation ages of the plutonic rocks. A 2.71 Ga rim phase is observed in zircons from the Purnu tonalite (Fig. 6) and is equivalent to the titanite age from the same sample. Overall, 2.71–2.69 Ga titanite ages are a characteristic feature in Karelia (Vaasjoki et al., 1993; Bibikova et al., 1999). This period is broadly syngenetic with the Archaean sanukitoid and leucogranite magmatism. It is considered that the 2.71 Ga zircon and titanite ages record a crustal heating event associated with those plutonic episodes, as also emphasised by Bibikova et al. (1999).

The Vartius granodiorite and the Katajavaara leucogranite have structurally homogeneous zircon domains with ages of ca. 2.68 and 2.65–2.63 Ga, respectively. A distinctive feature of these metamorphic 2.65–2.63 Ga zircon domains is their relatively low Th/U. A metamorphic event of corresponding age has also been inferred from 2.65 Ga metamorphic zircon growth and monazites in the Varpaisjärvi area from central Finland (Hölttä et al., 2000; Mänttäri and Hölttä, 2002). Furthermore, zircons from a mafic granulite from Pudasjärvi (Fig. 1) indicate a similar metamorphic age of 2.65 ± 0.02 Ga (Mutanen and Huhma, 2003).

6.2. Ages of Neoarchean plutonic suites in areas adjacent to the Kuhmo district

The oldest plutonic rock in Karelia is the 3.5 Ga Siurua gneiss (Mutanen and Huhma, 2003), but rocks of this age appear to be rare in Karelia. Some plutonism from the Vodlozero region in the south-eastern part of the Russian Karelia have ages between 3.1 and 3.2 Ga (Lobach-Zhuchenko et al., 1993). In addition, gneisses from Tojottamanselkä and from Varpaisjärvi in Finland show similar plutonic ages (Kröner and Compston, 1990; Mänttäri and Hölttä, 2002).

Most of the Archaean plutonic rocks in eastern Finland and Russian Karelia (west and central Karelian domains; Lobach-Zhuchenko et al., 2000a,b) have ages between 2.85 and 2.68 Ga (Fig. 13). The ages of 2.83 and 2.80 Ga have been widely reported from tonalitic and trondhjemitic gneisses; from the Suomujärvi complex (Evins et al., 2002), Koillismaa (Lauri et al., 2006), and Russian Karelia (Bibikova et al., 2003; Lobach-Zhuchenko et al., 2000a). In addition to the Viitavaara tonalite (A1705) there are 2.78 Ga tonalites in adjacent Russian Karelia and in eastern Finland (e.g. Samsonov et al., 2004; Luukkonen, 1989). The ages of sanukitoids within Karelia may be braceted between 2.74 and 2.70 Ga (Bibikova et al., 2005; Halla, 2002, 2005; Kovalenko et al., 2005). The 2.70–2.68 Ga granites and granodiorites (with some grey gneiss variants; Vaasjoki et al., 2001) are also widespread throughout Karelia (e.g. Lauri et al., 2006; Lobach-Zhuchenko et al., 2000a,b and references therein; Bibikova et al., 2003 and references therein). In general, the U–Pb data on plutonic rocks suggests that the time interval between 2.83 and 2.68 Ga has been a significant period of crustal growth in Karelia.

6.3. A remark on craton correlation

Bleeker (2003) proposed, with a certain ambivalence, that the Karelia could have been part of the Neoarchaean "Superia supercraton" – a coalition composed of some modern Archaean cratons (see also e.g. Heaman, 1997; Halls, 1998; Pesonen et al., 2003). Rifting of this supercontinent is considered to have been initiated at 2.47–2.45 Ga, which corresponds with age of widespread rift-related intrusions and extrusive equivalents in Karelia (Fig. 13). The syntheses by the Ontario Geological Survey (1992) and Bleeker (2003) show that the emplacement of granite magmatism at 2.71–2.64 Ga is recorded throughout the Superior Craton (ages varying with respect to terranes). As indicated in many studies (e.g. Luukkonen, 1988; Lobach-Zhuchenko et al., 2000b; Bibikova et al., 2003 and references therein;

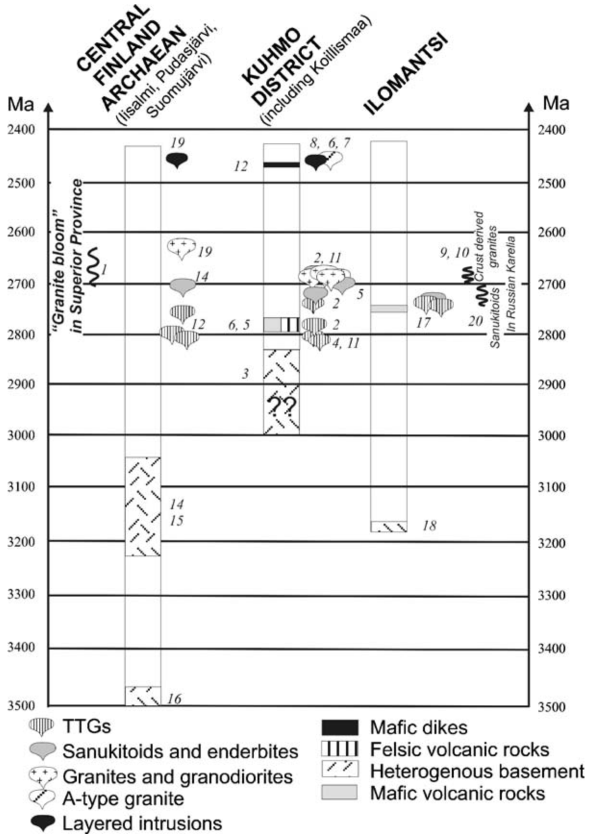

Fig. 13. Summary diagram illustrating U–Pb age distribution of Archaean magmatism within Finnish Karelia. Data sources—1: Bleeker (2003); 2: this study; 3: Luukkonen (1985); 4: Vaasjoki et al. (1999); 5: Hyppönen (1983); 6: Luukkonen (1988); 7: Lauri and Mänttäri (2002); 8: Alapieti (1982); 9: Lobach-Zhuchenko et al. (2000a); 10: Lobach-Zhuchenko et al. (2000b); 11: Lauri et al. (2006); 12: Vuollo (1994); 13: Evins et al. (2002); 14: Mänttäri and Hölttä (2002); 15: Hölttä et al. (2000); 16: Mutanen and Huhma (2003); 17: Vaasjoki et al. (1993); 18: Sorjonen-Ward and Claoué-Long (1993); 19: Perttunen and Vaasjoki (2001); 20: Bibikova et al. (2005).

Lauri et al., 2006; this study) most voluminous granite and granodiorite magmatism in Karelia occurred at 2.70–2.68 Ga. These ages from Karelia appear to correlate well with some areas in the Superior province (e.g. Berens River subprovince; cf. Corfu and Stone, 1998 and Opatica tonalite-gneiss belt cf. Davis et al., 1995), hence reinforcing the concept of these cratons having been contiguous during the Neoarchaean.

6.4. Petrogenetic implications of temporal relations

According to Moyen et al. (2001, 2003), Archaean cratons typically show secular evolutionary trends in which tonalites precede the sanukitoids. In the Pilbara Craton, Australia, sanukitoids are ~40 Ma younger than significant felsic magmatism, (Smithies and Champion, 2000) and in Russian Karelia sanukitoids postdate tonalites by 60–100 Ma (Bibikova et al., 2005). In the Berens river area, Superior Province, the Archaean sanukitoids are younger than the majority of the dated tonalites, but also partly coeval with them (Corfu and Stone, 1998). Similarly, in the Kuhmo district, the Archaean sanukitoids clearly post-date two older tonalite events, but may temporally overlapp with the ~2.74 Ga tonalitic magmatism.

Bibikova et al. (2005) noted that the significant age gap (60–100 Ma) between tonalites and sanukitoids in Karelia demands a different tectonic environment for these intrusive suites. They proposed that the tonalites are subduction related and the sanukitoids are related to a subsequent collisional event between Karelia and Belomoridian belt (Fig. 1). As our results show, there is a significalt age difference between the earliest tonalites (2.83 and 2.78 Ga) and sanukitoids. However, the ~2.74 tonalites and sanukitoids from Kuhmo district have a close temporal relationship, which reinforces the observation of Moyen et al. (2003) that after emplacement of TTG magmas, these magmas interacted with enriched mantle to produce the sanukitoids. Moyen et al. (2003) proposed a subduction setting for sanukitoids in general, but recent studies by Kovalenko et al. (2005) invoked other tectonothermal events, such as plume–related uplift or delamination and decompression melting, to explain some of the 2.74–2.70 Ga sanukitoid magmatism in Karelia. Overall, irrespective of absolute age, the common chronological sequence suggests that before emplacement of the sanukitoid magmas tonalitic crust has already been formed.

Late Archaean K-rich magmatism has commonly been thought to represent melting of pre-existing crustal material (Sylvester, 1994). However, a major remaining problem is the heat source responsible for such voluminous granite magmatism. Major and trace-element geochemical modelling was used by Moyen et al. (2001) to suggest that the Neoarchaean Closepet granite in India contains a significant component of enriched mantle and hence they recommended that the genesis of Neoarchaean potassium granites, in general, should be re-evaluated and that the temporal relationship between sanukitoids and leucogranites should be examined.

Archaean granites postdate sanukitoids by ~20 Ma in India (Moyen et al., 2001). In the Mallina basin, Pilbara Craton, the age diference is ~10–20 Ma (Smithies and Champion, 2000). Sanukitoids and granites occur nearly coevally in the Berens River area of the Superior Province, but as shown by Davis et al. (1995), sanukitoidlike monzodiorites (Bédard and Ludden, 1997) were followed by pink granites in the Opatica region of the western Superior Province. In the Kuhmo district, sanukitoid magmatism has also commenced earlier than more voluminous leucogranite and leucocratic granodiorite magmatism, but these magmatic events may have also been partially coeval.

Stevenson et al. (1999) and Whalen et al. (2004) suggested that hot asthenospheric magma triggered the formation of sanukitoids in the Western Superior Province, and the heating caused by this may have also been responsible for the formation of anatectic granite magmas. Similarly, Kovalenko et al. (2005) suggested that the same event that produced the sanukitoids was also responsible for melting the crust to generate the potassic granite magmas in Karelia. Such models are in accord with U–Pb data on sanukitoids and leucocratic granitoid rocks from the Kuhmo district.

6.5. Juvenile crust versus crustal recycling in the Kuhmo district compared to other Karelian plutonic suites

Nd isotope results on the tonalites of this study demonstrate that no significant older (>3.0 Ga) source contributed to their genesis, as most of the tonalites yield positive initial ε_{Nd} values (Fig. 12). In contrast, Nd isotope results on some tonalites from Koillismaa and Naavala (Fig. 1) demonstrate that some older component, possibly similar to the migmatite mesosome reported by Luukkonen (2001) could, however, be present (Luukkonen, 2001; Lauri et al., 2006).

The majority of the sanukitoids analysed from the Kuhmo district show positive initial ε_{Nd}, although sample AAK-02-21 suggests a limited contribution of pre-existing crustal material. Similar values were reported from Russia, where the ages of Archaean sanukitoids range from 2.74 to 2.70 Ga (Lobach-Zhuchenko et al., 2000b; Bibikova et al., 2005). Samples from the Taloveis pluton (=Kurgelampi, near Kostamuksha in Fig. 1), in Russia, 50 km east of the present study area, have ε_{Nd} (2.72 Ga) values from −1.2 to −2.6, which were attributed to crustal contamination of parental magma (Lobach-Zhuchenko et al., 2000b). Kovalenko et al. (2005) have reported similar values for Kuregelampi and Tulos intrusions, although they argued that the negative initial ε_{Nd} values in the Karelian sanukitoids reflect a prolonged time period between the enrichment and partial melting of a mantle source. The ∼2.70 Ga sanukitoids from Nilsiä and Lieksa (Fig. 1), south of present study area, have ε_{Nd} (2.70 Ga) values between +0.2 and +1.4 and T_{DM} ages from 2.75 to 2.86 Ga (Halla, 2002, 2005), which are comparable with the Arola granodiorite (Table 4). The initial ε_{Nd} values of the sanukitoids from Finnish Karelia are, however, significantly higher than the mesosome of the Lylyvaara migmatite, which may be considered as the most representative exposed example of the local >2.83 Ga crust (Fig. 12). The presence of ∼2.8 Ga zircon domains in the Siikalahti sample (Fig. 11) implies that some older crustal material was also involved in the genesis of sanukitoids of the Kuhmo district. Zircon cores with an age of ∼2.8 Ga were also reported from granodiorites and alkaline granites in Kurgelampi sanukitoid massif, Russian Karelia (Bibikova et al., 2005). Altogether, the chemical and isotopic data of this study are in agreement with the concept of a previously enriched mantle source for sanukitoids.

Leucogranites and leucocratic granodiorites have generally negative initial ε_{Nd} values, with the exception of sample A1703, which has ε_{Nd} (2697) of +1.1 (T_{DM} of 2766 Ma), indicating a rather short crustal prehistory. The majority of the 2.70–2.68 Ga granites and granodiorites are probably derived from melting of pre-existing crust (Fig. 12), as also suggested by Martin and Querré (1984) on the basis of Sr isotopic data. Alternatively, they can be interpreted as mixtures of a juvenile and less radiogenic sources (e.g. A 404b#2, Fig. 12). Most of the leucogranites and leucocratic granodiorites dated by SIMS contained inherited zircons. Pink leucoranite from Pohjajärvi [ε_{Nd} (at 2.7 Ga = −0.6)] has inherited zircons with $^{207}Pb/^{206}Pb$ ages varying between 2.73 and 2.76 Ga (Fig. 10; Table 3). The Pieni Tuomaanjärvi leucogranodiorite has 2.77 and 2.80 Ga inherited zircons. This sample yielded an ε_{Nd} (at 2686 Ma) value of −3.4, thus falling on the evolution line of the ∼2.84 Ga migmatite paleosome (Fig. 12). The ion probe and Nd isotope data are in good agreement, thus suggesting that a considerable amount of the material that took part in the formation of the ∼2.70–2.68 Ga granites and granodiorites was recycled crust.

In summary, the Nd isotopes on the granitoid rocks analysed give the general impression that the Kuhmo district is a rather juvenile Archaean block, which formed without a major input of significantly older crustal material (e.g. such as the 3.5 Ga gneisses from Siurua in Fig. 1; Mutanen and Huhma, 2003) (Fig. 12). If such a component is, however, present, its contribution to the granitoid rocks has been limited. The general decrease in initial ε_{Nd} values with decreasing age suggests progressive recycling of pre-existing basement, hence implying that recycling was important at ∼2.7 Ga, when the granite and granodiorite magmas were emplaced.

7. Conclusions

The Archaean plutonic rocks of the Kuhmo district in eastern Finland record magmatic evolution over a period of ∼140 Ma. The plutonism can be divided into three episodes: (I) formation of three discrete tonalite suites; 2.83–2.82 (see also Vaasjoki et al., 1999), 2.78, and 2.74 Ga; (II) emplacement of 2.74–2.70 Ga Archaean sanukitoid intrusions; (III) formation of granitic and granodioritic crust at 2.70–2.68 Ga. Sanukitoid magmatism probably also occurred at ∼2.68 Ga. A close temporal relation between the ∼2.74 Ga tonalites and sanukitoids suggest that their petrogenesis may be linked.

Granitoid rocks from Kuhmo district have formed without a major input of significantly older crustal material (e.g. such as the 3.5 Ga gneisses NW from the Kuhmo district; see Mutanen and Huhma, 2003). The observed general decrease in initial ε_{Nd} with decreasing age demonstrates progressive recycling of the pre-existing basement. Crustal recycling became an important process at ∼2.70–2.68 Ga when large amounts of leucogranites and granodiorites were emplaced. The temporal relationship implies that sanukitoid magmatism in Karelia may have caused melting of a pre-existing crust to form granites and granodiorites as also suggested by Kovalenko et al. (2005).

The new results, in conjunction with previously published data from the Kuhmo district, show temporal similarity to results from the Russian Karelia, thus demonstrating that 2.83–2.68 Ga was an extensive period of crustal growth throughout the entire Karelia craton.

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