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# Relationships between sanukitoids and crust-derived melts and their implications for the diversity of Neoarchaean granitoids: a case study from Surmansuo and nearby areas, Eastern Finland

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## Abstract

We present new isotopic data (U-Pb and Sm-Nd) from the Neoarchean granitoids of the Lentua complex, which is a part of the Western Karelia subprovince of the Fennoscandian Shield. Compositionally, the samples are granitoids belonging to the sanukitoid suite and K-rich granitoids. Certain samples interpreted as partial melts of pre-existing crust in this study display more mafic compositions than previously described from the surrounding areas. This indicates, at least locally, a source poorer in $SiO_2$ than the TTG (Tonalite-Trondhjemite-Granodiorite) suite granitoids, which are the likely sources for the majority of the anatectic granitoids within the Lentua complex. Based on new geochronological data (LA-MC-ICPMS U-Pb on zircon), the sanukitoids and anatectic granitoids are at least partly coeval (2.69 Ga) in the area, but interaction between the two felsic magmas was limited. The dated sanukitoid sample is distinctly younger (2687±8 Ma) than the average age of the sanukitoids of the Western Karelia subprovince (2718±3 Ma) indicating, together with one previously published sanukitoid age, the existence of a younger sanukitoid phase. This study gives new important constraints to understanding the formation of the Western Karelia subprovince by expanding the observed compositional heterogeneity and the temporal overlap of the different Neoarchean granitoid suites.

**Keywords**: sanukitoids, granites, leucogranite, partial melting, geochemistry, absolute age, isotopes, U/Pb, zircon, Archean, Neoarchean, Finland

## 1. Introduction

Sanukitoids and leucogranitoids formed in late- to post-tectonic environments, typically coevally to cratonisation of the Archean crust, and can be found e.g. from the Western part of the Karelia Province in Eastern Finland. Sanukitoids are considered to be derived from enriched subcontinental lithospheric mantle (e.g., Stern and Hanson, 1991; Martin et al., 2010; Heilimo et al., 2010), whereas the leucogranitoids are interpreted mainly as partial melts of TTGs (Tonalite-Trondhjemite-Granodiorite) (Manya et al., 2007; Dey et al., 2011; Feio & Dall' Agnol, 2012; Mikkola et al., 2012).

In the late 1980s the term "sanukitoid" referred strictly to plutonic rocks containing between 55 and 60 wt.% $SiO_2$, with Mg# > 0.6, Ni > 100 ppm, Cr > 200 ppm, $K_2O$ > 1 wt.%, Rb/Sr < 0.1, Ba > 500 ppm and Sr > 500 ppm (Stern et al., 1989). Since then the term "sanukitoid" has evolved and extended to include all Archean plutonic rocks with elevated $K_2O$, Ba, Sr, Mg#, Ni and Cr contents at any given $SiO_2$ level (Lobach-Zhuchenko et al., 2005; Halla, 2005; Heilimo et al., 2010). Their composition has been interpreted as a result of partial melting of a mantle source modified by variable felsic components rich in incompatible elements. Experimental study by Rapp et al. (2010) and geochemical modelling of Oliveira et al. (2011) showed that interaction between TTG melts and mantle can form source compositions of some sanukitoids, albeit certain isotope studies (King et al., 1998; Halla, 2005) and geochemical models (Laurent et al., 2011) propose that the felsic component could have been sediment in some instances. In addition to sanukitoids sensu stricto, a number of Archean suites resembling sanukitoids have been described over the years: e.g. Closepet-type from the Dharwar craton (Moyen et al., 2001), leucogranodiorite-granite suite of Rio Maria, Amazonia (Almeida et al., 2010) and quartz diorites from the Western Karelia subprovince (Mikkola et al., 2011a) and Greenland (Steenfelt et al., 2005). Rocks in the first two areas have been interpreted as a result of interaction between melts resembling the sanukitoid suite and anatectic melts, and in the last two as partial melting of mantle less intensively metasomatised than in the case of sanukitoid formation. All of these examples highlight the diversification of the granitoid compositions during Neoarchean.

The leucogranitoids that often represent the last major Archean magmatic events at cratons have not so far been uniformly named. This reflects the high degree of diversity observed in their mineral composition and geochemistry: e.g., potassic leucogranite and leucogranodiorite-granite suites (Almeida et al., 2010: Carajás Province), K-rich granites (Manya et al., 2007: Tanzania), biotite-granites and two-mica granites (Moyen et al., 2003: Dharwar Craton), low-Ca granites (Champion and Sheraton, 1997; Yilgarn Craton), granites (Feio & Dall'Agnol, 2012; Carajás Province) and GGM i.e. Granodiorite-Granite-Monzogranite suite (Hölttä et al., 2012a: Karelia Province) have been described. Regardless of the chosen terminology, the rocks referred to as leucogranitoids in this study are characterised by high concentrations of $SiO_2$ and LILE together with low MgO and Mg# and have most often been interpreted as partial melts of older, intermediate to felsic, continental crust. The partial melting is often associated with collisional thickening of the crust. The involvement of mantle-derived, i.e. sanukitoid-type, melts in genesis or evolution of the leucogranitoids has been tested experimentally (Lopez et al., 2005) and proposed in certain areas (Moyen et al., 2003; Almeida et al., 2010). Based on results of melting experiments, it is clear that simple partial melting of tonalitic crust cannot explain all of the observed natural compositions or the often large volumes of leucogranitoid rocks (e.g. Watkins et al., 2007).

During regional bedrock mapping in Eastern Finland, Mikkola et al. (2013) identified the Surmansuo porphyritic granodiorite-granite intrusion. The intrusion contains granodiorite parts that compositionally belong to the sanukitoid suite, but most of the intrusion consists of granites and granodiorites resembling the sanukitoid parts in appearance in the field but lacking the typical chemical characteristics of the suite. Both are accompanied by even-grained leucogranites. This paper describes the field relationships, petrography and composition of these three rock types from Surmansuo, and similar nearby intrusions, in addition to ages determined by single-grain zircon U-Pb dating. Our work illustrates that these contrasted granitoid types can be coeval and contributes to the discussion of possible interactions between melts derived from enriched mantle and crustal sources. We also provide evidence for sanukitoid magmatism significantly younger than previously described from the Western Karelia subprovince.

## 2. Geological setting

All of the rocks described and discussed in this study belong to the southern part of the Lentua complex (also known as the Kianta complex), which is part of the Western Karelia subprovince of the Karelia Province in the Fennoscandian Shield (Fig. 1; Hölttä et al., 2012b). The majority of the bedrock in the study area consists of TTGs, typically yielding ages close to 2.8 Ga (Käpyaho et al., 2006; Mikkola et al., 2013). Volcanic rocks are present as small slivers in the area, and most of them are presumably of the same age as the TTGs (e.g. Huhma et al., 2012a; Mikkola et al., 2013). Members of the sanukitoid suite are granodiorites, tonalites and diorites, and have yielded ages close to 2.72 Ga (Heilimo et al., 2011) in the Lentua complex, with the exception of the 2683±9 Ma Siikalahti intrusion (Käpyaho et al., 2006). Sanukitoid intrusions comprise ca. 5 % of the bedrock of the area and are typically less than 100 km$^2$ in size, excluding the ca. 2000 km$^2$ Koitere

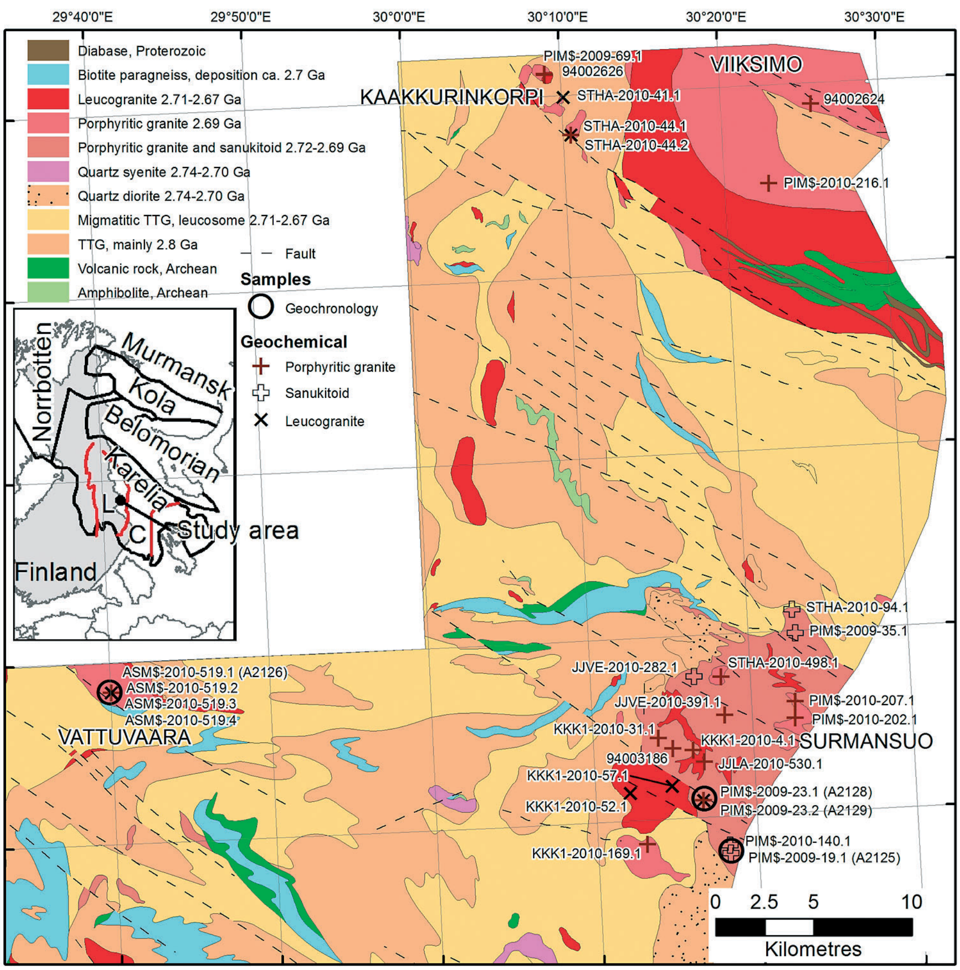


Fig. 1. Bedrock map of the study area showing sample locations. Map simplified from Mikkola et al. (2013). The Surmansuo intrusion is shown largely as a sanukitoid intrusion as, based on the field observations, it was difficult to distinguish the porphyritic granite parts. The inset shows the subdivision of the Archean nucleus of the Fennoscandian Shield, with province boundaries in black and subprovince/complex boundaries in red. L = Lentua complex, C = Central Karelian subprovince.

intrusion in the southern end of the Lentua complex. Sanukitoid magmatism was partly coeval with and partly followed by intrusion of quartz diorites that share some compositional characteristics, but lack the LILE enrichment characteristic only for the sanukitoids (Mikkola et al., 2011a). The quartz diorites make up ca. 5 % of the bedrock, include dioritic and tonalitic portions and form plutons that are typically less than 50 km$^2$ in size. Relatively $SiO_2$-poor and poorly studied quartz syenite intrusions make up less than 1 % of the crust and have yielded ages from 2.74 to 2.66 Ga (Mikkola et al., 2011b; Heilimo et al., 2013a). Complex-wide migmatisation and intrusion of heterogeneous anatectic leucogranitoids have been dated to ca. 2.7 Ga (Käpyaho et al., 2006, 2007; Mikkola et al., 2011a). The leucogranitoids comprise 10–15 % of the bedrock and form abundant dykes along with small intrusions that are rarely more than 2–3 kilometres across. After the Archean the area has been affected by 1.85–1.80 Ga dominantly amphibolite-facies metamorphism associated with the Svecofennian orogeny (Kontinen et al., 1992).

# 3. Materials and methods

The results of the geochemical analyses used in this study (Table 1, Electronic Appendix A) were originally published by Mikkola et al. (2013, n=26) and Rasilainen et al. (2007, n=3), but due to the nature of these publications, i.e. map sheet explanation and nation wide database respectively, the results were neither described in detail nor discussed in the

Table 1. Elemental compositions of the age samples. Results originally published by Mikkola et al. 2013. The rest of the analytical data can be found from the Electronic Appendix A.

| Sample | A2125 | A2128 | A2129 | A2126 |
|---|---|---|---|---|
| Location | Surmansuo | Laamasenpuro | Laamasenpuro | Vattuvaara |
| Type | Sanukitoid | Porphyritic granite | Leucogranite | Porphyritic granite |
| $SiO_2$ % | 67.40 | 67.80 | 72.50 | 71.82 |
| $TiO_2$ | 0.43 | 0.44 | 0.14 | 0.34 |
| $Al_2O_3$ | 15.80 | 15.80 | 14.50 | 14.08 |
| $Fe_2O_3t$ | 3.39 | 3.74 | 1.84 | 2.21 |
| MnO | 0.04 | 0.05 | 0.02 | 0.02 |
| MgO | 1.69 | 1.15 | 0.28 | 0.79 |
| CaO | 3.04 | 2.56 | 1.18 | 2.03 |
| $Na_2O$ | 4.78 | 4.42 | 3.06 | 4.16 |
| $K_2O$ | 2.85 | 3.36 | 6.02 | 3.89 |
| $P_2O_5$ | 0.21 | 0.26 | 0.09 | 0.13 |
| Ba ppm | 1076 | 866 | 105 | 1115 |
| Cl | 108 | 121 | 69 | 128 |
| Co | 8.20 | 7.35 | 0.84 | 4.61 |
| Cr | 53 | <30 | <30 | <30 |
| Ga | 25 | 28 | <20 | 23 |
| Hf | 3.16 | 5.84 | 5.32 | 5.23 |
| Nb | 3.81 | 10.10 | 1.94 | 4.89 |
| Ni | 39 | <20 | <20 | 29 |
| Pb | 13 | <20 | 23 | 24 |
| Rb | 82 | 176 | 191 | 159 |
| S | 28 | 554 | <60 | 32 |
| Sc | 7.58 | 4.88 | 1.71 | 5.1 |
| Sn | 12 | <20 | <20 | 6 |
| Sr | 708 | 448 | 307 | 470 |
| Ta | 0.14 | 1.34 | 0.23 | 0.42 |
| Th | 6.2 | 35.9 | 22 | 18.59 |
| U | 0.57 | 5.49 | 3.31 | 3.6 |
| V | 44.0 | 39.3 | 10.6 | 31.5 |
| Y | 9.1 | 14.10 | 6.31 | 6.03 |
| Zn | 77 | 82 | 38 | 55 |
| Zr | 127 | 235 | 206 | 188 |
| La | 28.2 | 111 | 46.9 | 51.98 |
| Ce | 58.4 | 208.0 | 94.8 | 95.9 |
| Pr | 6.97 | 21.00 | 9.94 | 10.06 |
| Nd | 27.8 | 71.0 | 34.1 | 34.6 |
| Sm | 5.07 | 9.34 | 4.83 | 5.01 |
| Eu | 1.18 | 1.12 | 0.58 | 1.05 |
| Gd | 3.98 | 6.85 | 3.43 | 3.42 |
| Tb | 0.51 | 0.82 | 0.37 | 0.37 |
| Dy | 2.04 | 3.65 | 1.58 | 1.69 |
| Ho | 0.33 | 0.54 | 0.22 | 0.23 |
| Er | 0.86 | 1.39 | 0.58 | 0.53 |
| Tm | 0.10 | 0.18 | <0.10 | 0.07 |
| Yb | 0.65 | 1.12 | 0.54 | 0.48 |
| Lu | 0.10 | 0.15 | <0.10 | 0.07 |
| Mg# | 49.7 | 37.9 | 23.2 | 41.5 |
| $K_2O/Na_2O$ | 0.60 | 0.76 | 1.97 | 0.94 |
| Ba+Sr | 1784 | 1314 | 412 | 1585 |
| $(La/Yb)_N$ | 29.3 | 67.0 | 58.7 | 73.2 |
| Eu/Eu* | 0.80 | 0.43 | 0.44 | 0.78 |
| $La_N$ | 76.8 | 302.5 | 127.8 | 141.6 |

<30 = below detection limit and the respective detection limit
Mg#=(Mg/(Mg+Fetot))*100
Normalizing values from Boynton (1984)
$Eu/Eu^* = Eu_N/(Sm_N*Gd_N)^{0.5}$

current geological context. Major elements and the trace elements As, Ba, Bi, Cl, Cr, Cu, Ga, Mo, Ni, Pb, S, Sb, Sn, Sr and Zn were analysed using X-ray fluorescence (XRF) method. The remaining trace elements (Ce, Co, Dy, Er, Eu, Gd, Hf, Ho, La, Lu, Nb, Nd, Pr, Rb, Sc, Sm, Ta, Tb, Th, Tm, U, V, Y, Yb and Zr) were analysed with inductively coupled plasma mass spectrometer (ICP-MS). Analyses were done in Labtium Ltd. and the analytical methods are described in Rasilainen et al. (2007). All geochemical diagrams were originally drawn using GDCKit (Janoušek et al., 2006). Four age samples were collected for single grain U-Pb dating of zircon and whole-rock Sm-Nd analysis to determine depleted mantle model ages ($t_{DM}$) and initial $\varepsilon_{Nd}$-values. U-Pb analyses were performed with Laser Ablation Multicollector Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICPMS) at the Finnish Isotope Geosciences Laboratory (SIGL) with procedures described in Huhma et al. (2012a). The zircons were pictured with secondary electron microscope (SEM) and cathodoluminescence (CL) methods. Based on these images the spot locations were selected to avoid inclusions and metamict domains. Analytical results for individual spots are shown in Electronic Appendix B. Sample preparation and measurement of Sm–Nd isotope ratios from whole-rock powders were performed at the isotope laboratory of the Geological Survey of Finland (GTK) using VG Sector 54 thermal ionisation multiple collector mass spectrometer (TIMS) following the methods described in Huhma et al. (2012b).

# 4. Classification and terminology of granitoids

The samples used in this study are divided into three groups: sanukitoids, porphyritic granites and leucogranites. Sanukitoids and porphyritic granites resemble each other in mineral composition and texture and cannot be distinguished reliably in the field or under the microscope, except in the case of the most felsic and mafic variants. Thus, division into sanukitoids and porphyritic granites is based on geochemical compositions using the criteria suggested for sanukitoid suite rocks by Heilimo et al. (2010): $SiO_2$ = 55–70 wt.%, Mg# = 45–65, MgO = 1.5–9.0 wt.%, $Na_2O/K_2O$ = 0.5–3, $K_2O$ = 1.5–5.0 wt.%, Ba+Sr > 1400 ppm and $Gd_N/Er_N$ = 2–6. Samples fullfilling at least 6 of the 7 the criteria were assigned as sanukitoids and other porphyritic samples as porphyritic granites. The division between porphyritic granites and leucogranites is based on mineral composition and texture. The leucogranite samples do not display the porphyritic texture and are more leucocratic than the porphyritic granites, most often containing < 5 vol.% of biotite.

# 5. Results

## *5.1. Field geology and petrography*

### *5.1.1. Surmansuo*

Surmansuo intrusion is ca. 70 km$^2$ in size on the Finnish side of the border and it continues east into Russia (Fig. 1). The majority of the intrusion consists of granodiorite and granite, with euhedral potassium feldspar (Ø = 10–40 mm) comprising up to 5–15 vol.% of the rock (Fig. 2A). In addition to the amount of K-feldspar, the quartz contents of the rocks vary, and rocks both with and without sanukitoid signature are present in the area. Main minerals in sanukitoids and porphyritic granites are K-feldspar, plagioclase, quartz and biotite; in some sanukitoids hornblende is also present. Accessory phases are titanite, opaque minerals, apatite, zircon and secondary epidote and muscovite. Strength of the orientation of the medium-grained groundmass varies as does the extent of recrystallisation to granoblastic texture. Medium- to coarse-grained, equigranular leucogranite bodies and veins are also present. Contacts between these and the porphyritic granites and sanukitoids vary from sharp, clearly cross-cutting (Fig. 2D) into gradational. Main minerals of the leucogranites are feldspars and quartz. Accessory phases are biotite, apatite and zircon in addition to secondary epidote, chlorite and muscovite.

## 5.1.2. Viiksimo, Kaakkurinlampi and Vattuvaara

Samples from the three other areas that contain porphyritic granites and granodiorites together with leucogranitoids were also included in this study (Fig. 1). Samples from the Viiksimo area represent a porphyritic granite intrusion that is 80 $km^2$ in size on the Finnish side of the border and continues into Russia. This area is poorly exposed due to extensive swamps and Quaternary coverage. In the Kaakkurinlampi area, four small intrusions consisting of porphyritic granite and leucogranite were identified. The rocks show partly sharp and partly gradational contacts, but field relationships indicate that the leucogranite is the younger of the two. All samples from the Vattuvaara area are from the same aggregate quarry, but similar rocks were identified over a larger area (ca. 9 $km^2$). The main rock type in the quarry is porphyritic granite that contains dark-coloured enclaves of similar mineral composition, but finer grain size (Fig. 2C). Abundant cross-cutting granite veins with sharp contacts to the host rock vary in width from 1 to 100 cm and display random strikes (Fig. 2D).

Macroscopically, the rocks from these areas resemble those from Surmansuo, but no samples with clear sanukitoid signature could be indentified. Porphyritic granites are relatively homogenous, reddish grey rocks with subhedral K-feldspar phenocrysts (Ø = 10–40 mm) that make up 5–15 vol.% of the rock. The groundmass is medium-grained, often recrystallised to mortar structure and variably oriented. In addition to feldspars and quartz, the fourth main mineral is biotite. Accessory phases are titanite, opaque minerals, apatite and

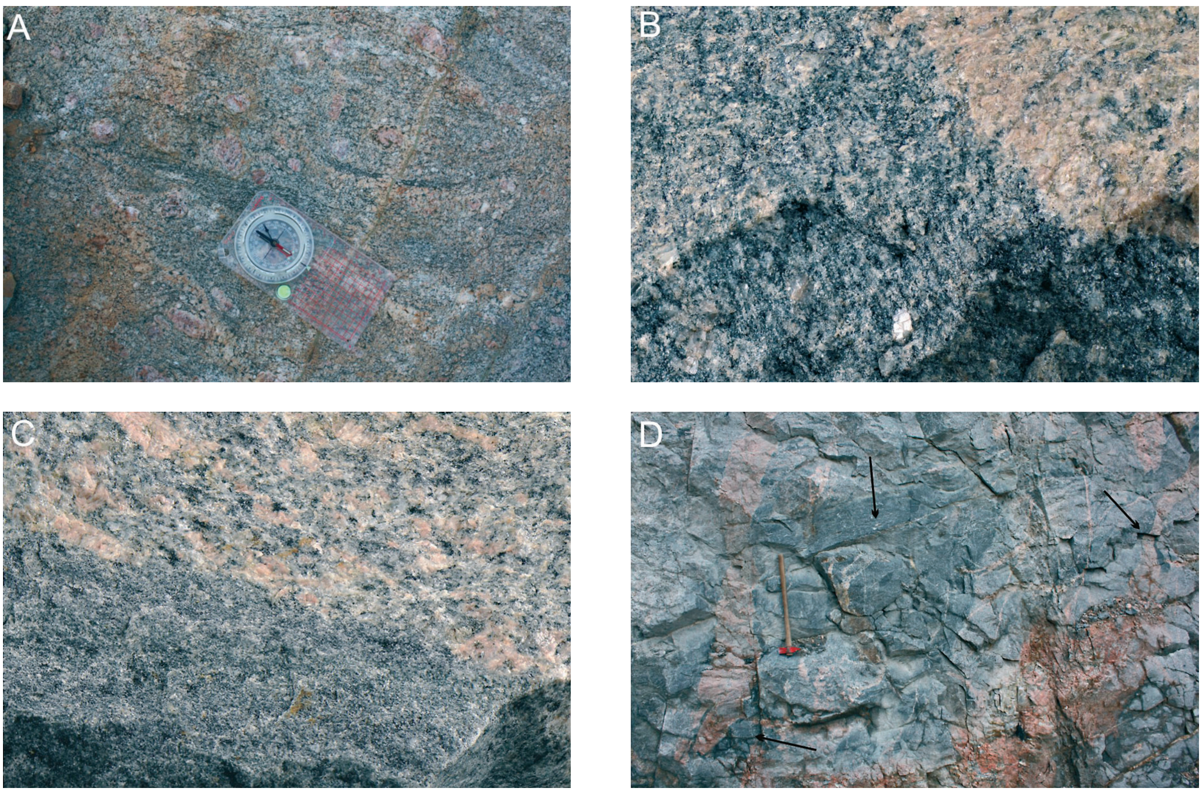


Fig. 2. A) Sanukitoid from the Surmansuo area, displaying typical porphyritic texture and a cross-cutting epidote vein. Length of the compass is 12 cm. B) Contact between leucogranite and porphyritic granite from the Laamasenpuro sample site (A2128 and A2129). Width of the view ca. 4 cm) C) Close-up of a sample from Vattuvaara quarry with a more mafic and finer grained enclave in a porphyritic granite. Width of the view ca. 6 cm. D) Porphyritic granite in the Vattuvaara quarry with cross-cutting pink granite veins and darker enclaves (black arrows). Length of the hammer 60 cm.

zircon together with secondary muscovite, epidote and carbonate. Leucogranites display variable grain size (Ø = 1–5 mm) and are weakly oriented and mortar-structured. The main minerals are K-feldspar, plagioclase and quartz. Primary accessory phases are biotite, titanite and apatite, whereas secondary phases are chlorite and epidote.

## 5.2. Geochemistry

### 5.2.1. Surmansuo

Out of the 18 samples from the Surmansuo area, five are classified as sanukitoids and display compositions typical for the porphyritic sanukitoid intrusions in Eastern Finland: e.g. $SiO_2$ = 65.6–67.4 wt.%, $K_2O$ = 2.85–4.13 wt.%, Mg# = 46.6–54.8 and Ba+Sr = 1126–2369 ppm (Figs. 3, 4). $K_2O/Na_2O$ varies from 0.60 to 0.96 and all samples are metaluminous (A/CNK = 0.87–0.99). LREE concentrations are high ($La_N$ = 77–244) and REE spectra moderately fractionated ($La_N/Yb_N$ = 29–69) and display negative Eu-anomalies (Eu/Eu* = 0.40–0.89). Cr and Ni are above the respective detection limits of 30 and 20 ppm in three of the samples.

Porphyritic granite samples from Surmansuo area (n = 10) are richer in $SiO_2$ (67.4–73.8 wt.%) and poorer in ferromagnesian elements than the sanukitoid samples. The major elements follow similar fractionation trends as sanukitoids on the Harker diagrams (Fig. 3). The samples straddle the metalumionous-peraluminous boundary (A/CNK = 0.96–1.07). LILE enrichment compared to the sanukitoids is variable (Figs. 3, 4), porphyritic granites are richer in $K_2O$ (3.27–5.89 wt.%), contain similar amounts of Ba (637–1401 ppm) and are poorer in Sr (229–470 ppm). $K_2O/Na_2O$ in porphyritic granites is higher than in sanukitoids, i.e. from 0.76 to 1.90. In respect to high field strength elements (HFSE) the porphyritic granites are richer than the sanukitoids in U, Th, Hf and Ta, whereas Nb and Zr do not display significant differences (Electronic Appendix A; Table 1; Fig. 4). Sc and V concentrations of the porphyritic granites are lower than those of the sanukitoids as the respective averages are 4.5 vs. 7.2 ppm and 30.9 vs. 49.2 ppm. LREE enrichment in porphyritic granites is of the same order of magnitude as in sanukitoids ($La_N$ = 101–305), but on average slightly higher (Fig. 4). Fractionation of REE ($La_N/Yb_N$ = 18–83), excluding one outlier ($La_N/Yb_N$ = 181), is similar to the sanukitoids (Fig. 4). Eu anomaly is variably negative (Eu/Eu* = 0.30–0.80). Cr is below detection limit in all of the samples and Ni in eight out of 10 samples.

Leucogranitoids from the Surmansuo area (n = 3) are poor in $Fe_2O_3t$ (1.0–2.2 wt.%), have low Mg# (23.2–31.2) and are rich in silica ($SiO_2$ = 72.4–74.9 wt.%) and potassium ($K_2O$ = 5.1–6.3 wt.%; Fig. 3). Ba concentrations are lower and Th higher in leucogranitoids than in porphyritic granites. LREE is strongly enriched ($La_N$ = 106–250) and Eu-anomalies strongly negative (Eu/Eu* = 0.26–0.44). The fractionation of REE is similar to the porphyritic granites and sanukitoids as $La_N/Yb_N$ varies from 25.1 to 59.1. The compositions are comparable to the ones reported earlier for the anatectic leucogranitoids of the Lentua complex (Mikkola et al., 2012; Fig. 3)

### 5.2.2. Viiksimo, Kaakkurinlampi and Vattuvaara

The porphyritic granite samples (n = 7) from Viiksimo, Kaakkurinlampi and Vattuvaara areas display variable $SiO_2$ abundances (63.2–72.8 wt.%) and form clear trends in respect to for example MgO, $K_2O$, $P_2O_5$ and Sr on Harker diagrams (Fig. 3). Compositional similarities to the porphyritic granites from Surmansuo are evident in both major and trace element compositions (Figs. 3, 4), with the exception of Th, which is lower (11.8–24.7) than in Surmansuo (13.6–42.3). The leucogranite samples from the aforementioned areas are richer in $SiO_2$ and $K_2O$ than coexisting porphyritic granites. They are compositionally akin to the respective samples from other parts of the Lentua complex and in most respects also to the samples from the Surmansuo area, the main differences being the higher Ba and Sr, lower U and Th and less pronounced negative Eu-anomaly of the former relative to the latter.

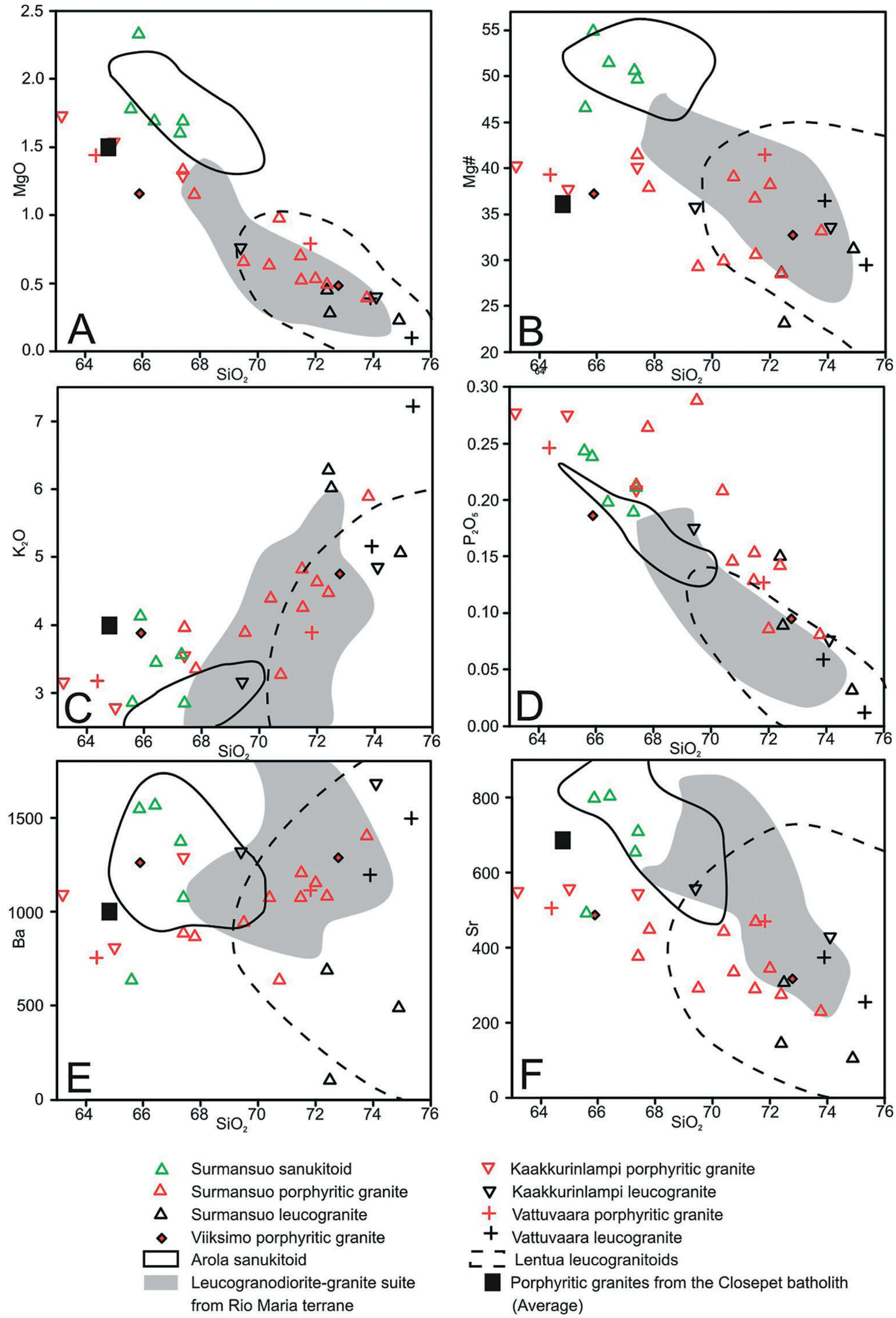


Fig. 3. Studied samples plotted in Harker diagrams for selected major and trace elements. Reference data field for the Arola sanukitoid intrusion based on data from Käpyaho (2006) and for the Lentua leucogranitoids on data from Mikkola et al. (2012), excluding the samples with flat REE patterns and highly negative Eu-anomalies. Field for the leucogranodiorite-granite suite from the Rio Maria terrane drawn based on analyses from Almeida et al. (2010). Values for porphyritic granites from the Closepet batholith are averages from Jayananda et al. (1995), note in D that the $P_{205}$ average concentration from Closepet (0.36 wt.%) is off the scale.

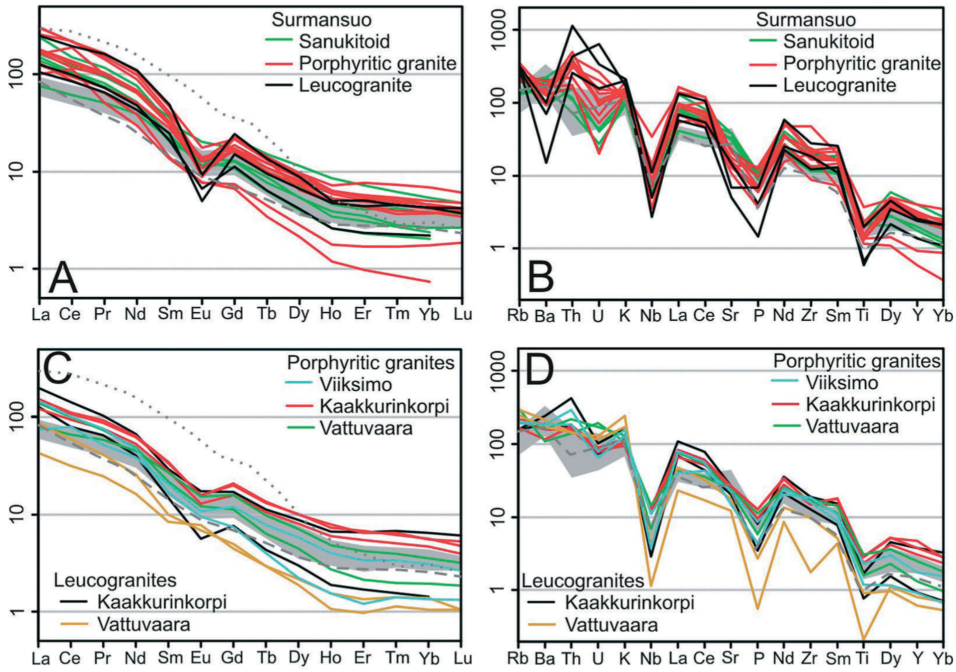


Fig. 4. Surmansuo (A and B) and other (C and D) samples in chondrite-normalised REE patterns of the studied samples and in trace element diagrams normalised to primitive mantle. Chondrite values from Taylor and McLennan (1985) and primitive-mantle values from Sun and McDonough (1989). Reference field marked with grey is based on the Arola sanukitoid intrusion (Käpyaho 2006). Grey dashed line marks the average of the Rio Marria terrane Leucogranodiorite-granite suite (Almeida et al., 2010). Grey dotted line in A and C is the sample J10, representative porphyritic granite from the Closepet batholith (Jayananda et al., 1995).

## *5.3. U-Pb age determinations*

### *5.3.1. Surmansuo sanukitoid (A2125)*

The Surmansuo sample is K-feldspar porphyritic biotite-hornblende granodiorite that belongs to the sanukitoid group. Separation of the crushed sample produced oscillatory zoned euhedral zircons that contain metamict domains. Core-rim structures were not observed (Fig. 5). Out of the analysed 21 spots 16 are concordant, four variably discordant, and one spot was discarded due to high common lead (Electronic Appendix B). All concordant analyses yielded a concordia age of 2687±8 Ma (MSWD = 2.0) which can be regarded as the crystallisation age of the Surmansuo granodiorite; the discordant spots are also likely to represent the same population ($^{207}Pb/^{206}Pb$ ages = 2633–2709 Ma; Fig. 6A).

### *5.3.2. Laamasenpuro porphyritic granodiorite (A2128)*

The Laamasenpuro K-feldspar porphyritic biotite granodiorite sample belongs to the porphyritic granite group from the Surmansuo area. Separation of the crushed sample produced weakly zoned euhedral zircons that contain abundant metamict domains (Fig. 5). Out of the 30 analysed spots 29 are concordant and define a concordia age of 2690±6 Ma (MSWD = 0.16), which can be regarded as the age of the granodiorite. The one discordant spot seems to belong to the same population as the rest of the analysed spots ($^{207}Pb/^{206}Pb$ age = 2692 Ma; Fig. 6B).

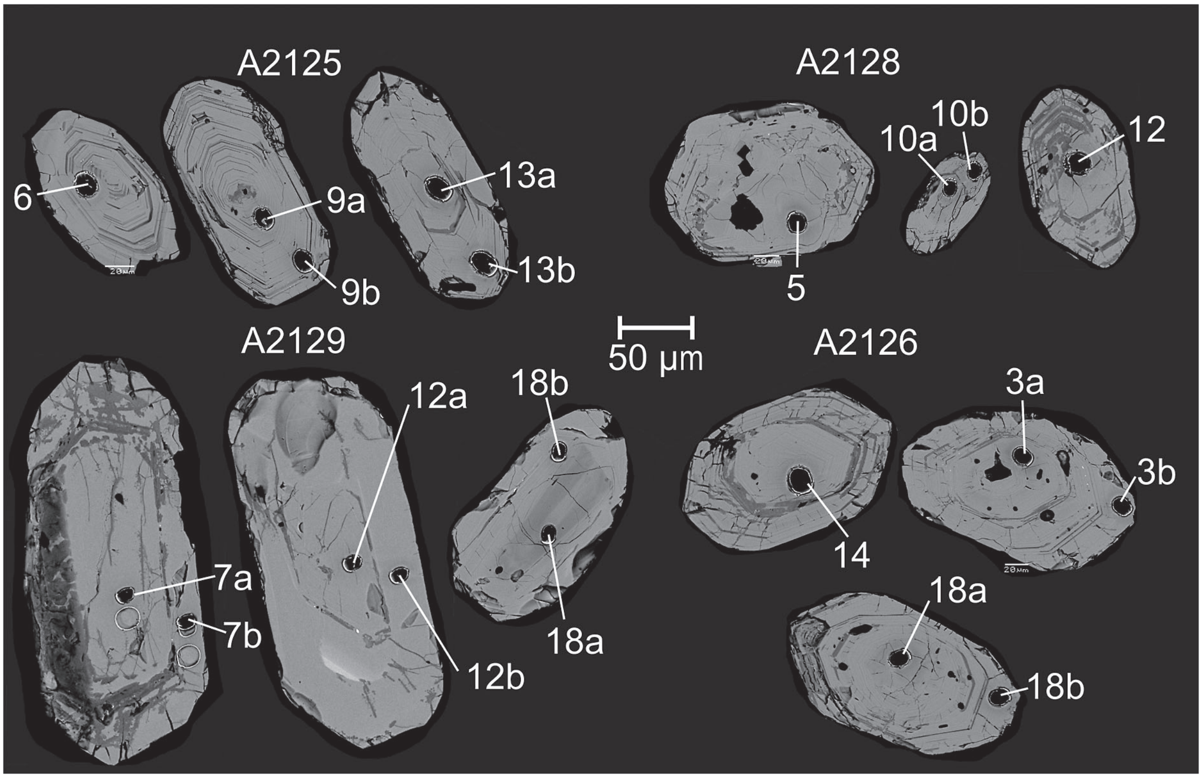


Fig. 5. Back scatter electron (BSE) images of selected zircons with analysed spots as blac cirkles.

## 5.3.3. Laamasenpuro leucogranite (A2129)

The Laamasenpuro leucogranite sample is from the Surmansuo area and represents medium-grained vein material parallel to the orientation of granodiorite sample A2128. Separation of the crushed sample produced variably zoned, mainly euhedral zircons. Core-rim structures were evident in some grains, typically with zoned cores surrounded by more homogenous rims (Fig. 5). Due to high Pb and U concentrations, spot size of 10 µm was used instead of the normal 20 µm. Out of the analysed 25 spots 22 are concordant within error limits, but their $^{207}Pb/^{206}Pb$ ages vary between 2639 and 2812 Ma. Six of the analysed cores are notably older than the main population (Fig. 6C) and are interpreted as inherited. However, it must be noted that 7 of the analysed cores yielded ages belonging to the main population. Weighted average of the $^{207}Pb/^{206}Pb$ ages from the remaining 16 spots is 2666±10 Ma, which can be interpreted as the best estimate for the crystallisation age of the granite.

## 5.3.4. Vattuvaara porphyritic granite (A2126)

The Vattuvaara K-feldspar porphyritic biotite granite sample represents the porphyritic granite group outside the Surmansuo area. Separation of the crushed sample produced variably zoned, mainly euhedral zircons, some grains exhibiting clear core-rim structures (Fig. 5). All analysed 21 spots are concordant and 19 of them yield ages between 2645 and 2724 Ma. One spot is clearly older and another younger yielding $^{207}Pb/^{206}Pb$ ages of 2852 and 2565 Ma, respectively. The older age is interpreted as inherited and the younger age as reflecting later disturbance. There is a negative correlation between the U concentration and the age of the zircons, likely caused by stronger lead-loss tendency of the U-rich zircons. If the two spots with U > 1000 ppm are

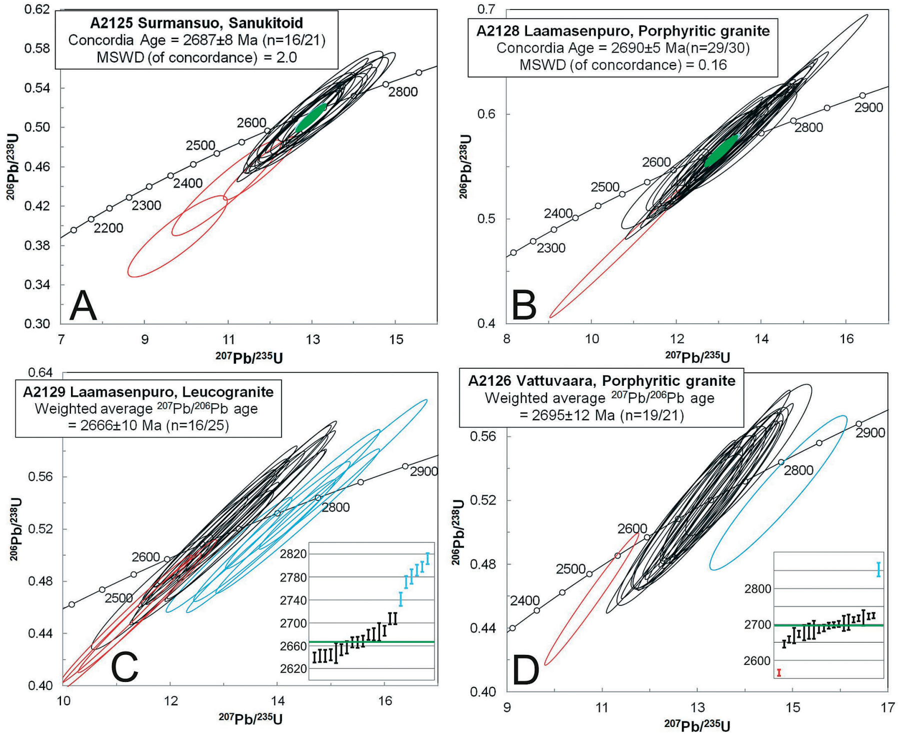


Fig. 6. Concordia diagrams for U–Pb LA-ICP-MS isotope data. Black colour indicates spots used in calculations, blue spots are interpreted as inherited, and red spots are discarded due to discordance or later disturbance. Filled green ellipsoid is the calculated concordia age. Error ellipsoids are drawn at 2σ confidence level. Figures were drawn using Isoplot version 3.70 (Ludwig, 2008). The insets (C and D) show the $^{207}Pb/^{206}Pb$ ages of the concordant zircons and the weighted average with colours as in the concordia diagrams and error bars drawn at 1σ confidence level.

excluded a concordia age of 2702±7 Ma can be calculated based on the remaining 17 spots. However, as there is no morphological differences between the spots, we interpret 2695±12 Ma, the weighted average of the $^{207}Pb/^{206}Pb$ ages (Fig. 6D) of the main population (n = 19), as the best estimate for the crystallisation age of the granite.

### *5.4. Whole-rock Sm-Nd analysis*

Whole-rock Sm-Nd isotope analyses were performed on all four geochronology samples. Initial $\varepsilon_{Nd}$-values vary from -0.4 to +0.9 (2σ = ±0.4; Table 2; Fig. 7), the lowest value is from the sanukitoid sample. Depleted mantle model ages vary from 2777 to 2885 Ma, the oldest age calculated for the sanukitoid sample. These results are within error limits similar to those previously reported for other Archean granitoids from nearby areas (Käpyaho et al., 2006, Huhma et al., 2012b, Mikkola et al., 2013) and indicate that the sources of these rocks did not include significantly older (i.e. > 3 Ga) crustal material.

## 6. Discussion

### *6.1. Ages*

Previous studies have divided sanukitoids of the Karelia Province into two different zones based on their ages, the older eastern (2740±3 Ma) and younger western (2718±3 Ma) zone (Bibikova et al., 2005; Heilimo et al., 2011). Eastern zone intrudes the Central Karelia subprovince and the western zone the Western Karelia subprovince, which the Lentua complex is part of. Anatectic

Table 2. Results of the whole-rock Sm-Nd isotope analysis.

| | | | Sm | Nd | $^{147}Sm/^{144}Nd$ | $^{143}Nd/^{144}Nd$ | t (Ma) | Initial $\varepsilon_{Nd}$ | $t_{DM}$ (Ma) |
|---|---|---|---|---|---|---|---|---|---|
| Sample | Location | Group | (ppm) | (ppm) | ±2σ | ±2σ | | | |
| A2125 | Surmansuo | Sanukitoid | 5.35 | 29.79 | 0.1086 ±4 | 0.511062 ±10 | 2687 | -0.4 | 2885 |
| A2126 | Vattuvaara | Porphyritc granite | 4.41 | 30.76 | 0.0866 ±3 | 0.510707 ±11 | 2695 | 0,4 | 2807 |
| A2128 | Laamasenpuro | Porphyritc granite | 5.87 | 39.04 | 0.0909 ±4 | 0.510809 ±10 | 2690 | 0,9 | 2777 |
| A2129 | Laamasenpuro | Leucogranite | 3.88 | 26.01 | 0.0902 ±4 | 0.510776 ±10 | 2666 | 0,1 | 2803 |

The Sm/Nd was determined using isotope dilution. Nd ratios are normalized to $^{146}Nd/^{144}Nd$= 0.7219, the initial ƐNd was calculated using present CHUR values $^{147}Sm/^{144}Nd$=0.1966 and $^{143}Nd/^{144}Nd$=0.512640 (Jacobsen and Wasserburg, 1980), and $T_{DM}$ after DePaolo (1981). Within run precision for Sm-Nd analysis is ±2δ in the last significant digits. Error in initial $\varepsilon_{Nd}$ is ±0.4 units.

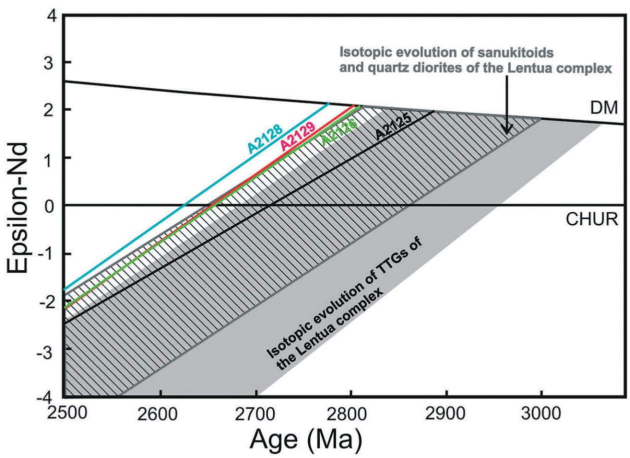


Fig. 7. Whole-rock $\varepsilon_{Nd}$ vs. age diagram for the studied samples. DM and CHUR are depleted mantle (DePaolo, 1981), and chondritic uniform reservoir (DePaolo and Wassenburg, 1976), respectively. Samples: A215 Surmansuo sanukitoid, A2126 Vattuvaara porphyritic granite, A2128 Laamasenpuro porphyritic granite, and A2129 Laamasenpuro leucogranite. Reference evolution curves are drawn after data from Huhma (1986), Käpyaho et al. (2006), Mikkola et al. (2011a), Huhma et al. (2012b) and Heilimo et al. (2013b)

leucogranites and migmatite leucosomes from the Lentua complex have yielded ages between 2.71 and 2.67 Ga (Käpyaho et al., 2006, 2007; Mikkola et al., 2011a; Lauri et al., 2011). The Surmansuo sanukitoid sample (A2125) with its 2687±8 Ma age is distinctly younger than the sanukitoids of the Western zone and coeval with the poorly constrained 2683±9 Ma age of the Siikalahti sanukitoid intrusion 45 km to the west (Käpyaho et al., 2006). The significance and the reliability of the age measurement for the Siikalahti intrusion has been questioned (Käpyaho, 2007), and its zircon O-isotope composition (Mikkola et al., 2011a) differs significantly from those of the other sanukitoid samples from the Lentua complex (Heilimo et al., 2013b). Our new data, however, indicate that the sanukitoid magmatism in the Karelia Province continued periodically for 50 Ma and that the Surmansuo and Siikalahti intrusions represent a third ~2685 Ma sanukitoid event, probably less voluminous than the two older ones.

The two porphyritic granite samples (A2126 and A2128) have ages (2695±12 Ma and 2690±6 Ma, respectively) that overlap with the age of the Surmansuo sanukitoid. The ages are similar to those previously published for anatectic leucogranitoid intrusions and the complex-wide migmatisation at 2.71–2.67 Ga, but unlike them, the porphyritic granites do not contain significant amounts of inherited zircons (Käpyaho et al., 2006, 2007; Mikkola et al., 2011a).

The 2666±10 Ma age derived of the leucogranite sample (A2129) is at the younger end of the age spectrum of previously published leucosome and leucogranitoid ages from the Lentua complex. However, as is typical for the anatectic leucogranitoids of the area, its age is not well constrained. The relatively young age and the observed scatter might result from lead loss caused by prolonged Neoarchean high-grade metamorphism following the emplacement or by the Paloproterozoic overprinting (Kontinen et al., 1992; Käpyaho et al., 2006; Mikkola et al., 2011a).

## 6.2. Geochemistry and petrogenesis

Despite the distinct age difference, the samples that fill the sanukitoid criteria from the Surmansuo intrusion are compositionally close to the Arola intrusion (Käpyaho, 2006), which is a typical representative of the $SiO_2$-rich porphyritic granodiorite intrusions of the sanukitoid suite (Figs. 3, 4). Based on recent subprovince-wide studies (Heilimo et al., 2010, 2011, 2013b), the genesis of these rocks that display enrichment in both LILE and compatible elements has been linked to partial melting of an enriched mantle source, after or during a convergent event.

Certain geochemical characteristics of the porphyritic granites could be explained as a result of mixing between leucogranite and sanukitoid magmas as they plot between the sanukitoid and leucogranite compositions. The relatively poorly defined age of the leucogranite sample is younger (2666±10 Ma) than those of the porphyritic granites and sanukitoids (2695–2680 Ma); possible explanations for this are that the sampled leucogranite represents a relatively young phase in the prolonged anatectic event or that the age difference is caused by ancient lead loss. As the porphyritic granites and sanukitoids in the Surmansuo area are coeval, and on the basis of field observations, do not form clearly separate sections, the magmas presumably interacted with each other. On the other hand, the compositional gap between them suggests that the mixing between the two likely viscose felsic magmas was inefficient. Additional geochemical complexity might have been caused by assimilation and fractional crystallization processes. Hypothetically, it would be possible to produce porphyritic granites via fractional crystallisation of sanukitoid magma and by mixing the residual magma with leucogranitoid magma. In such a case, the negative correlations of MgO and Sr relative to $SiO_2$, as observed in the sanukitoids (Figs. 3A and 3F), would indicate the fractionation of hornblende and plagioclase from the parental magmas. On the other hand, positive correlations of REE, Zr and $P_2O_5$ (Fig. 3D) relative to $SiO_2$ exclude the fractional crystallisation of apatite and other REE-carrying accessory minerals. Such cumulates have not been identified from the Lentua complex, but have been used in a model proposed to explain the evolution of the leucogranodiorite-granite suite from the Rio Maria terrane (Almeida et al., 2010), a group of rocks sharing some, but not all compositional characteristics of the sanukitoids and porphyritic granites of this study (Figs. 3, 4). Applying a model similar to that of Almeida et al. (2010) to our porphyritic granites would require large volumes of sanukitoids and their cumulates,but such have not been observed in the field at least at the current erosion level. Because 11 out of the 18 porphyritic granite samples and all leucogranitoid samples of this study are compositionally akin to the leucogranitoid samples from the northern part of the Lentua complex (Fig. 3), they can in our opinion be most readily explained as partial melts of a source that consists mainly of TTG suite rocks (Mikkola et al., 2012).

Seven out of the 18 porphyritic granite samples display $SiO_2$ values that are too low (< 68 wt.%; Electronic Appendix A) for them to be interpreted as partial melts of TTGs. Producing the Si-poor porphyritic granites from sanukitoid magma via fractional crystallisation would require efficient fractionation of mafic minerals and plagioclase in order to sufficiently reduce the Sc, V, MgO and Sr concentrations of the magma without a significant change in $SiO_2$. They cannot be explained by mixing of the observed sanukitoid and leucogranite magmas either, as Mg#, MgO and Sr are too low and $P_2O_5$ too high to fit a simple two-component mixing model (Fig. 3). The Closepet batholith, the most intensively studied Neoarchean example of interaction between mantle derived and crustal melts (Moyen et al., 2003) from the Dharwar Craton, contains porphyritic granites with roughly similar compositions to our porphyritic granites, especially in terms of $SiO_2$ and Mg# (Jayananda et al., 1995). Closer inspection, however, reveals that the porphyritic granites from Closepet are relatively enriched in $K_2O$, $P_2O_5$, LREE, Cr and Sr (Figs. 3, 4).

The compositions of the most Si-poor samples of our study match those of the partial melts derived from amphibolites via dehydration melting experiments (see compilation of Johannes and Holtz, 1996), with the exception of the relatively higher $K_2O$ (2.8–4.0 wt.%) in the former (Fig. 3C). Similar excess $K_2O$ relative to the results of the melting experiments have also been observed in the leucogranitoids of the northern parts of the Lentua complex (Mikkola et al., 2012) and in anatectic systems elsewhere (Slagstad et al., 2005). Lopez et al. (2005) performed experiments on a double-layered model to simulate the intrusion of sanukitoid magma into tonalitic crust. The experiments proved that fluids released from crystallizing sanukitoid magma efficiently transferred K into the tonalitic layer and increased its melt fertility. This model, when applied to partial melting of a source more mafic than the TTGs, could explain the high $K_2O$, low Mg# and relatively low $SiO_2$ character of these samples. Albeit amphibolites (originally basalts) are not abundant at the present level of erosion, they may be more voluminous in deeper sections as proposed by seismic studies (Kontinen and Paavola, 2006), and could likewise have produced $K_2O$-enriched magmas during interaction with the sanukitoid magma. Such a scenario would require LREE enrichement associated with the $K_2O$ transfer or alternatively melting in the stability field of garnet in order to produce magmas with strong LREE enrichment and REE fractionation from a source with unfractioned REE patterns (data in Mikkola et al., 2013). The latter option has been proposed for certain Mesoarchean granites from the Carajás Province (Feio & Dall'Agnol, 2012). An alternative source material is provided by quartz diorites which flank the Surmansuo intrusion in south and northwest (Fig. 1). In case of partial melting of these quartz diorites the melting could have occurred at shallower crustal levels as the quartz diorites themself display variably enriched LREE levels (average $La_N$ = 72) and fractionated REE patterns (average $La_N/Yb_N$ = 16) (data in Mikkola et al., 2013). The observed initial $\varepsilon_{Nd}$ values of the porphyritic granites are higher than those typical for the local TTGs, and more akin to the values of the quartz diorites (Fig. 7; Huhma et al., 2012b; Mikkola et al., 2013).

Based on the above discussion, we prefer a model of partial melting from a source consisting of TTGs and a more mafic rock type, likely the local quartz diorites, to explain the genesis of the porphyritic granites. Sc, V, MgO and Sr, all relatively depleted in porphyritic granites, are elements retained in a residue containing plagioclase and pyroxene or hornblende. Fluids released from the coeval sanukitoid magma could have transferred $K_2O$, U and Th into the sources.

Published models assessing the petrogenesis of the compositionally variable Neoarchean granite-granodiorite intrusions worldwide has produced numerous models involving different sources (crust vs. mantle), metasomatic components (fluid vs. melt) and assimilation as well as fractional crystallisation processes (e.g. Moyen et al., 2003; Almeida et al., 2010; Dey et al., 2011; Mikkola et al., 2012; Feio & Dall'Agnol, 2012). This reflects the fact that, by the Neoarchean, continental crust had become increasingly heterogeneous and at the same time the tectonic regime had evolved from "TTG only"-setting (be it subduction or not) to one accommodating a wider variety of settings for granitoid genesis. Higher Archean heat flow would have facilitated partial melting of such a heterogeneous lithosphere resulting in the wide compositional spectrum of the granitoids from this era.

## *6.3. Implications for regional crust forming processes*

Our new findings add certain limiting factors for models proposed to explain the Neoarchean evolution of the Lentua complex and adjacent areas, but they do not cause complete re-evaluation of the Neoarchean development of the area. The timeline remains mostly unchanged: TTG and greenstone belt volcanism peaked close to 2.8 Ga and subsequently gave way to Neoarchean magmatism (2.75–2.67 Ga) that consisted of sanukitoids, quartz diorites, quartz syenites and anatectic leucogranites. This evolution has been interpreted as a change from the Mesoarchean system where granitoids (i.e.

TTGs) were produced via partial melting of thickened crust or subducting slab into a Neoarchean subduction setting where sanukitoids, quartz diorites and quartz syenites were produced via partial melting of variably metasomatised mantle. The last phase of cratonisation, i.e. formation of anatectic leucogranites around 2.7 Ga was caused by heating of continental crust thickened in collision of different fragments making up the Karelia Province. (Käpyaho et al., 2006, 2007; Halla et al., 2009; Heilimo et al., 2011; 2013b; Mikkola et al., 2011a, 2011b, 2012, 2013; Huhma et al., 2012a)

The young age of the Surmansuo sanukitoid requires that any setting proposed for the genesis of the sanukitoids and their source should explain how the melting of the sanukitoid magma source, if not also the formation of the source, continued periodically for 50 Ma. This long-lasting and periodic sanukitoid activity fits the proposed subduction model in which fluids and melts from the subducting slab modify the composition of the mantle wedge and several successive slab breakoffs trigger partial melting (Lobach-Zhuchenko et al, 2008; Halla et al., 2009; Heilimo et al., 2010). Based on the temporal constraints, i.e. the concurrent generation of anatectic leucogranites, the slab breakoff responsible for the 2685 Ma sanukitoid event would have been the one following the final collision between Central and Western Karelia.

Furthermore, our new findings, together with other recent studies (Heilimo et al., 2010, 2011, 2013a; Mikkola et al., 2011a, 2011b, 2013), emphasise the temporal overlap and the compositional heterogeneity of the different Neoarchean granitoid suites of the Lentua and its adjacent complexes. The majority of the sanukitoid intrusions are 2.74 and 2.72 Ga old, whereas the majority of the quartz diorites are 2.70 Ga old, although ages up to 2.74 Ga have also been reported for the latter (Mikkola et al., 2013). Furthermore, a separate 2.74–2.70 Ga quartz syenite suite has been recognised (Mikkola et al., 2011b; Heilimo et al., 2013a). These magmatic episodes were followed by migmatisation and leucogranitoid magmatism at 2.70–2.69 Ga (Heilimo et al., 2011; Mikkola et al., 2011a). On the other hand, the youngest sanukitoids are 2.69–2.68 Ga in age (Käpyaho et al., 2006; this study) and thus temporally overlap with the anatectic leucogranites.

# 7. Conclusions

The Surmansuo intrusion of porphyritic granodiorite–granite contains parts with clear compositional characteristics of the sanukitoid suite, but consists mainly of rocks that cannot be included into the sanukitoid suite.

Age of the Surmansuo sanukitoid (2687±8 Ma) indicates that sanukitoid magmatism occurred in the Lentua complex at least to some extent 30 Ma after the “main event” of the Western sanukitoid zone (avg. 2718±3 Ma).

Some of the described porphyritic granites represent a new addition to the wide compositional spectrum of the 2.71–2.67 Ga leucogranitoid magmatism, mostly because of their low $SiO_2$ content. They indicate that, at least locally, also source(s) more mafic than the TTGs (e.g. quartz diorites) were partially melted and contributed to the genesis of anatectic granites in the Lentua complex.

The Neoarchean granitoid magmatism following the TTG formation in the Lentua complex is not a straightforward continuum, but more likely represents a wide range of compositionally distinct magmatic events that overlap in time and space. This heterogeneity is likely related to tectonic evolution from a subduction setting to a collisional environment.

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# Supplementary data

Electronic Appendices A and B for this article are available via Bulletin of the Geological Society of Finland web page.

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