Bulletin of the Geological Society of Finland, Vol. 96, 2024, pp 59–80 https://doi.org/10.17741/bgsf/96.1.003

1.88 Ga granitoids at Sorsakoski, Central Finland: A-type magmatism within the Raahe-Ladoga suture zone

Perttu Mikkola[1*], Maija Pietilä[2], O. Tapani Rämö[2] and Hannu Huhma[3]

[1]*Geological Survey of Finland, Viestikatu 7, 70211 Kuopio, Finland*
[2]*University of Helsinki, Department of Geosciences and Geography, Gustaf Hällströmin katu 2, 00014 Helsinki, Finland*
[3]*Geological Survey of Finland, Vuorimiehentie 5, 02151 Espoo, Finland*

Abstract

Four quartz monzonite – granite intrusions forming the Sorsakoski granite lithodeme, are found within the Raahe-Ladoga suture zone in Central Finland. The prevailing potassium feldspar megacrystic quartz monzonites and granites form a bimodal association with diorites and gabbros. The granitoids are mainly calc-alkaline, ferroan, per- to metaluminous, and have high Zr and REE contents. Dominant mafic minerals are biotite and hornblende, clinopyroxene and orthopyroxene are locally present. The mafic units display effects of fractionation of clinopyroxene. In our interpretation, these intrusions were emplaced during regional late stages of deformation and post-crystallisation deformation partitioned into major shear zones leaving bulk of the intrusions relatively undeformed. Based on one new (1876 ± 6 Ma) and one pre-existing (1882 ± 5 Ma) U-Pb zircon age determination, the crystallisation age of the granitoids can be assumed at ca. 1880 Ma. Based on mineralogy, petrography, geochemistry, bimodal nature of magmatism and age, we correlate these intrusions to the A-type rocks of the previously described Saarijärvi suite. This shows that the syn-orogenic A-type magmatism extended eastwards beyond the Central Finland Granitoid Complex.

Keywords: Central Finland Granitoid Complex, Paleoproterozoic, geochemistry, zircon age, U-Pb, A-type, granite, diorite, bimodal, Svecofennian, Finland

*Corresponding author (e-mail: perttu.mikkola@gtk.fi)

Editorial handling: Jarmo Kohonen (email: jarmo.kohonen@helsinki.fi)

1. Introduction

Much of the Precambrian bedrock of south-central Finland is characterised by granitoids and their lower-silica counterparts. Studying and classifying these abundant rocks has a long history (e.g., Sederholm 1932; Simonen 1960, 1980), which has led to the current classification into preorogenic, synorogenic (with synkinematic and postkinematic subclasses), lateorogenic and postorogenic rocks. These classes are based on distribution, absolute and relative ages, tectonic setting, interpreted source rocks and whole-rock geochemical composition (Nironen 2005). The intensively studied postkinematic group (e.g., Elliott et al. 1998; Nironen et al. 2000; Rämö et al. 2001; Elliot 2003; Nikkilä et al. 2016; Virtanen & Heilimo 2018; Halkoaho et al. 2020) comprises locally voluminous 1880–1860 Ma intrusions displaying A- and C-type granite affinities within and around the Central Finland Granitoid Complex (CFGC; Fig. 1), marking the latest major magmatic event in this area. A-type granites are relatively alkaline, have high Fe/Fe+Mg ratios, high contents of SiO_2, Zr, Nb, Y, Ga and Ce, and low CaO and Sr. (e.g. Whalen et al., 1987). C-type granitoids contain magmatic pyroxene, have high K_2O, TiO_2, P_2O_5, LILE, Zr and low CaO at given SiO_2 level when compared to other more common granitoid types (Kilpatrick & Ellis, 1992).

Nironen et al. (2000) divided the postkinematic plutons into three types: Type 1 intrusions are peraluminous and found within the supracrustal belts that surround the CFGC in the south; Type 2 intrusions are metaluminous to peraluminous, high in SiO_2, Fe- and F-enriched and resemble the classic A-type rapakivi granites (Rämö & Haapala 1995); Type 3a and 3b intrusions are also metaluminous to peraluminous and unlike Types 1 and 2 contain magmatic pyroxene and show C-type granite affinity (Elliott 2003). In Type 3a pyroxene is constrained to phases along the intrusion boundaries whereas in Type 3b pyroxene is present throughout. Excluding Type 1, the geochemical differences between the types are mainly subtle and the classification is largely based on the mineralogical differences.

The unit division used in this study follows Geological Survey of Finland's (GTK) unit database (Finstrati). In the applied lithodemic classification (NACSN 2005; Strand et al. 2010), the granitoids (lithodemes) are assembled to 'suites' in a way that suite forms a regional assemblage of lithodemes with similar lithological characteristics. The most relevant lithodemic units, their key characteristics and references are listed in Table 1.

The purpose of this paper is to describe and characterize the potassium feldspar megacrystic granitoid intrusions in the Sorsakoski area east of the CGFC using petrographical and geochemical methods as well as U-Pb zircon geochronology. The results are used to evaluate the source and petrogenesis of the Sorsakoski granitoids and their correlation with the A- and C-type intrusions in Central Finland (see e.g. Nironen et al. 2000). The paper is based on the unpublished M.Sc. thesis of the second author (Pietilä 2020).

2. Geological setting and previous studies

Our study area is located within the broad, NW-trending Raahe-Ladoga shear complex that overprints a the Raahe-Ladoga suture zone, which separates the Archaean province in the east from the Svecofennian province in the west (Fig. 1, Kohonen et al. 2021). The eastern crustal province consists of Archaean complexes and their Paleoproterozoic cover sequence, whereas the western province is characterized by Svecofennian (Paleoproterozoic) granitoids, metasedimentary and metavolcanic rocks. The voluminous paragneisses of the Suonenjoki suite (Fig. 2) surrounding the studied intrusions have been interpreted as turbiditic sediments with maximum depositional age of ~1.91 Ga and metamorphosed in upper amphibolite facies during the 1.9–1.8 Ga Svecofennian orogeny (Mikkola et al. 2016, 2022; Hölttä & Heilimo 2017). The paragneisses are associated with

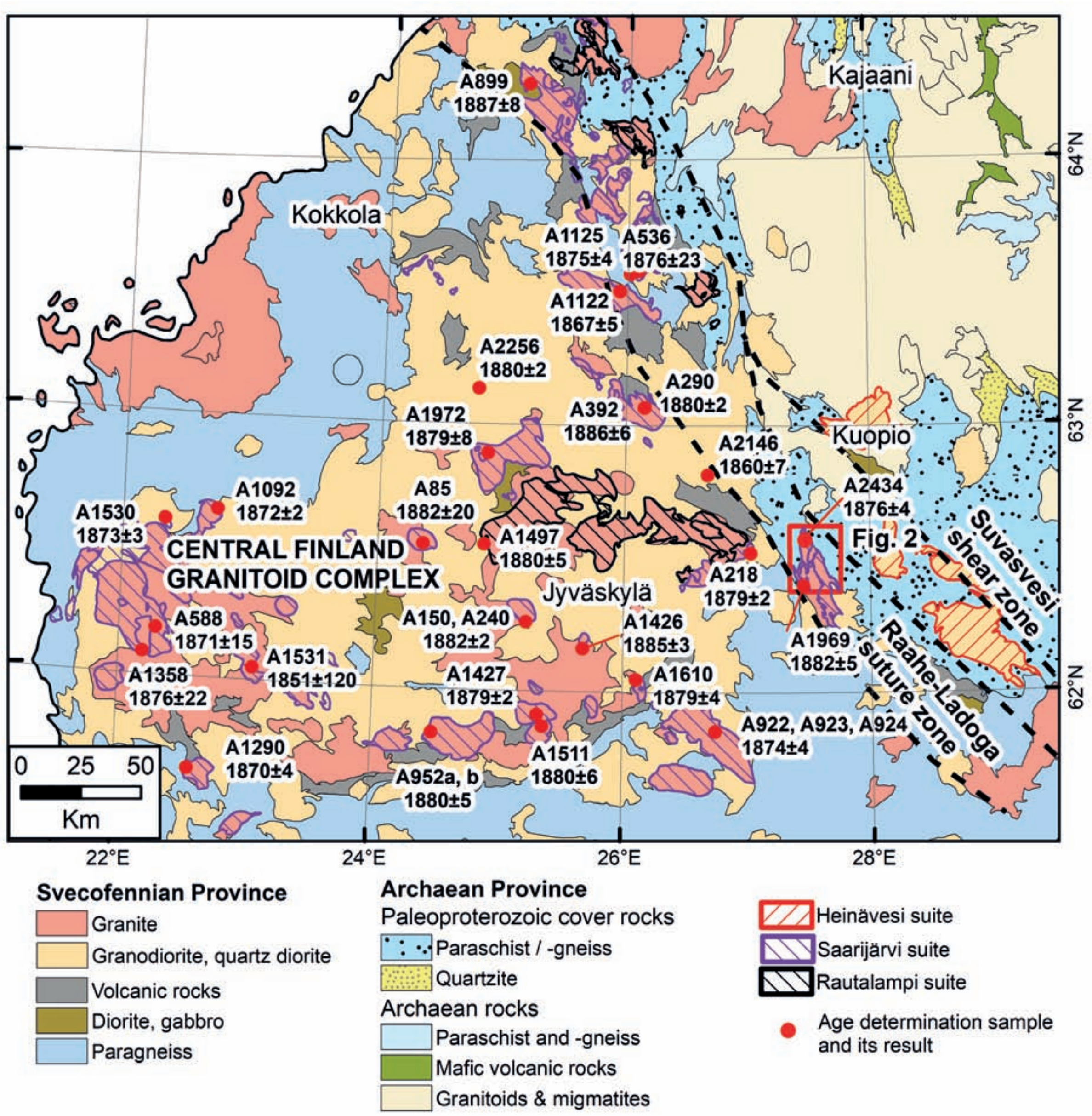

Fig. 1. Geological map of south-central Finland, modified from Bedrock map of Finland - DigiKP and Nironen et al. (2016). Age data for Saarijärvi and Rautalampi suite intrusions are from Huhma (1986), Nironen & Front (1992), Kousa et al. (1994), Kilpeläinen (1998), Mäkitie & Lahti (2001), Rämö et al. (2001), Lahtinen et al. (2016), Nikkilä et al. (2016), Heilimo et al. (2023) and this study.

hornblende gneisses that have been tentatively linked (Bedrock of Finland – DigiKP) to the older Svecofennian (ca. 1.93–1.91 Ga) magmatism within the approaching arc prior the collision with the Archaean Karelia craton (Lahtinen et al. 2015; Kousa et al. 2018; Huhma et al. 2021).

The mafic intrusions of the Kotalahti suite crystallised from tholeiitic basalt melts with EMORB characteristics and vary, as a result of fractional crystallisation, from ultramafic to dioritic. Based on data from the Kotalahti type area (Fig. 2) they were emplaced into the Raahe–Ladoga suture

Table 1. Main characteristics and references to the relevant intrusive suites. Granitoid type classification of postkinematic intrusions according to Nironen et al. (2000).

Lithodemic main unit	Spatial extent (see Fig. 1)	Rock types	Mafic minerals	Chemical chracteristics	References
Saarijärvi suite (1885–1860 Ma)	CFGC and its proximity				
Granitoid type 1	Southwest boundary zone of CFGC	Granodiorite Monzogranite	Biotite	Peraluminous Alkali-calsic Eu-anomaly - Magnesian/Ferroan A/CNK 1.01–1.28 SiO_2=61.5–72.7 wt.%	Nironen et al. 2000
Granitoid type 2	CFGC	Monzogranite	Biotite ± hornblende	Met- to peraluminous Alkali-calsic Eu-anomaly - Ferroan A/CNK 0.93–1.13 SiO_2=61.7–76.7 wt.%	Nironen et al. 2000 Virtanen & Heilimo 2018
Granitoid type 3a	CFGC	Monzogranite Quartz monzonite Quartz syenite	Biotite, hornblende ± pyroxene (in intrusion margins)	Met- to peraluminous Alkali-calsic Eu-anomaly -/+ Ferroan A/CNK=0.90–1.12 SiO_2=51.9–72.6 wt.%	Nironen et al. 2000 Virtanen & Heilimo 2018
Rautalampi suite Granitoid type 3b (~1880 Ma)	East CFGC Northern Raahe–Ladoga suture zone	Granodiorite Quartz monozonite	Biotite, hornblende, pyroxene ± olivine	Met- to peraluminous Alkali-calsic Eu-anomaly -/+ Ferroan A/CNK=0.84–1.08 SiO_2=51.9–72.6 wt.%	Nironen et al. 2000
Kotalahti suite (1885–1880 Ma)	Raahe–Ladoga suture zone	Ultramafic cumulates Gabbro Diorite	Olivine, pyroxenes, amphiboles	Tholeiitic basalt EMORB characteristics	Gaál 1980 Makkonen 2015
Heinävesi suite (~1870 Ma)	Southeast Karelia Province	Granite, granodiorite, locally diorites	Biotite, hornblende in diorites	I-type Magnesian Calc-alkaline Peraluminous	Lahtinen et al. 2016 Rantanen 2021
Haukivesi intrusive suite (1880–1870 Ma)	Raahe–Ladoga suture zone	Granitoids Dioritoids	Biotite, hornblende	I-type (Some with S-type characteristics) Magnesian Calc-alkaline Met- to peraluminous	Lahtinen et al. 2016 Mikkola et al. 2022

zone at 1885–1880 Ma (Gaál 1980). This period was also the peak of calc-alkaline plutonism and volcanism that characterised the CFGC from 1895 to 1875 Ma (e.g., Nironen 2017; Mikkola et al. 2018a and references therein).

In addition to the Sorsakoski granite intrusions, the study area also hosts intrusions that have been classified as part of the Haukivesi suite (Table 1, Fig. 2). The Haukivesi suite consists of rocks varying in composition from quartz diorite to granite, which have been dated from two locations at 1882 ± 6 and 1872 ± 9 Ma (Fig. 2; Lahtinen et al. 2016; Mikkola et al. 2022). The geochemical composition of the Haukivesi suite has not been described in detail, but this suite having mainly I-type characteristics also displays certain S- type characteristics. This is in contrast with the coeval, clearly I-type Heinävesi suite granitoids on the eastern side of the suture zone (Rantanen 2021; Mikkola et al. 2022). For example, the Haukivesi suite displays on average higher Mg#, A/NK and La_N. than the Heinävesi suite. The presence of S-type granitoid component correlates with the commonly higher degree of partial melting of the paragneisses within the Raahe–Ladoga suture zone compared to the areas farther east (Mikkola et al. 2016, 2022).

The last voluminous magmatism within and around the CFGC is represented by the A- and C-type megacrystic granitoids, which form a bimodal association with diorites and gabbros as a minor mantle sourced mafic component. The A- and C-type granitoids have been interpreted to derive mainly from lower crustal melts, and based on field relationships they postdate the main phase of calc-alkaline magmatism (1885–1875 Ma) although the obtained U-Pb ages overlap when experimental errors are considered (e.g., Rämö et al. 2001; Virtanen & Heilimo 2018; Heilimo et al. 2023). Owing to their relatively undeformed character, these rocks have also been referred to as postkinematic in respect to prominent deformation in the CFGC area, and their more deformed calc-alkaline host rocks as synkinematic (Nironen et al. 2000). The postkinematic intrusions seem to have been emplaced within or in proximity of major shear zones, which controlled their emplacement within an extensional or transtensional regime after the main compressional period of the Svecofennian orogeny (Nironen 2017). In a more recent lithodemic unit division (Table 1), postkinematic intrusions are represented by the Saarijärvi and Rautalampi suites (Fig. 1). The suites show some correlation to the postkinematic granitoid types of Nironen et al. (2000, see Table 1). However, in case of less studied intrusions, the distinction between the suites is mainly based on presence of pyroxene; intrusions with pyroxene throughout belong to the Rautalampi suite and those with pyroxene only in intrusion margins to the Saarijärvi suite (Bedrock of Finland − DigiKP). The Saarijärvi and Rautalampi suite granitoids are typically coarse porphyritic with alkali feldspar megacrysts. They range from biotite-hornblende quartz monzonite to syenogranite, may include iron-enriched pyroxene and olivine and show polybaric, reduced liquid lines of descent (from 2-4 to 5-7 kbar, DFMQ from -0.3 to -1.5; Elliott et al. 1998).

The studied intrusions in the Sorsakoski area form a 40-km-long and 10-km-wide entity in the core of the Raahe–Ladoga suture zone, named as the Sorsakoski granite lithodeme in the unit nomenclature applied by GTK. It consists of four intrusions: Sorsavesi, Karvalevä, Löytölamminvuori and Ruuhilamminsuo (Fig. 2). As the southern parts of the Sorsavesi intrusion lack the compositional variation from quartz monzonite to granite (Pekkarinen 2002) it was excluded from this study focusing on the compositional variation within the intrusions. In addition to the four main intrusions, a number of smaller ones not studied here have been incorporated in the Sorsakoski lithodeme (Fig. 2). The lithodeme consists mainly of megacrystic quartz monzonite and granite in addition to lesser amount of diorite and gabbro (Pääjärvi & Äikäs 2005; Mikkola et al. 2016). Lahtinen et al. (2016) reported a zircon U-Pb age of 1882 ± 5 Ma for the Ruuhilamminsuo intrusion (Fig. 2). About 20 km west of the study area, the pyroxene-bearing Haukilampi intrusion of the Rautalampi suite was dated at 1879 ± 2 Ma (Lahtinen et al. 2016).

3. Materials and methods

The area was mapped and most of the samples were collected during GTK's national mapping program (Pääjärvi & Äikäs 2005). Additional sampling and revision mapping were carried out in 2018. Thin sections or polished thin sections were prepared from all samples selected for analyses. Analytical data for all analysed samples include the main elements and certain trace elements determined using the X-ray fluorescence method (XRF) on pressed pellets. Eight samples were analysed for full

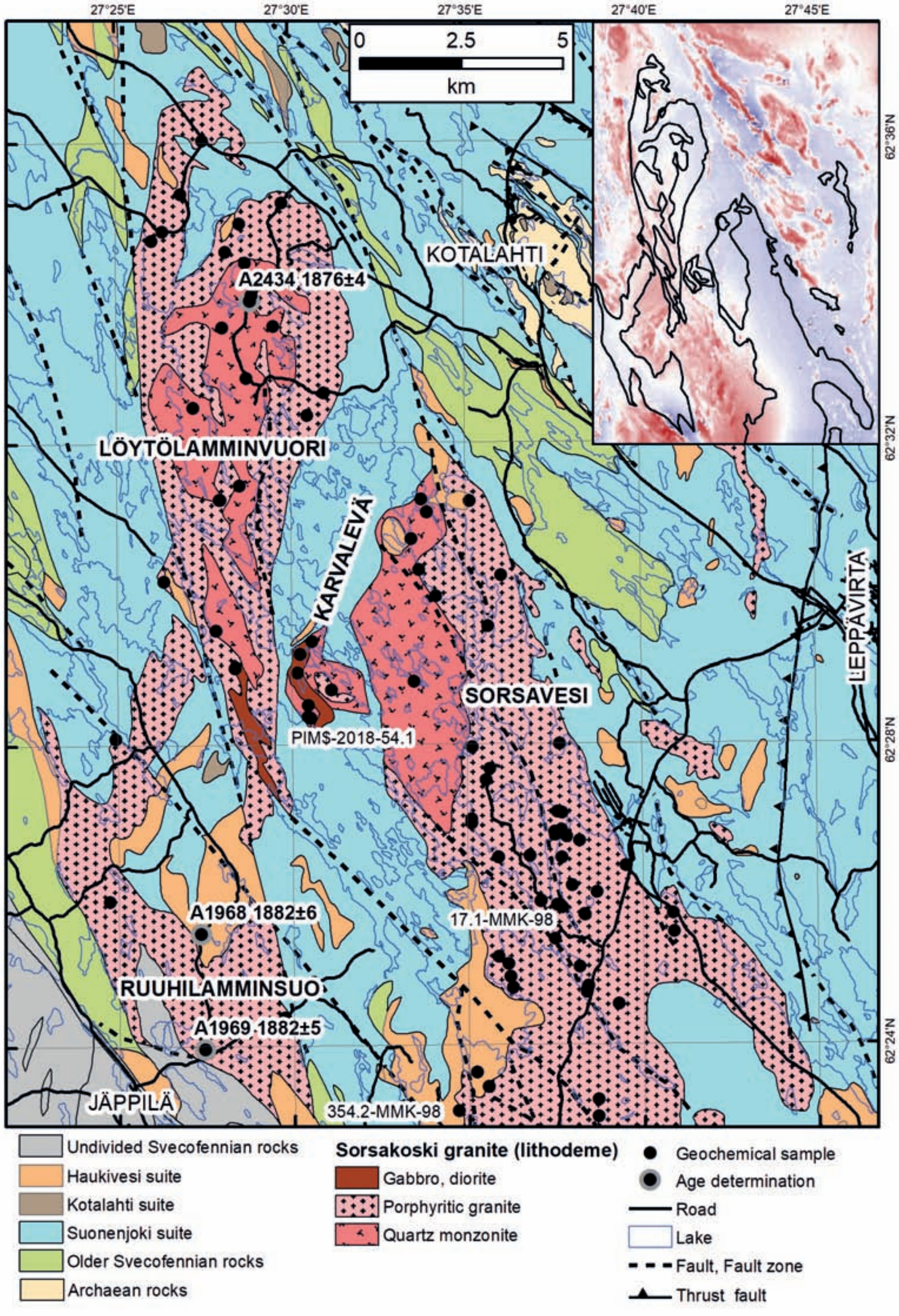

Fig. 2. Geological map of the study area with sample locations indicated. Geological map modified after Bedrock of Finland - DigiKP. Age determination sample locations A1968 and A1969 are from Lahtinen et al. (2016). In inset aerogeophysical map of the same area with outlines of the intrusions belonging to the Sorsakoski granite. Basemap © National Land Survey.

trace element spectra using the inductively coupled plasma mass spectrometry method (ICP-MS). The total number of previously unpublished whole-rock analyses is 93. Four analyses from Rasilainen et al. (2007) were added to the data set. The older sample set was analysed in the geochemical laboratory of GTK and the later data set in Labtium Ltd. All analytical results can be found from the Electronic Appendix. Applied analytical methods are described in detail by Rasilainen et al. (2007). Plotting of geochemical data was done using Geochemical Data Toolkit (GCDkit) version 6.0 (Janoušek et al. 2006).

An in-situ zircon U-Pb age determination was made from one granitoid sample using a Nu Plasma AttoM single collector ICPMS connected to a Photon Machine Excite laser ablation system at the Geological Survey of Finland in Espoo. Measurements were made directly from thin sections. In-house standard A382 (1877 ± 2 Ma; Huhma et al. 2012) was used for calibration and in-house standard A1772 (2711 ± 3 Ma/TIMS; 2712 ± 1 Ma/SIMS; Huhma et al. 2012) as well as the GJ-01 zircon standard (609 ± 1 Ma; Belousova et al., 2006) as reference data. Detailed description of the applied method can be found in Molnár et al. (2018). The U-Pb results were calculated using Isoplot/Ex 4.15 program (Ludwig 2003) with 2σ errors and excluding decay constant errors.

4. Results

4.1 Field observations and petrography

4.1.1 Granitoids

The Löytölamminvuori, Sorsavesi, Karvalevä and Ruuhilamminsuo intrusions consist mainly of megacrystic granite and quartz monzonite (Fig. 2, Fig. 3a), collectively referred to as megacrystic granitoids. The euhedral to subhedral potassium feldspar megacrysts are typically 2 to 4 cm across and make up 20 to 30% of the rock, in some cases up to 50%. In outcrop, the megacrystic granitoids appear unoriented or weakly oriented, excluding intensively mylonitized shear zones (Fig. 3d) varying in width from few centimetres to tens of meters and typically NW-trending. Country rock xenoliths (paragneisses and granitoids) are relatively common, locally abundant and in most cases display sharp contacts with the host rock. Crosscutting equigranular leucocratic granitoid dykes varying in width from tens of centimetres to 20 metres are also present. The leucogranites appear typically as nearly vertical dykes but also as larger "pockets" which are tens of meters across without clear continuations. These pockets plausibly represent shallow dipping parts t of the dyke network.

Biotite is the dominant mafic mineral in the megacrystic granitoids, and hornblende is also relatively common. Pyroxenes (both clino- and orthopyroxene) are only present in the quartz monzonite samples. Biotite is present both as a primary phase and as an alteration product of hornblende. Both primary and secondary biotite are locally chloritized, in some cases strongly. Potassium feldspar in the groundmass is variably orthoclase or microcline. The former is more abundant in the Löytölamminvuori and Karvalevä intrusions and the latter is common for the Sorsavesi and Ruuhilampi intrusions. In a small number of samples microperthite is observed. Narrow rims of quartz and plagioclase (Fig. 3e) mantle some of the potassium feldspar megacrysts visually resembling the rapakivi texture. Sericitization of both feldspars is relatively common, as are weak signs of shear-induced deformation. Typical accessory minerals are apatite, zircon, titanite, epidote and opaque minerals. Garnet is present in few locations in vicinity of paragneiss xenoliths. Leucogranites contain variable amount of biotite and secondary muscovite and chlorite. Two of the samples contain also small garnet grains. Structure varies from unoriented hypidiomorphic to strongly sheared.

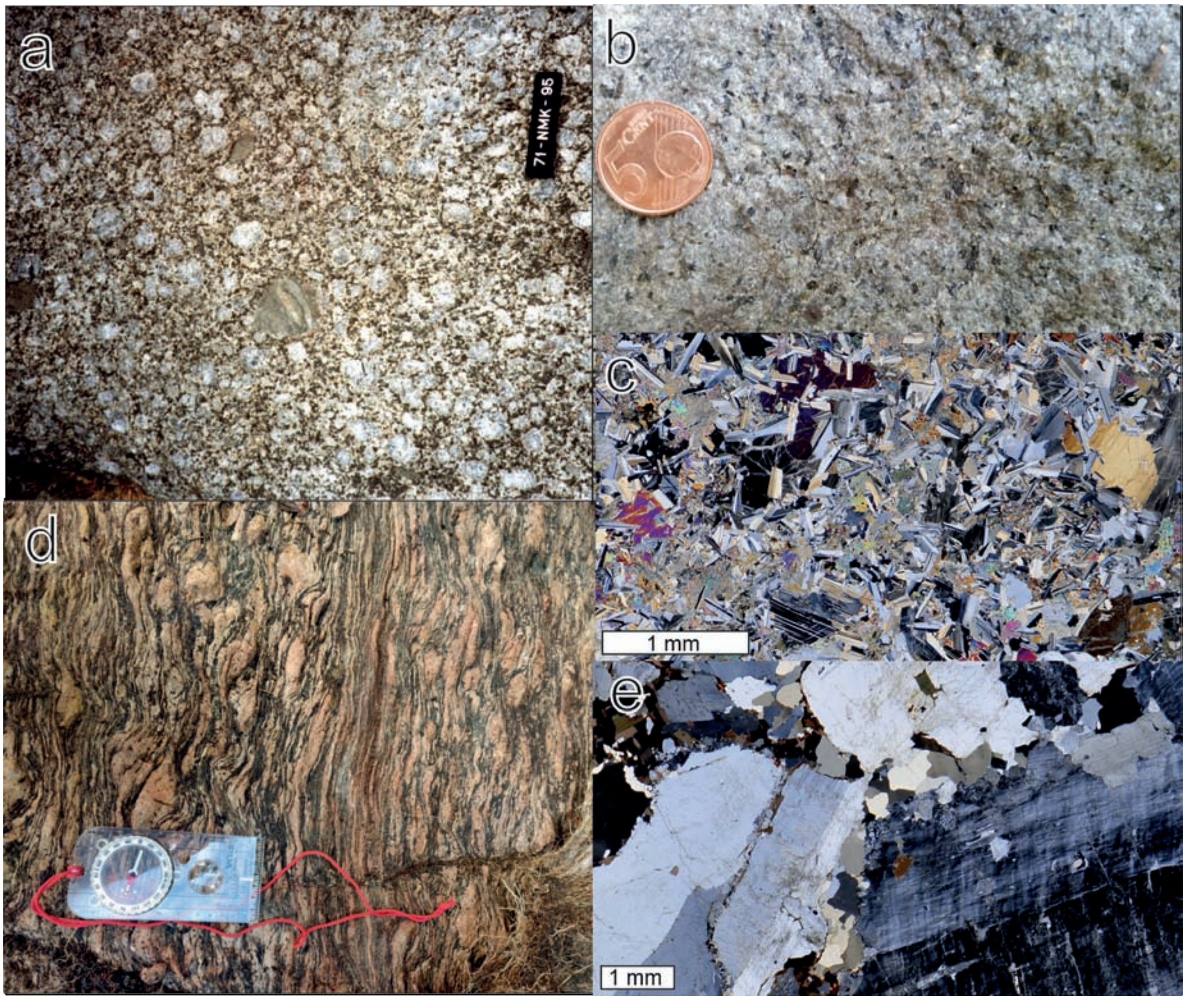

Fig. 3. a) Megacrystic granite from northern contact of the Löytölamminvuori intrusion, in the middle two small paragneiss enclaves with sharp contacts. Length of scale bar 15 cm. Photo: Nina Hendriksson/GTK. b) Diorite from the Karvalevä intrusion, diameter of the coin 21 mm. c) Photomicrograph of a fine-grained diorite sample from Karvalevä intrusion under crossed polarized light, showing unoriented texture with plagioclase laths and intercumulus pyroxene. Pyroxene has locally been altered to biotite and chlorite. Photo: Tarja Neuvonen/GTK. Width of field of view 4 mm. d) Intensively mylonitized megacrystic granite. Photo: Sara Huusansaari. e) Photomicrograph of a megacrystic granite from the Löytölamminvuori intrusion under crossed polarized light. Potassium feldspar in the lower right corner is mantled by fine-grained quartz. Width of field of view 8 mm. Photo: Tarja Neuvonen/GTK.

4.1.2 Diorites and gabbros

The mafic magmatic component is most voluminous in the Karvalevä intrusion where it forms more than 20% of the mapped surface area (Figs. 2, 3b). Larger mafic units are present also in the southern part of the Löytölamminvuori intrusion. The observed contacts between the porphyritic granitoids and mafic rocks are sharp, and mafic dykes crosscut the Sorsavesi and Karvalevä intrusions. Evidence of magma mingling was found in one outcrop only. The megacrystic granitoid forms a network surrounding rounded diorite mingling fragments, and the diorite contains a small number of potassium feldspar megacrysts captured from the granitoid magma during emplacement.

The mafic rocks from the Karvalevä intrusion display a texture of unoriented plagioclase laths and interstitial pyroxene (Fig. 3c). Orthopyroxene is present in all the samples from the Karvalevä intrusion and clinopyroxene in half of them. Poorly crystallised amphibole and biotite are variably present as alteration products of pyroxene, the latter also as a primary mineral. In the most altered rocks biotite is altered to chlorite. Potassium feldspar and quartz are also locally present. Oxides and apatite are the typical accessory minerals.

4.2 Geochemistry

4.2.1 Felsic rocks

Both within the individual studied intrusions, and in the Sorsakoski granite as a whole, the megacrystic granitoids mostly display a clear negative correlation between SiO_2 and other major elements. However, K_2O (Fig. 4e) shows a weak positive correlation and a large scatter. SiO_2 concentration shows a continuous trend from 55.3 to 75.5 wt.%. On average, the Sorsavesi intrusion is more felsic than the Löytölamminvuori intrusion. Scatter in K_2O is likely related to the uneven distribution of potassium feldspar megacrysts.

Ba and Zr concentrations of the megacrystic granitoids scatter, but are typically high, 199–2880 ppm (average 1246 ppm) and 80–733 ppm (average 364 ppm), respectively, and display negative correlation with SiO_2 (Figs. 4f, h). Chondrite-normalised REE patterns of the megacrystic granitoids display moderate LREE enrichment over HREE with $(La/Yb)_N$ values from 11.3 to 18.1 (Fig. 5). On average the Eu-anomaly (Eu/Eu*=0.45–0.96) is negative and more pronounced in samples from the Löytölamminvuori intrusion than in those from the Sorsavesi intrusion.

Samples PIM$-2018-54.1 (Karvalevä intrusion) and 17.1-MMK-98 (Sorsavesi intrusion) deviate from the main trends and plot below the general trend of the megacrystic granitoids in respect to Zr and P_2O_5 (Figs. 4d, f). The former also deviates from the trend with higher Mg# and lower Na_2O, the latter with higher K_2O and Al_2O_3 together with lower FeOt. The high K_2O and Al_2O_3 combined indicate that 17.1-MMK-98 likely represents a potassium feldspar cumulate. For PIM$-2018-54.1 see discussion.

The leucogranitic dykes and pockets (n=6) show calc-alkaline characteristics and are silica rich with SiO_2 ranging from 71.80 to 77.50 wt.%. Differences to the most felsic members of Sorsakoski granite and Haukivesi suite are insignificant (Figs. 4, 5). In respect to the trace element concentrations, the group is heterogeneous, e.g., Sr varies from 12 to 196 ppm, Zr from 59 to 349 ppm and Ba from 44 to 916 ppm.

4.2.2 Mafic rocks

The mafic units included to the Sorsakoski granite lithodeme (n=11) do not display significant spread in SiO_2 (48.3–53.0 wt.%) and the samples from Karvalevä intrusion form a relatively tight group in the diagrams, whereas the samples from the Sorsavesi intrusion display a spread in several elements, e.g., Al_2O_3, MgO, P_2O_5, CaO and Zr (Fig. 4). One anomalous sample (354.2-MMK-98, Sorsavesi intrusion) displays very high K_2O, Ba and Zr concentrations, 4.46 wt.%, 1096 ppm and 757 ppm, respectively. The one sample from Löytölamminvuori intrusion has higher TiO_2, FeOt, P_2O_5, Sr and lower Mg# and Cr compared to the ones from Karvalevä intrusion (TiO_2, FeOt, Cr not shown). In turn, it has similar concentrations as some of the mafic rocks from the Sorsavesi intrusion for these elements. Because of the small spread in SiO_2, and small sample number silica-controlled concentration trends cannot be identified. It is, however, clear that, in respect to most elements, the mafic members do not plot on the same trend as the megacrystic granitoids and that there is a distinct compositional gap between the groups. LREE enrichment is weak ($(La/Yb)_N$=2.0–2.71) and Eu-anomaly small (Eu/Eu*=0.84–1.22).

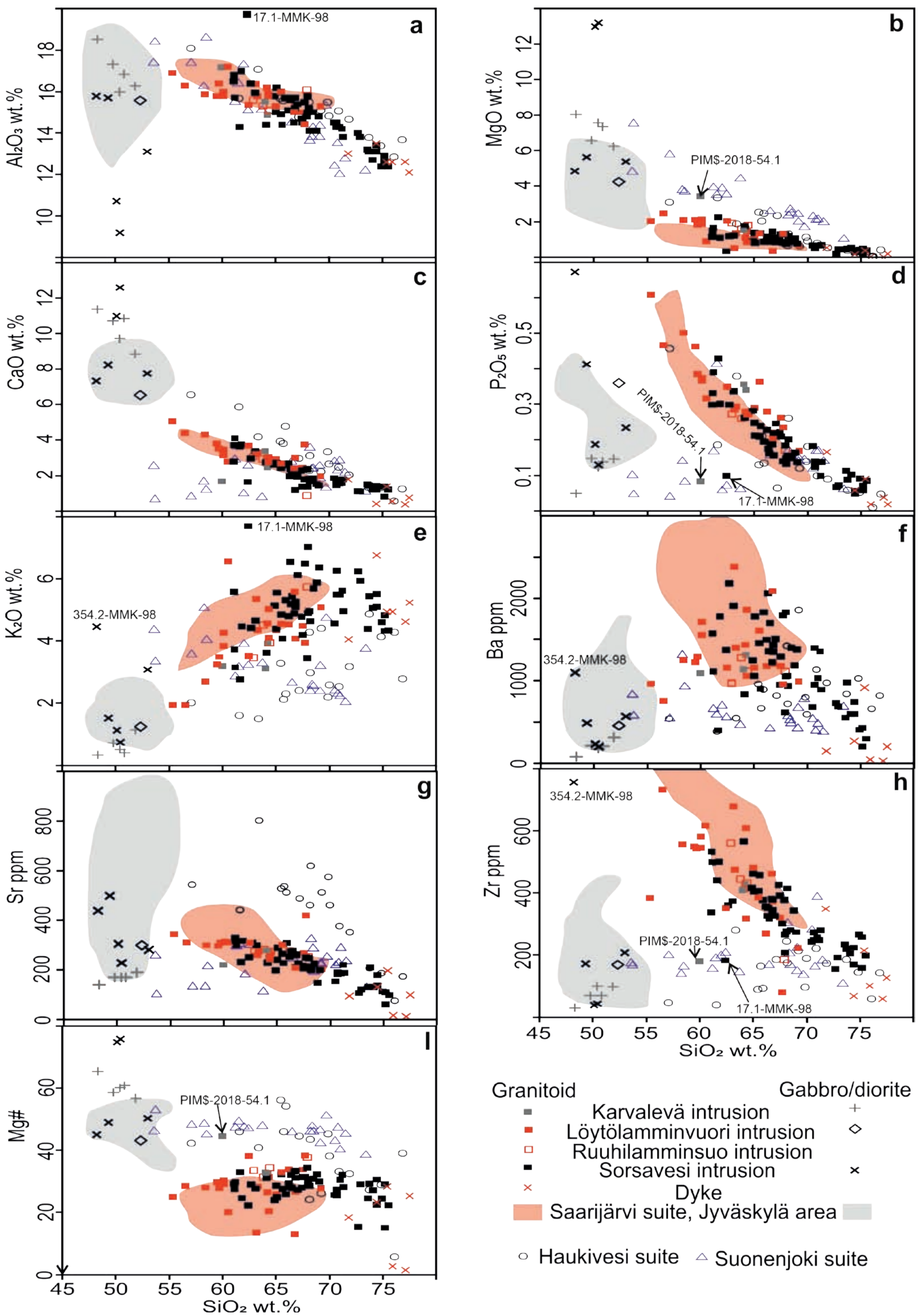

Fig. 4. Harker diagrams for the Sorsakoski granite and associated mafic rocks. a) Al_2O_3, b) MgO, c) CaO, d) P_2O_5, e) K_2O, f) Ba, g) Sr, h) Zr and i) Mg#. Reference data for Suonenjoki and Haukivesi suites from Rasilainen et al. (2007) and Mikkola et al. (2016, 2022). Saarijärvi suite intrusions from Jyväskylä area (Types 2 and 3a) are based on data from Virtanen & Heilimo (2018). Note that in D the high-P_2O_5 (P_2O_5 ~1.5 wt.%) subtype of the Saarijärvi suite mafic intrusions not observed within our study area and is not plotted.

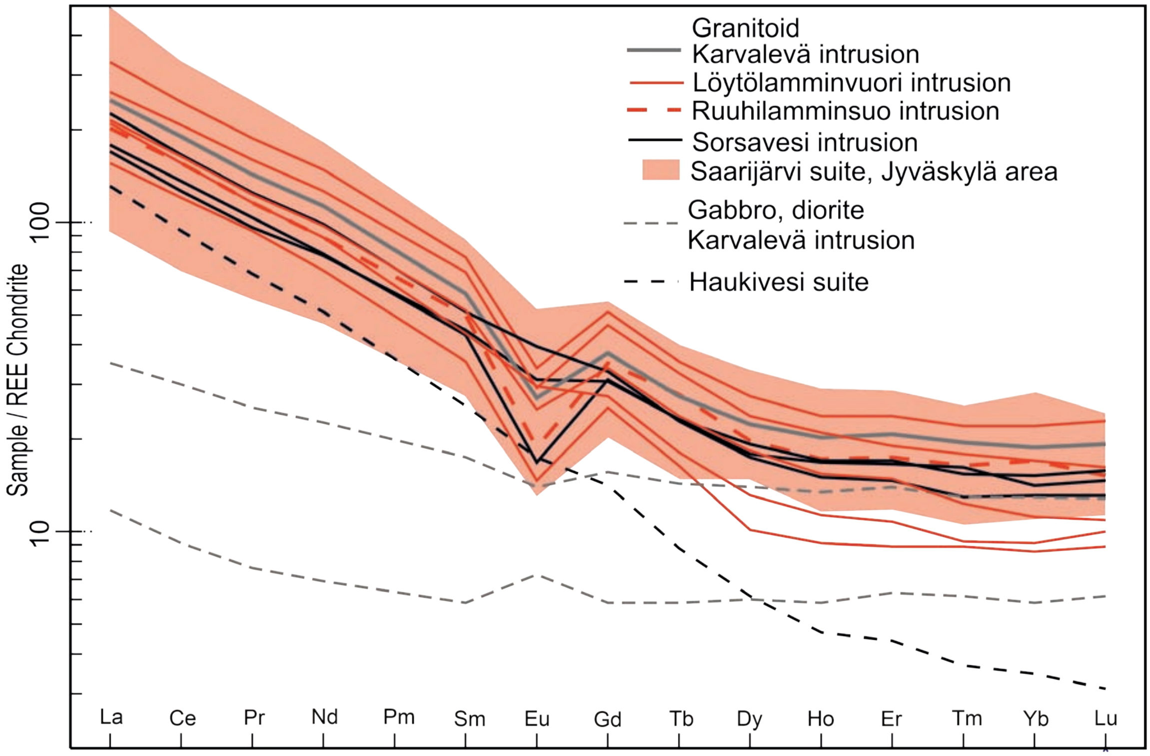

Fig. 5. Chondrite-normalised REE patterns of the Sorsakoski granite and associated mafic rocks. Median value for Haukivesi samples is shown for reference. Normalisation values from Boynton (1984).

4.3 U-Pb geochronology

Sample A2434 Vehkalamminvuori represents the quartz monzonite core of the Löytölamminvuori intrusion (Fig. 2). Zircon grains are typically prismatic, 100–200 µm in size. They display oscillatory zoning and some crystals exhibit core-rim structures. Altogether 51 spots from 39 individual grains were analysed. All but one slightly older spot (1945 ± 38 Ma), measured from a core yield $^{207}Pb/^{206}Pb$ ages spanning from 1848 to 1899 Ma (Fig. 7). Scatter prevents calculation of a concordia age, but we regard the weighted average $^{207}Pb/^{206}Pb$ age, 1876 ± 4 Ma, calculated excluding the one outlier, as well constrained and reliable estimate of the crystallisation age of the quartz monzonite.

5. Discussion

5.1 Classification of the Sorsakoski granite

The overall geochemistry of the Sorsakoski granite is similar to that of the Saarijärvi suite in (1) high REE and Zr concentrations and (2) ferroan and alkali-calcic character (Figs. 4, 5, 6). However, certain differences with other Saarijärvi suite intrusions can be identified, as the Sorsakoski granite is slightly more peraluminous in addition to having lower Y and Nb; because of the latter features the Sorsakoski granite plots in the volcanic arc field (Fig. 5e). Geochemically the Sorsakoski granite resembles both Type 2 and 3a of Nironen et al. (2000). For example, the observed SiO_2 range 55.3–75.50 wt.% covers that of both types, which are 61.7–76.7 and

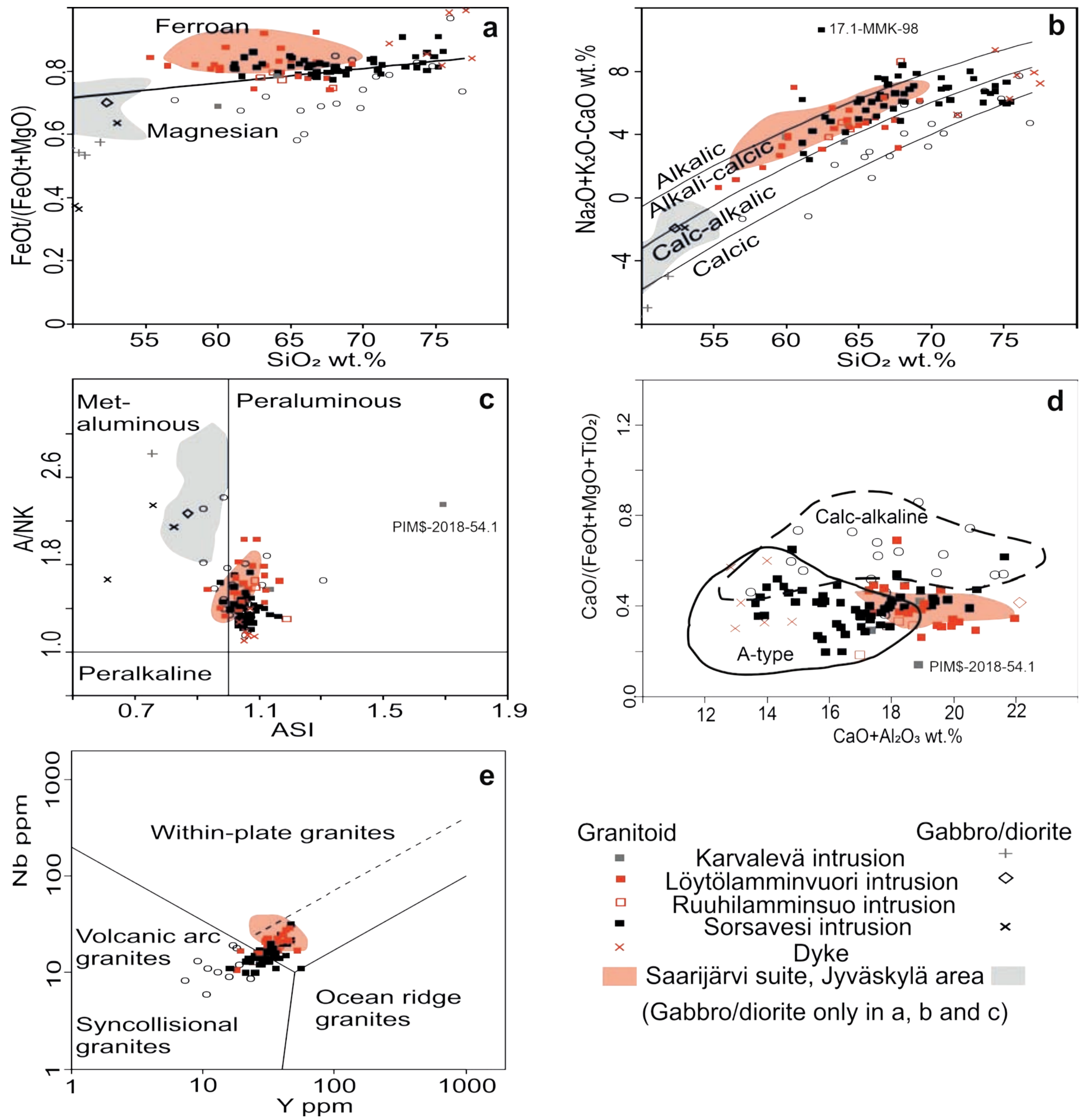

Fig. 6. Classification diagrams for the Sorsakoski granite intrusions and associated mafic rocks. a) Fe-number vs, SiO_2 for ferroan – magnesian classification (Frost et al. 2001). b) Calcic-alkalic classification (Frost et al. 2001). c) A/CNK – A/NK diagram. d) $CaO+Al_2O_3$ vs. $CaO/(FeOt+MgO+TiO_2)$ diagram of Dall'Agnol & Oliveira (2007). e) Y vs. Nb diagram of Pearce et al. (1984). Reference data as in Fig. 4.

57.2–71.4 wt.% for Types 2 and 3a, respectively. The observed variably negative Eu-anomaly, average 0.69 is also intermediate to that of type 3a 0.94 than 0.37 of type 2. TiO_2 and Al_2O_3 concentrations of the Sorsakoski granite averaging 0.69 and 15.2 wt.%, respectively, are similar to those of the type 3a, 0.67 and 15.7 wt.% and distinctly higher than those of Type 2, 0.35 and 13.9 wt.%. Perhaps the clearest chemical characteristic are the FeOt/(FeOt+MgO) values, as the averages are 0.81, 0.86 and 0.92 for Sorsakoski granite, Type 3a and Type 2, respectively. It should be noted that Types 2 and 3a follow the

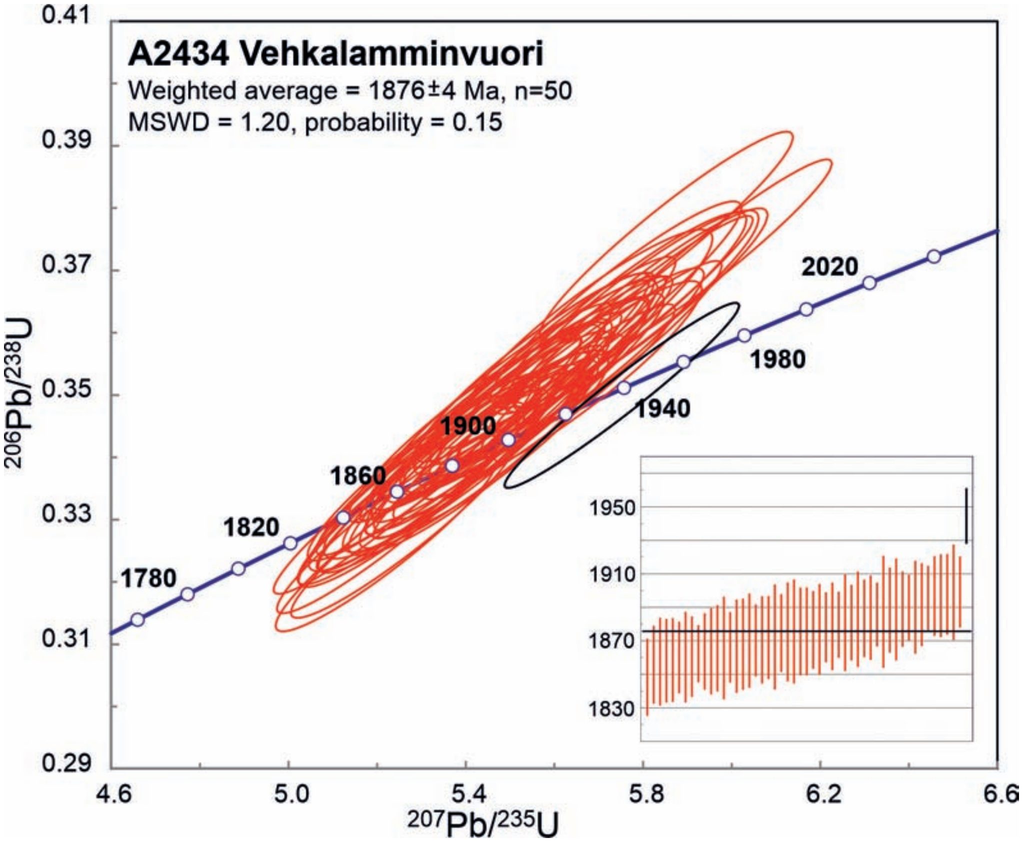

Fig. 7. U-Pb concordia diagram of the analysed quartz monzonite sample A2434. The one older core is drawn in black. In inset $^{207}Pb/^{206}Pb$ ages of the spots. Data plotted at the 2σ level.

same fractionation trends and the compositional differences largely attribute to the more felsic character of Type 2 and the classification of Nironen et al. (2000) relies also significantly on mineralogy.

The mineral characteristics of the Sorsakoski granite, containing biotite and hornblende as mafic minerals throughout the intrusions and pyroxene only locally compare to the Type 3a (Elliot et al. 1998, Nironen et al. 2000) and sets it apart from the Rautalampi suite (Nironen et al. 2000: Type 3b) for which pyroxene is characteristic. In the Sorsavesi and Löytölamminvuori intrusions, these pyroxene-bearing varieties are found also within the plutons, not just in the outer rims of the intrusions. In the model proposed by Nironen et al. (2000) the change in Type 3a from pyroxene to hornblende bearing mineral assemblage is attributed to a change from reduced to oxidised conditions. As the studied intrusions do not show such systematic changes it could be possible that the pyroxene bearing and quartz monzonitic variants represent a different magma pulse than the granitic variants which typically have only hornblende and biotite as mafic minerals.

The proportion of mafic component of the Sorsakoski granite lithodeme is voluminously small, except for the Karvalevä intrusion. This is not uncommon as other intrusions of the Saarijärvi suite display significant differences in felsic/mafic ratios (Bedrock of Finland – DigiKP; Nironen et al. 2000; Rämö et al. 2001; Virtanen & Heilimo 2018).

The observed spread in the Sorsakoski mafic samples in Al_2O_3, MgO, P_2O_5 and CaO is most likely related to accumulation of clinopyroxene later variably altered to amphibole. As a whole, the compositions resemble those reported for the Saarijärvi suite by Nironen et al. (2000) and Virtanen & Heilimo (2018), although they are slightly less evolved (Fig. 4, higher Mg#). Similarities also include mineral paragenesis as the studied mafic samples dominantly consist of plagioclase, biotite, hornblende and pyroxenes in addition to quartz in the more felsic cases. The one compositional outlier (354.2-MMK-98) with high K_2O, Ba and Zr concentrations is however interesting (Fig. 4). Increase in K_2O and Ba in this sheared potassium feldspar bearing sample could be caused by metasomatism, but this is an unlikely explanation for the elevated Zr. Despite its lower TiO_2 and higher Mg# values the sample displays certain resemblance with the Zr and Sc enriched Kiviniemi ferrodiorite intrusion (Halkoaho et al. 2020) 50 km to the northwest from our study area, suggesting that processes that formed this world class scandium deposit could have operated elsewhere as well.

5.2 Sources and magmatic evolution

Genetic models for the Saarijärvi suite granitoids involve mantle derived melts intruding the lower crust and, in doing so, causing partial melting (e.g. Nironen et al. 2000; Elliott 2003; Virtanen & Heilimo 2018). These crustal melts interact, to a varying extent, with the mafic melts to form the voluminous granitoid magma, which is then emplaced higher up in the crust. A small fraction of the initial mantle melts rises through the crust without significant interaction with felsic melts and forms the less voluminous mafic component of the bimodal system. Stronger involvement of the mantle-derived melts would also explain the relatively high Mg# (25–35) of the Saarijärvi suite compared to the typical A-type rocks (e.g., Elliot 2003; Virtanen & Heilimo 2018).

An alternative explanation, however, is that the studied intrusions are C-type. Kilpatrick & Ellis (1992) interpreted C-type as being crystallised from exceptionally high temperature melts from dehydrated, yet fertile, lower crust. The low H_2O content and weakly magnesian character of the magma formed under these conditions would have resulted in stabilization of pyroxene. In addition to the moderate Mg#, also the high K_2O, Zr, Ba, TiO_2 and low CaO of Sorsakoski granite support the C-type classification. However, P_2O_5 is lower than what would be characteristic for C-type. Granitoid magmas crystallising pyroxene, however, do range from iron enriched to magnesian and the existence of a specific C-type has been challenged by Frost et al. (2000) who concluded that pyroxene can crystallise regardless of the magma composition if water activity is low enough. Only in low-Mg systems, anhydrous mafic rock-forming mineral assemblages may stabilize without water activity as the prime variable (cf. Frost et al., 2001). Following this reasoning the change from pyroxene bearing to pyroxene free assemblage in Sorsakoski granite, and Saarijärvi suite Type 3a intrusions in general, would be due to enrichment of magma in water during crystallisation.

The geochemical variation within the Saarijärvi suite was interpreted by Nironen et al. (2000) to represent differences in the composition of the lower crust sources (Nironen et al. 2000). The Al_2O_3, Ba and Sr contents are higher in the Saarijärvi suite than in typical A-type granites. The high Al_2O_3 concentration results in a number of samples plotting beyond the A-type field on the $CaO+Al_2O_3$ versus $CaO/(FeOt+MgO+TiO_2)$ diagram (Fig. 6d). Also, the ASI values are relatively high at low SiO_2 concentrations (~1.0 at 60 wt.% SiO_2). Enrichment in feldspar-compatible (Al_2O_3, Ba, K_2O) elements has been interpreted as the result of the crustal source component having melted under high pressure, leaving behind a clinopyroxene-rich residue (cf. Elliott 2003). As the Sorsakoski granites intruded dominantly into paragneisses, the elevated Al_2O_3 and Ba could be explained by interaction of S-type granitoid melts or assimilation of the country rock. However, as also Sr is elevated and the Sorsakoski granite has similar A/CNK values (0.90–1.15) than the Saarijärvi suite intrusions in the Jyväskylä area (0.93–1.11) emplaced into calc-alkaline granitoids (Virtanen & Heilimo 2018), significant involvement of S-type magmas seems unlikely. It should also be noted that the Type 1 intrusions of the Saarijärvi suite, interpreted to have been derived from dominantly metasedimentary sources (Nironen et al. 2000) have, on average, distinctly higher A/CNK varying from 1.01 to 1.28 (Nironen et al. 2000). Based on the above we conclude that metasedimentary sources only played a limited role in the genesis of the currently studied intrusions. Additionally, the effect of assimilation during ascent was probably limited, despite the locally abundant paragneiss xenoliths. This is in line with the observation that the xenoliths have sharp contacts with their host rock and that the granitoids form mainly a clear fractionation trend without scatter into the direction of the paragneisses (Fig. 4).

Based on field observations, the contacts between the mafic and felsic units are sharp and limited interaction between the magmas is also supported by the compositional gap between the granitoid and mafic samples. Composition of only one sample (PIM$-2018-54.1) suggests mixing of the two magma types with e.g., its relatively low Zr, P_2O_5 and high Mg#, 180 ppm, 0.08 wt.% and 45 respectively, falling between the two compositional groups (Fig, 4). Interaction limited to local mingling between the compositional end members has been described by Virtanen & Heilimo (2018).

The shift from alkali-calcic to calc-alkalic, displayed by the most felsic members of the Sorsakoski granite, is not typical for magmatic evolution of A-type associations in which the calc-alkalic intrusives typically form separate batholiths (cf. Frost & Frost 2011). The Sorsakoski samples with calc-alkalic affinity are from the central parts of the Sorsavesi intrusion, but also a large number of samples with alkali-calcic compositions are from the same area. The calc-alkalic nature is mainly caused by lower K_2O and is combined with slightly higher Zr (Fig. 4), which is difficult to explain by varying fractionation of potassium feldspar or biotite. Instead, it could be the result of a separate magma pulse. Calc-alkalic compositions are contributed to either melting of quartzofeldspathic sources (Dall'Agnol & Oliveira 2007) or fractional crystallisation of tholeiitic magma (Lindsley et al. 1969). Theoretically the tholeiitic magmas of the Kotalahti suite could have fractionated far enough to produce the Sorsakoski granite. As A-type granitoids formed by such extensive fractional crystallisation should have very high FeOt/(FeOt+MgO) not observed in Sorsakoski granite this is an unlikely explanation.

Negative correlation between SiO_2 and Ba, together with positive correlation between SiO_2 and K_2O (Fig. 4), indicates that the concentration of K_2O was controlled by a cotectic phase other than potassium feldspar. Most likely this was biotite, present as primary mafic mineral with relatively high K_D for Ba (Ewart & Griffin 1994).

5.3 Age correlations and regional geological significance

The U-Pb zircon age of the Löytölamminvuori intrusion (1876 ± 4 Ma) is robust and can be taken as reliable estimate of its crystallisation age. The one observed older core is inherited, most likely incorporated from the surrounding paragneisses as their detrital population contains zircon grains with similar ages (Mikkola et al. 2022). The obtained crystallisation age is typical for both the Saarijärvi and Rautalampi suites (Fig. 1) and overlaps within error with the age of Ruuhilamminsuo (1882 ± 5 Ma, Lahtinen et al. 2016) and the Haukilampi intrusion 20 km farther west (1879 ± 2 Ma, Lahtinen et al. 2016). The age of the Kiviniemi intrusion, 1860 ± 7 Ma (50 km NE, Halkoaho et al. 2020), however, shows that the magmatism resulting in intrusion of Saarijärvi suite rocks continued in the area for 20 Ma. It should also be noted that close to 1.86 Ga the suture zone was also intruded by numerous mafic to felsic intrusions and dykes tapping an enriched mantle lithosphere source (Kontinen et al. 2013a, b).

The Kotalahti suite intrusions and the mafic component of the Saarijärvi suite are both interpreted as mantle melts variably modified during ascent. In our study area these units are found in spatially overlapping areas and our

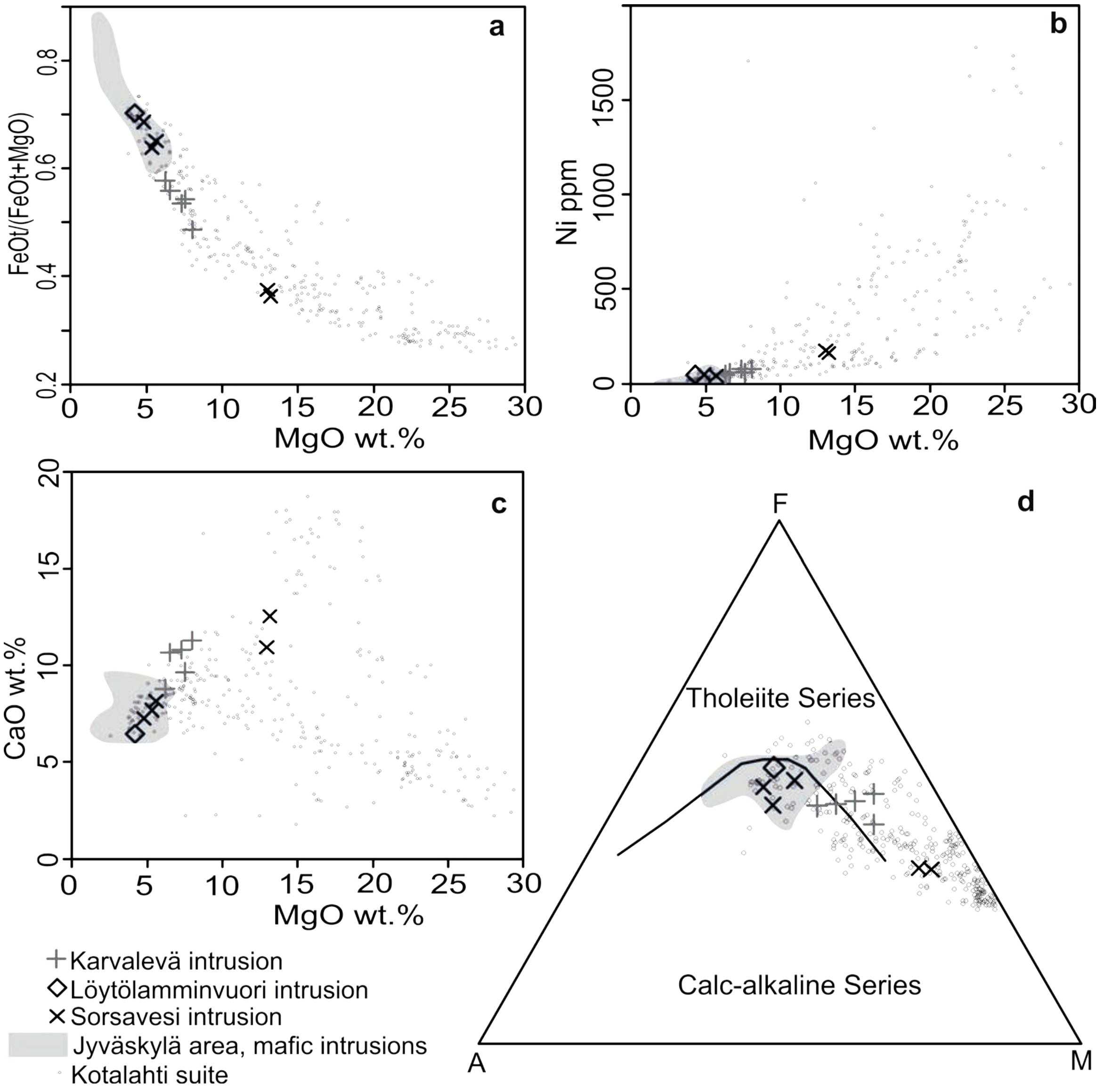

Fig. 8. Mafic samples from the Sorsakoski lithodeme plotted on a) MgO vs.FeOt/(FeOt+MgO) b) MgO vs. Nic) MgO vs. CaO and d) Al2O3-FeOt-MgO diagram (AFM, Irvine & Baragar 1971) diagrams. As reference data the mafic members of the Saarijärvi suite from Jyväskylä area (Virtanen & Heilimo 2018) and unmineralized Kotalahti suite samples with SiO_2=40–55 wt.% from Leppävirta (Makkonen, unpublished data, n=333).

samples, interpreted as belonging to the Saarijärvi suite, overlap in composition with the more evolved members of the Kotalahti suite (Fig. 8). Especially the samples from the Karvalevä intrusion plot outside the field defined by samples from Jyväskylä area, and it should be noted that even the Jyväskylä samples are less evolved than the samples from westernmost CFGC where the Mg# is typically <40 (Nironen et al. 2000). This overlap has been earlier discussed by e.g., Peltonen (2005) who noted that some of the mafic intrusives of the Saarijärvi suite could represent highly evolved members of the Kotalahti suite.

East of the Raahe–Ladoga suture zone, the Heinävesi suite granitoids (Fig. 1) overlap in age within error with the Sorsakoski granite, although all nominal values point to a slightly younger age (1865 ± 6, 1868 ± 7 and 1870 ± 2 Ma, Lahtinen et al. 2016). Rantanen (2021) concluded on geochemical bases that the main source of Heinävesi suite, which consists of I-type, peralkaline, calc-alkaline rocks straddling the ferroan–magnesian boundary, was mainly Archaean felsic crust. Additionally, also the Heinävesi suite contains a small amount of more mafic mantle-derived magmas. Based on the observed differences of coeval granitoid magmas, the Sorsakoski granite and Heinävesi suite are one more indication of the eastern boundary of the Svecofennian lower crust capable of producing significant volumes of A-type magmas when intruded by mafic magmas from the mantle.

Based on two published age determinations (1882 ± 6 & 1872 ± 9 Ma, Lahtinen et al. 2016, Mikkola et al. 2022) the less voluminous, and poorly studied, Haukivesi suite within the Raahe–Ladoga suture zone also overlaps in age with the Sorsakoski granite but differs from it geochemically. Compared to the Haukivesi suite granitoids, the Sorsakoski megacrystic granitoids are poor in CaO and rich in K_2O, Zr and REE (Figs. 4, 5). Furthermore, they are mainly ferroan, alkali-calcic and slightly peraluminous, whereas the Haukivesi suite granitoids are mainly magnesian and calcic to calc-alkalic (Fig. 6). Haukivesi suite has also compositional similarities with the Heinävesi suite but has for example slightly higher MgO values and a more metaluminous nature (Mikkola et al. 2022). The available geochemical data do not show any clear signs of mixing between rocks of the Haukivesi suite and Sorsakoski granite. The question whether the leucogranite dykes represent the last remaining melt fractions of the Sorsakoski granite or belong to the Haukivesi suite is challenging with only compositional data at hand. The observed compositional characteristics could represent end members of both systems as the compositional differences between the granitoids of the two suites disappear in the most fractionated samples (Fig. 4). One indirect evidence favouring them as part of the Sorsakoski granite is that representatives of the more mafic compositions of the Haukivesi suite were not observed to cut the megacrystic intrusions. To further characterise the sources and study the potential interrelationships between the magmatic units in vicinity of the Sorsakoski granite, radiogenic isotopic methods (e.g., Sm–Nd, Lu–Hf) should be utilised.

5.4. Structural setting

The youngest major structures in the Raahe–Ladoga suture zone are approximately NW-trending shear zones which can be detected on aeromagnetic maps (Fig. 2); the observed mylonite zones in the Sorsakoski granite intrusions are outcrop expressions of these. Shear zones with similar NW-SE orientation are observable throughout CFGC and appear close to some of the Saarijärvi suite intrusions and some are crosscut by these zones. Nironen et al. (2000) interpreted that these zones controlled the emplacement of the Saarijärvi suite intrusions in an extensional or transtensional regime after the main compressional period of the Svecofennian orogeny. Kotalahti suite intrusions present in the vicinity of, and overlapping in age with, the Sorsakoski granite (1883 ± 6 Ma, Gaál 1980) have also been interpreted as being emplaced in a transtensional setting (Peltonen 2005).

The Sorsakoski granite appears internally unoriented or weakly oriented, which is somewhat unexpected, as the intrusions are within the large shear zones which remained active until 1.80 Ga (Nironen 2017). This indicates that post-crystalisation deformation was not continuous and penetrative but partitioned into distinct shear zones. The ragged form of the intrusions (Fig. 2) together with the schistosity of the enveloping paragneisses being parallel to the contacts (Pääjärvi & Äikäs 2005) suggest deformation during or after their emplacement. In the case of syn-emplacement deformation, originally single magma flux may have departed into separate intrusions. Such dynamic crystallisation environment could also explain occurrence of the pyroxene bearing variants as patches and not along the intrusion contacts according to the ideal model of Nironen et al. (2000). Assesment of the structural regime during emplacement in detail would however require detailed structural observations beyond the scope of this study. The obtained crystallisation ages of the Sorsakoski granite match the timing of the regional D3 (Mikkola et al. 2022). The mylonite zones indicate that shearing continued after crystallisation, but age of the last observed activity cannot be solved based on the available information.

Geochemically and mineralogically, the Sorsakoski granite is similar to the rocks of the Saarijärvi suite, and thus correlative to post-kinematic class of Nironen et al. (2000). However, the term postkinematic refers to "prominent deformation within the area" (Nironen et al. 2000); as the Sorsakoski granite was plausibly emplaced within an active shear complex, it cannot be regarded literally as postkinematic.

6 Conclusions

The potassium feldspar megacrystic quartz monzonites and granites of the Sorsakoski area are calc-alkalic A-type intrusive rocks, which form, together with less voluminous diorites and gabbros, a bimodal association. This extends the occurrence of the syntectonic A-type granites towards east and clearly outside the Central Finland Granitoid Complex.

In the lithodemic unit classification of GTK, the Sorsakoski granite lithodeme is incorporated into the Saarijärvi suite.

The obtained age of the Löytölamminvuori intrusion (1876 ± 6 Ma) corresponds to ages typical for the granitoids classified to Saarijärvi and Rautalampi suites

The Sorsakoski granite was emplaced into the Raahe–Ladoga suture zone, plausibly within a shear complex, during the late stages of the regional deformation.

Acknowledgements

There are two types of projects: shorter and longer. This one clearly belongs to the latter as it managed to linger on from the late 1990s to 2023. Over the years, it showed significant resilience by surviving all GTK's organisational restructurings, retirements and career changes of all the experts initially involved and yet was blessed, when needed, with understanding, support and funding from several managers to all of whom we are grateful. We also acknowledge the work of everyone involved in gathering the original field data and samples during the bedrock mapping in the Sorsakoski area. Hugh O'Brien and Yann Lahaye from GTK's isotope laboratory are thanked for keeping the LA-SC-ICPMS running. We also acknowledge the helpful reviews by Dr Mikko Nironen and an anonymous reviewer. Editor Jarmo Kohonen provided also numerous valuable suggestions.

Supplementary Data

Electronic Appendices are available via Bulletin of the Geological Society Finland web page.

Electronic Appendix A: Analytical data

References

Bedrock of Finland – DigiKP. Digital map database [Electronic resource]. Espoo: Geological Survey of Finland [referred 31.03.2022].

Boynton, W. V., 1984. Cosmochemistry of the rare earth elements: meteorite studies. In: Henderson, P. (ed.) Rare earth element geochemistry. Amsterdam: Elsevier, 63–114.

Dall'Agnol, R. & Oliveira, D. C., 2007. Oxidized, magnetite-series, rapakivi-type granites of Carajás, Brazil: Implications for classification and petrogenesis of A-type granites. Lithos 93, 215–233. https://doi.org/10.1016/j.lithos.2006.03.065

Elliott, B. A., 2003. Petrogenesis of the Post-kinematic Magmatism of the Central Finland Granitoid Complex II; Sources and Magmatic Evolution. Journal of Petrology 44, 1681–1701. https://doi.org/10.1093/petrology/egg053

Elliott, B. A., Rämö, O. T. & Nironen, M., 1998. Mineral chemistry constraints on the evolution of the 1·88–1·87 Ga post-kinematic plutons in the Central Finland Granitoid Complex. Lithos 45, 109–129. https://doi.org/10.1016/S0024-4937(98)00028-0

Ewart, A. & Griffin, W. L., 1994. Application of Proton-Microprobe Data to Trace-Element Partitioning in Volcanic-Rocks. Chemical Geology 117, 251–284. https://doi:10.1016/0009-2541(94)90131-7

Frost, C. D. & Frost B. R., 2011. On Ferroan (A-type) Granitoids: their Compositional Variability and Modes of Origin. Journal of Petrology 52, 39–53. https://doi.org/10.1093/petrology/egq070

Frost, B. R., Arculus, R. J., Barnes, C. G., Collins, W. J., Ellis, D. J. & Frost, C. D., 2001. A geochemical classification of granitic rocks. Journal of Petrology 42, 2033–2048. http://dx.doi.org/10.1093/petrology/42.11.2033

Frost, N. R., Frost, C. D., Hulsebosch, T. P. & Swapp, S. M., 2000. Origin of the Charnockites of the Louis Lake Batholith, Wind River Range, Wyoming. Journal of Petrology 41, 1759–1776. https://doi.org/10.1093/petrology/41.12.1759

Gaál, G. 1980., Geological setting and intrusion tectonics of the Kotalahti nickel-copper deposit, Finland. Bulletin of the Geological Society of Finland 52, 101–128. https://doi.org/10.17741/bgsf/52.1.005

Halkoaho, T., Ahven, M., Rämö, O. T., Hokka, J. & Huhma, H., 2020. Petrography, geochemistry, and geochronology of the Sc-enriched Kiviniemi ferrodiorite intrusion, eastern Finland. Mineralium Deposita 55, 1561–1580. https://doi.org/10.1007/s00126-020-00952-2

Heilimo, E., Mikkola, P., Ahven, M., Huhma, H., Lahaye, Y. & Virtanen, V. J., 2023. Evidence of crustal growth during the Svecofennian orogeny: New isotopic data from the central parts of the Paleoproterozoic Central Finland Granitoid Complex. Precambrian Research 395, 107–125. https://doi.org/10.1016/j.precamres.2023.107125

Hölttä, P. & Heilimo, E., 2017. Metamorphic map of Finland. Geological Survey of Finland, Special Paper 60, 77–128.

Huhma, H., 1986. Sm–Nd, U–Pb and Pb–Pb isotopic evidence for the origin of the early Proterozoic Svecokarelian crust in Finland. Geological Survey of Finland, Bulletin 337, 52 p.

Huhma, H., Kousa, J. & Luukas, J., 2021. Geochronology of the Paleoproterozoic Pyhäsalmi-Vihanti district, central Finland. GTK Open File Research Report 8/2021, 31 p.

Huhma, H., Mänttäri, I., Peltonen, P., Kontinen, A., Halkoaho, T., Hanski, E., Hokkanen, T., Hölttä, P., Juopperi, H., Konnunaho, J., Layahe, Y., Luukkonen. E., Pietikäinen. K., Pulkkinen, A., Sorjonen-Ward, P., Vaasjoki, M. & Whitehouse, M., 2012. The age of the Archaean greenstone belts in Finland. In: Hölttä, P. (ed.), The Archaean of the Karelia Province in Finland. Geological Survey of Finland, Special Paper 54, 74–175.

Irvine, T. N. & Baragar, W. R. A., 1971. A Guide to the Chemical Classification of the Common Volcanic Rocks. Canadian Journal of Earth Science, 8, 523–548. https://doi.org/10.1139/e71-055

Janoušek, V., Farrow, C. M. & Erban, V., 2006. Interpretation of whole-rock geochemical data in igneous geochemistry: introducing Geochemical Data Toolkit (GCDkit). Journal of Petrology 47, 1255–1259. https://doi.org/10.1093/petrology/egl013

Kilpatrick, J. A. & Ellis, D. J., 1992. C-type magmas: igneous charnockites and their extrusive equivalents. Transactions of the Royal Society of Edinburgh: Earth Sciences 83, 155–164. https://doi.org/10.1017/S0263593300007847

Kilpeläinen, T., 1998. Evolution and 3D modelling of structural and metamorphic patterns of the Palaeoproterozoic crust in the Tampere-Vammala area, southern Finland. Geological Survey of Finland, Bulletin 397, 124 p.

Kohonen, J., Lahtinen, R., Luukas, J. & Nironen, M., 2021. Classification of regional-scale tectonic map units in Finland. Geological Survey of Finland, Bulletin 412, 33–80.

Kontinen, A., Huhma, H., Lahaye, Y. & O'Brien, H., 2013a. New U-Pb zircon age, Sm-Nd isotope and geochemical data on Proterozoic granitic rocks in the area west of the Oulunjärvi Lake, Central Finland. In: Hölttä, P. (ed.), Current Research: GTK Mineral Potential Workshop, Kuopio, May 2012. Geological Survey of Finland, Report of Investigation 198, 70–74.

Kontinen, A., Huhma, H., Lahaye, Y., O'Brien, H. & Torppa, A., 2013b. Shoshonitic and alkaline 1.86–1.85 Ga magmatism at the contact of the Svecofennian and Karelian domain in the Pyhäntä area, Central Finland. In: Hölttä, P. (ed.), Current Research: GTK Mineral Potential Workshop, Kuopio, May 2012. Geological Survey of Finland, Report of Investigation 198, 75–79.

Korsman, K., Hölttä, P., Hautala, T. & Wasenius, P., 1984. Metamorphism as an indicator of evolution and structure of the crust in Eastern Finland. Geological Survey of Finland, Bulletin 328. 40 p.

Kousa, J., Huhma, H., Hokka, J. & Mikkola, P., 2018. Extension of Svecofennian 1.91 Ga magmatism to the south, results of the reanalysed age determination samples from Joroinen, central Finland. Geological Survey of Finland, Bulletin 407, 56–62.

Kousa, J., Marttila, E. & Vaasjoki, M., 1994. Petrology, geochemistry and dating of Paleoproterozoic metavolcanic rocks in the Pyhäjärvi area Central Finland. In: Nironen, M. & Kähkönen, Y. (eds.), Geochemistry of Proterozoic Supracrustal Rocks in Finland. Geological Survey of Finland, Special Paper 19, 7–27.

Lahtinen, R., Huhma, H., Lahaye, Y., Lode, S., Heinonen, S., Sayab, M. & Whitehouse, M. J., 2016. Paleoproterozoic magmatism across the Archean-Proterozoic boundary in central Fennoscandia: Geochronology, geochemistry and isotopic data (Sm-Nd, Lu-Hf, O). Lithos 262, 507–525. https://doi.org/10.1016/j.lithos.2016.07.014

Lahtinen, R., Huhma, H., Lahaye, Y., Kousa, J. & Luukas, J., 2015. Archean–Proterozoic collision boundary in central Fennoscandia: Revisited. Precambrian Research 261, 127–165. https://doi.org/10.1016/j.precamres.2015.02.012

Lindsley, D. H., Brown, G. M., Muir, I. D., Papike, J. J., Boyd, F. R., Clark, J. R. & Ernst W. G., 1969. Conditions of the ferrowollastoinite–ferrohedenbergite inversion in the Skaergaard intrusion, East Greenland, Pyroxenes and amphiboles: crystal chemistry and phase petrology. Mineralogical Society of America, Special Papers 2, 193–201.

Ludwig, K. R., 2003. Isoplot/Ex 3. A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronologicy Center, Special Publication No. 4.

Mäkitie, H. & Lahti, S. I., 2001. The fayalite-augite quartz monzonite (1.87 Ga) of Luopa, western Finland, and its contact aureole. In: Mäkitie, H. (ed.), Svecofennian granitic pegmatites (1.86-1.79 Ga) and quartz monzonite (1.87 Ga), and their metamorphic environment in the Seinäjoki region, western Finland. Geological Survey of Finland, Special Paper 30, 61–98.

Makkonen, H. V., 2015. Nickel Deposits of the 1.88 Ga Kotalahti and Vammala Belts. In: Maier, W.D. et al. (eds.), Mineral Deposits of Finland. Elsevier, 253–290. https://doi.org/10.1016/B978-0-12-410438-9.00010-8

Mikkola, P., Lukkarinen, H. & Luukas, J., 2016. Suonenjoen kartta-alueen 3241 kallioperä ja kivilajiyksiköt. Geological Survey of Finland, Archive Report 29/2016, 29 p. (in Finnish)

Mikkola, P., Aatos, S., Halkoaho, T., Heinonen, S., Hietava, J., Hietala, S., Kurhila, M., Jäsberg, J., Laine, E.-L., Luukas, J., Niskanen, M., Nousiainen, M., Nygård, H., Piispanen, A., Pirinen, H., Rantanen, H. & Romu, I., 2022. Geological evolution and structure along the western boundary of the Outokumpu allochthon. GTK Open File Research Report 23/2022, 117 p.

Mikkola, P., Heilimo, E., Luukas, J., Kousa, J., Aatos, S., Makkonen, H., Niemi, S., Nousiainen, M., Ahven, M., Romu, I. & Hokka, J., 2018. Geological evolution and structure along the southeastern border of the Central Finland Granitoid Complex. Geological Survey of Finland, Bulletin 407, 5–27.

Molnár, F., Middleton, A., Stein, H., O'Brien, H., Lahaye, Y., Huhma, H., Pakkanen, L. & Johanson, B., 2018. Repeated syn- and post-orogenic gold mineralization events between 1.92 and 1.76 Ga along the Kiistala Shear Zone in the Central Lapland Greenstone Belt, northern Finland. Ore Geology Reviews, 936–956. https://doi.org/10.1016/j.oregeorev.2018.08.015

Nikkilä, K., Mänttäri, I., Nironen, M., Eklund, O. & Korja, A., 2016. Three stages to form a large batholith after terrane accretion – An example from the Svecofennian orogen. Precambrian Research 281, 618–638. https://doi.org/10.1016/j.precamres.2016.06.018

Nironen, M., 2005. Proterozoic orogenic granitoid rocks. In: Lehtinen, M. et al. (eds.), The Precambrian Bedrock–of Finland – Key to the evolution of the Fennoscandian Shield. Elsevier Science B.V., 443–479.

Nironen, M., 2017. Guide to the Geological Map of Finland. In: Nironen, M. (ed.) 2017. Bedrock of Finland at the scale 1:1 000 000 – Major stratigraphic units, metamorphism and tectonic evolution. Geological Survey of Finland, Special Paper 60, 41–75.

Nironen, M. & Front, K., 1992. The 1.88 Ga old Mäntylä complex central Finland: emplacement and deformation of mafic to felsic plutonic rocks and associated Mo mineralization. Bulletin of the Geological Society of Finland 64, 75–90. https://doi.org/10.17741/bgsf/64.1.006

Nironen, M., Elliott, B. A. & Rämö, O. T., 2000. 1.88–1.87 Ga post-kinematic intrusions of the Central Finland Granitoid Complex: a shift from C-type to A-type magmatism during lithospheric convergence. Lithos 53, 37–58. https://doi.org/10.1016/S0024-4937(00)00007-4

Nironen, M., Kousa, J., Luukas, J. & Lahtinen, R., 2016. Geological Map of Finland – Bedrock 1:1 000 000. Geological Survey of Finland.

North American Commission on Stratigraphic Nomenclature, NACSN 2005. North American Stratigraphic Code. AAPG Bulletin 89 (11), 1547–1591.

Pääjärvi, A. & Äikäs, O., 2005. Suonenjoki. Geological map of Finland 1:100 000, pre-Quaternary rocks, Sheet 3241. Geological Survey of Finland.

Pearce, J. A., Harris, N. B. W. & Tindle, A. G., 1984. Trace Element Discrimination Diagrams for the Tectonic Interpretation of Granitic Rocks. Journal of Petrology 25, 956–983. https://doi.org/10.1093/petrology/25.4.956

Pekkarinen, L., 2002. Haukivuori and Pieksämäki. Explanation to the Geological map of Finland, pre-Quaternary rocks, Sheets 3231, 3232. 98 p (in Finnish with English summary).

Peltonen, P., 2005. Svecofennian mafic-ultramafic intrusions. In: Lehtinen, M. et al. (eds.), The Precambrian Bedrock of Finland – Key to the Evolution of the Fennoscandian Shield. Elsevier Science B.V., 407–441.

Pietilä, M., 2020. Petrography, Geochemistry and Geochronology of the Post-kinematic A-type Intrusions of the Sorsavesi Area, Central Finland. M.Sc. Thesis, University of Helsinki, Finland, 80 p (in Finnish).

Rämö, O. T. & Haapala, I., 1995. One hundred years of Rapakivi Granite. Mineralogy and Petrology 52, 129–185.

Rämö, O. T., Vaasjoki, M., Mänttäri, I., Elliott, B. A. & Nironen, M., 2001. Petrogenesis of the Post-kinematic Magmatism of the Central Finland Granitoid Complex I; Radiogenic Isotope Constraints and Implication for Crustal Evolution. Journal of Petrology 42, 1971–1993. https://doi.org/10.1093/petrology/42.11.1971

Rantanen, H., 2021. Mineralogy, Petrology, and Petrogenesis of the Suvasvesi Granitoid Intrusion. M.Sc. Thesis, University of Helsinki, Finland, 77 p.

Rasilainen, K., Lahtinen, R. & Bornhorst, T. J., 2007. The Rock Geochemical Database of Finland Manual. Geological Survey of Finland, Report of Investigation 164. 38 p.

Sederholm, J. J., 1932. On the geology of Fennoscandia with special reference to the pre-Cambrian. Explanatory notes to accompany a general geological map of Fennoscandia. Geological Survey of Finland, Bulletin 98, 30 p.

Simonen, A., 1960. Plutonic rocks of the Svecofennides in Finland. Geological Survey of Finland, Bulletin 189, 101 p.

Simonen, A., 1980. The Precambrian in Finland. Geological Survey of Finland, Bulletin 304, 58 p.

Strand, K., Köykkä, J. & Kohonen, J. (eds) 2010. Guidelines and Procedures for Naming Precambrian Geological Units in Finland. Stratigraphic Commission of Finland: Precambrian Sub–Commission. Geological Survey of Finland, Guide 55, 41 p.

Virtanen, V. J. & Heilimo, E., 2018. Petrology of the geochemically A-type Saarijärvi suite: evidence for bimodal magmatism. Geological Survey of Finland, Bulletin 407, 130–150.

Whalen, J. B., Currie, K. L. & Chappell, B. W., 1987. A-type granites: geochemical characteristics, discrimination and petrogenesis. Contributions to Mineralogy and Petrology 95, 407–419. https://doi.org/10.1007/BF00402202