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Evidence of crustal growth during the Svecofennian orogeny: New isotopic data from the central parts of the Paleoproterozoic Central Finland Granitoid Complex

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A B S T R A C T

The Central Finland Granitoid Complex (CFGC) is the Paleoproterozoic core of the Svecofennian orogeny composed mainly of plutonic rocks varying from diorites to granodiorites and granites. Common mixing and mingling textures, synplutonic dykes, and mafic magmatic enclaves highlight the simultaneous nature of mafic, mantle derived magmatism and more evolved felsic magmatism in the CFGC. New U-Pb geochronological data support crustal growth during 1.90–1.87 Ga for the CFGC. Both Sm-Nd (ε_{Nd} -1.7–+2.5) from whole rocks and Lu-Hf (ε_{Hf} -8–+9) from zircons point towards relatively juvenile sources for the plutonic rocks without Archean crustal component. On the whole, isotopic evidence collectively points to crustal growth with maturing arc characteristics at 1.90–1.87 Ga, and a possible amalgamation of island arcs during the Svecofennian orogeny. In a larger scale, the CFGC was 1.9 Ga ago located in the active margin of the Great Proterozoic Accretionary Orogen when supercontinent Columbia (Nuna) formed.

1. Introduction

The Svecofennian Province is a part of the Fennoscandian Shield extending from Central Finland and Sweden southeast to Estonia and Russia in the southeast (Fig. 1) where the rocks are covered by younger sedimentary successions. It is considered as an active margin of the Great Proterozoic Accretionary Orogen (Condie, 2013), during which multiple island arcs or terranes accreted to the Archean Karelia Province (e.g. Nironen, 1997). Svecofennian events partially temporally overlap with the Lapland-Kola orogeny along the northern margin of the Karelia Province (e.g. Daly et al., 2001, 2006; Lahtinen et al., 2005). The overall development of the Svecofennian orogeny is well constrained but discussion on its details continues (Ekdahl, 1993; Eskola, 1963; Kotilainen et al., 2016; Korsman et al., 1999; Lahtinen et al., 2005; Mikkola et al., 2018a; Nironen, 1997, 2017; Nikkilä et al., 2016; Simonen, 1960; Stephens and Andersson, 2015). During the past two decades, the focus of studies and discussions has been on the formation mechanisms of the various, temporally closely spaced granitoid types of the Central Finland Granitoid Complex (CFGC) that forms the core of the Svecofennian domain in Finland (e.g. Elliott, 2003; Lahtinen et al., 2016, 2022; Mikkola et al., 2018a; Nikkilä et al., 2016).

We represent new zircon U-Pb and Lu-Hf data as well as whole-rock Sm-Nd data from the plutonic rocks of the south-east corner of the CFGC. Both Lu-Hf and Sm-Nd data are used to evaluate the juvenility and type of the magma sources. Together with the obtained crystallization ages of the same rocks, the new isotopic data allow us to evaluate the crustal growth. In addition, we provide evidence of magma mingling processes in the CFGC and discuss its role in the Svecofennian orogeny.

2. Geological setting

Rifting of the Archean core (3.5–2.6 Ga) of the Fennoscandian Shield started in the very beginning of the Paleoproterozoic, i.e. close to 2.5 Ga, as evidenced by mafic-layered intrusions, mafic dykes and A-type granites (e.g. Alapieti, 1982; Bayanova et al., 2009; Lauri et al., 2012; Zozulya et al., 2001). Episodic rifting continued for 500 million years and created gradually deepening basins filled mainly with sediments and, to a lesser extent, volcanic, mainly mafic rocks (e.g. Hanski and Huhma, 2005; Laajoki, 2005; Lehtonen et al., 1998; Huhma et al., 2018). During the Lapland–Kola orogeny (1.93–1.91 Ga), the Kola Province

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reaccreted to the Karelia Province, sandwiching the allochthonous Lapland granulite belt in between the two provinces. (e.g. Daly et al., 2001, 2006; Fig. 1a).

The Svecofennian orogeny commenced when the Savo arc, consisting of 1.93–1.91 Ga calc-alkaline plutonic and volcanic rocks, collided with the Archean craton in the northeast (Fig. 1a; Lahtinen et al., 2005; Nironen, 2017). These older Svecofennian units of the Savo arc form a sporadic belt between the CFGC and the Karelia Province, mainly in the proximity of the suture zone with the Archean craton (Fig. 1; e.g. Ekdahl, 1993; Vaasjoki et al., 2003; Kousa et al., 2018). The collision ended the older magmatic phase and deformed the supracrustal units deposited in a passive margin setting between the CFGC and the Karelia Province.

Following the collision, voluminous turbidites were deposited at 1.91–1.90 along the new passive margin. Their detrital zircon populations are typically bimodal at ca. 2.7 and ca. 2.0–1.92 Ga (e.g. Huhma et al., 1991; Claesson et al., 1993; Lahtinen et al., 2002; Mikkola et al., 2018b). The Archean population has been interpreted to originate from the Karelia Province, whereas multiple possible sources have been suggested for the Paleoproterozoic population; i.e. the Lapland-Kola orogeny, the Central Russian fold belt and Keitele "microcontinent", or unknown source (Lahtinen et al., 2005; Mikkola et al., 2018b). The existence of the Keitele "microcontinent" is, however, controversial because it has been inferred only based on the widespread 2.0–1.92 Ga zircon population in the metasedimentary rocks,which has no known plutonic rock counterparts in the Finnish bedrock, except the youngest 1.93–1.91 Ga age of the preorogenic granitoids and volcanic rocks of the Savo arc (e.g. Nironen, 2005).

The CFGC is dominated by granitoids aged 1895–1875 Ma, but it contains also small coeval volcanic segments (Figs. 1, 2) in addition to paragneisses. The majority of the coeval volcanic units form a discontinuous belt along the contact between the CFGC and the surrounding paragneisses (Pirkanmaa migmatite suite; Fig. 2). Sm-Nd data from the CFGC imply involvement of older crust (~2.1 Ga based on T_{DM}) in the formation of the granitoids. Alternatively, the observed initial ε_{Nd} values could be caused by mixing of the Archean and juvenile components from variable sources (Lahtinen and Huhma, 1997). The youngest part of the exposed Svecofennian crust is the Southern Finland subprovince (1.88–1.83 Ga), shaped mainly by convergent stages, with possible alternating short-term extensional stages (Lahtinen and Nironen, 2010; Nironen, 2017; Väisänen et al., 2012). Our study area is in the southeastern corner of the CFGC (Figs. 1 and 2). The regional geology has been described in more detail by Mikkola et al. (2016, 2018a), and the key characteristics of the various plutonic rock units are summarized in Table 1 after Heilimo et al. (2018). The granitoids display a short age range from 1.89 to 1.87 Ga, with a distinct peak at 1.88 Ga (Lahtinen et al., 2016; Nikkilä et al., 2016; Nironen, 1997; Mikkola et al., 2018a; Table 1).

Oldest plutonic rocks in the study area are the ~1895 Ma old volumetrically minor intermediate granitoids of the Lammuste lithodeme belonging to the Makkola suite (Fig. 2), which consists mainly of volcanic units. Calc-alkaline I-type intrusions of the Kangasniemi lithodeme (Pirkanmaa suite) are coeval with the Lammuste lithodeme, but were emplaced further south into the migmatitic Pirkanmaa paragneisses. The northern part of our study area is dominated by rocks of the Jyväskylä suite (1885–1880 Ma; Heilimo et al., 2018; Mikkola et al., 2016), which forms a continuum from quartz diorites and granodiorites (Vaajakoski lithodeme) to granodiorites and granites (Muurame lithodeme; Fig. 2). The felsic and more mafic components display signs of mixing in several locations. The main component of the locally voluminous Saarijärvi suite (1880–1875 Ma) are the porphyritic granitoids with A-type geochemical affinity (Puula lithodeme), which form a bimodal association with diorites (Istruala lithodeme). Ages from the Jyväskylä and Saarijärvi suites overlap within uncertainties, but based on observed cross-cutting relationships, the Saarijärvi suite is the younger of the two. The Oittila suite is represented by several intrusions, especially on the western side of the study area, and locally voluminous dykes down to 5 cm in width (Fig. 2). It consists of evolved granodiorite and granitoids (~1875 Ma) and is the youngest suite in the area (Fig. 2), temporally overlapping with the Saarijärvi suite.

The volcanic rocks in the area are a continuum of the well-studied Tampere belt (e.g. Kähkönen et al., 1989; Fig. 1b). They are calc-alkaline in character, 1895–1875 Ma old, and have been interpreted as having been formed in a continental arc environment (Mikkola et al., 2018c). Detrital zircon populations of the paragneisses that are located mainly south of the volcanic sequence are bimodal with peaks at ~2700 Ma and ~2100–1920 Ma. Thus, they lack detrital zircon grains coinciding with volcanism and have been interpreted as having been deposited before the onset of volcanism (Mikkola et al., 2018b).

3. Methods

Here we shortly describe the instruments and analytical conditions used to acquire the data presented in this study. More detailed descriptions of the methods and data can be found in the Supplementary material 1, including sample coordinates, additionally used standard zircons and control samples are available in Supplementary material 2 and 3. After separation and sample preparation zircon images were

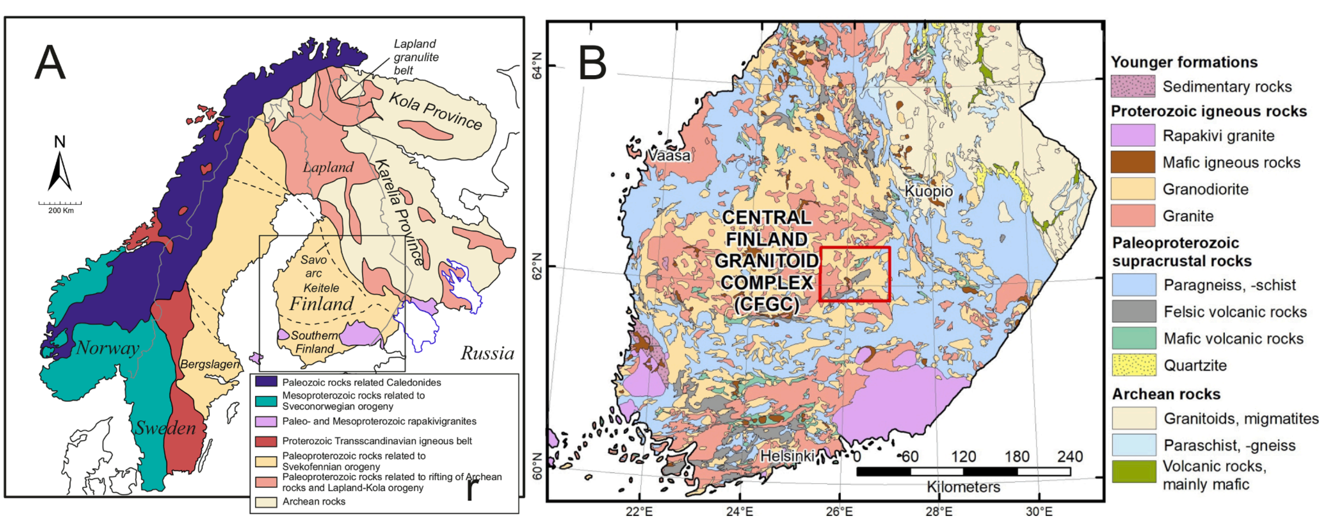

Fig. 1. (A) The geological framework of the Fennoscandian Shield. (B) Geological map of Southern Finland modified from Nironen et al. (2016). A detailed geological map of the study area is presented in the Fig. 2.

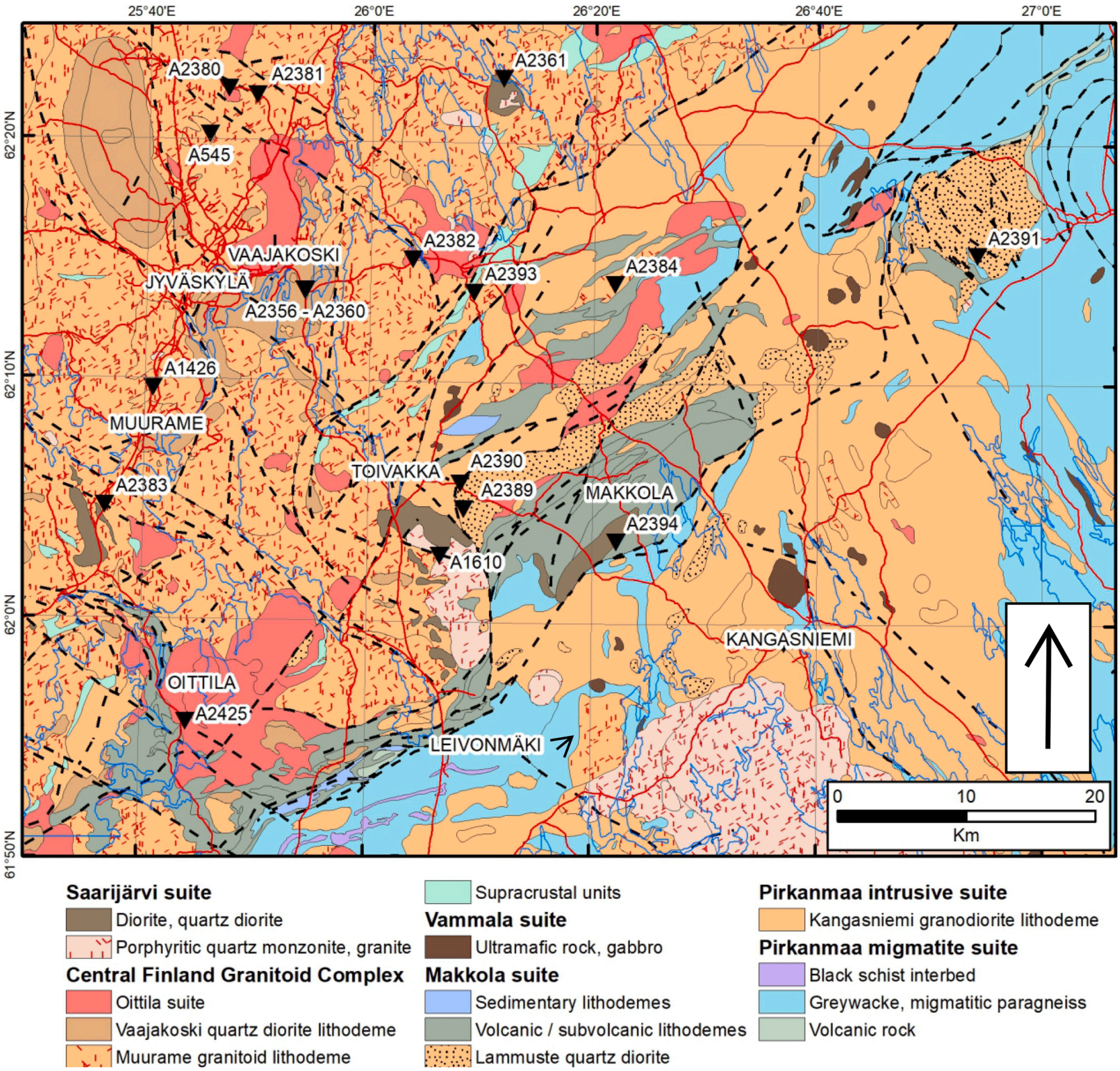

Fig. 2. Bedrock map of the study area with sample sites. Dashed lines represent major fault zones. Map modified from Mikkola et al. (2016). Basemap ©National Land Survey.

captured of the sample mounts for spot selection using BSE (back scatter electron microprobe) and CL (cathodoluminescence) methods. Single grain U-Pb data from part of the samples was acquired with a Cameca secondary ion mass spectrometer (SIMS) IMS 1280 at the NordSIMS laboratory in Stockholm. Zircon U-Pb data from the rest of the samples were acquired using laser ablation multi-collector Inductively Coupled Plasma Mass Spectrometer (LA-MC-ICPMS) Nu Plasma HR MC-ICPMS and laser ablation single-collector Inductively Coupled Plasma Mass Spectrometer (LA-SC-ICPMS) Nu Plasma AttoM at the Finnish Geoscience Laboratory (SGL) located at the Geological Survey of Finland in Espoo. All data are in Supplementary material 2, including BSE images of zircons grains. Whole-rock Sm-Nd data were collected with thermal ionization mass spectrometry (TIMS) and ICP-MS in the isotope laboratory of the Geological Survey of Finland. Single grain Lu-Hf analyses were carried out with LA-MC-ICPMS in the same laboratory. All ages have been calculated with 2σ error limits excluding decay constant errors. Sample locations are shown in Fig. 2. The electron microprobe analyses used for least-square approximation were performed at the Geological Survey of Finland with a Cameca SX100. The measured compositions and the least-square approximation are included in the Supplementary material 5.

4. Isotopic data

4.1. U-Pb geochronological results

4.1.1. Kainulaisenkylä (A2391), 1897 ± 7 Ma

This hornblende diorite sample with clear deformation-induced foliation was collected from the type locality of the Lammuste lithodeme (Solismaa et al., 2018) in the northeast corner of the study area. The homogeneous zircons in the sample lack observable internal structures, and they are subhedral to anhedral measuring 150 µm long and 30–50 µm wide. Altogether, 24 spots from 23 zircon grains were analyzed using LA-MC-ICPMS. All the analyses are concordant and yield

Table 1
Key characteristics of the studied plutonic rock units after Heilimo et al. (2018).

Suite and age (Ma)	Lithodeme	Typical geochemical characters	Mineralogy, texture	Other comments	Samples in this study and age (Ma)
Makkola suite					
ca. 1895 Ma	Lammuste lithodeme	Mainly intermediate with some outliers SiO_2 = 45–65 wt%, weak negative Eu anomaly	Deformed, weakly porhyritic quartz diorites, quartz monzonites		Kainulaisenkylä (A2391) 1897 ± 7 Ma, Jauhovakka (A2389) 1893 ± 5, Partiokolkka (A2390) 1892 ± 7 Ma
Pirkanmaa suite					
ca. 1895 Ma	Kangasniemi lithodeme	Mainly intermediate to acid SiO_2 = 41–72 wt% and K_2O = 1–4 wt%, weak negative Eu anomaly	Equigranular, variablydeformed granodioritesand tonalites.		Pylvänälä (A2392) 1893 ± 7 Ma
	Vammala suite	Mafic, containing few intermediate samples as fractionates SiO_2 37–58 wt %, MgO = 3–26 wt%	Gabbros and ultramafic plutonic rocks	Intrudes into Pirkanmaa migmatite and intrusive suites	
Jyväskylä suite					
					Lehesvuori (A545) 1892 ± 2 Ma (Lahtinen et al., 2016)
1885–1880 Ma	Muurame lithodeme	Mainly acidic SiO_2 = 60–75 wt%, and slightly enriched K_2O = 3.5–9 wt%, negative Eu anomaly	Deformed K-feldspar porphyritic granitoids	Bulk of the Central Finland Granitoid Complex in the study area	Ruuhimäki (A2393) 1885 ± 6 Ma, Muurame (A1426) 1885 ± 3 Ma (Rämö et al., 2001), Jylhänperä (A2381) 1882 ± 4 Ma, Vaajakoski 4 1882 ± 3 Ma, Suolikko (A2383), 1881 ± 4 Ma (Kallio et al., 2018)
1885–1880 Ma	Vaajakoski lithodeme	Mainly intermediate; SiO_2 = 43–58 wt%	Deformed quartz diorites and granodiorites hornblende and biotite as mafic minerals, pyroxenes locally preserved		Vaajakoski 3 (A2358) 1884 ± 3 Ma, Vaajakoski 1 (A2356) 1880 ± 2 Ma, Vaajakoski 2 (A2357) 1879 ± 5 Ma
Saarijärvi suite					
1880–1875 Ma	Istruala lithodeme				
1880–1875 Ma	Puula lithodeme	Bimodal suite, felsic members display A-type geochemical characteristics	Felsic members typically K-feldspar porphyritic quartz monzonites and granites. Mafic members equigranular diorites	Mingling texture between the endmembers common. Located in the vicinity of major fault zones	Viininperä (A2441) 1882 ± 3 Ma (Virtanen, 2017), Simuna (A2361) 1880 ± 2 Ma, Riitalampi (A1610) 1880 ± 3 Ma, 1875 ± 5 Ma Hiiteri (A2394) 1875 ± 5 Ma, Puula samples (A922, monazite TIMS; Rämö et al., 2001) 1875 ± 4 Ma, (A923, monazite TIMS; Rämö et al., 2001) 1874 ± 5 Ma, (A923, monazite TIMS; Rämö et al., 2001) 1874 ± 5 Ma
Oittila suite					
ca. 1875 Ma	Oittila lithodeme	Mainly elevated SiO_2 = 64–78 wt%, and K_2O = 4–8 wt%, mainly negative Eu anomalies	Equigranular or weakly porpyritic granitoid dykes and small intrusions, relatively undeformed and leucocratic		Soimavuori (A2380) 1879 ± 4 Ma, Oittila (A2425) 1876 ± 6 Ma, Kelkkamäki (A2382) 1875 ± 4 Ma, Vaajakoski 5 (A2360) 1875 ± 8 Ma
	Rutalahti lithodeme	High MgO (up to 32 wt%), Mg#, Ni, and Cr			

a concordia age of 1897 ± 7 Ma with small MSWD of concordance 0.47, which we interpret as the crystallization age of the sample (Fig. 3a).

4.1.2. Jauhovakka (A2389), 1893 ± 5

Sample A2389 is from a 40 cm wide plagioclase porphyrite dyke associated with the mainly volcanic Makkola suite intruding a quartz diorite of the Lammuste lithodeme. The zircon grains show weak oscillatory zoning. They are subhedral, prismatic stubby bipyramids ca. 150–200 μm long. Some of the grains have a narrow darker rim, or partial rim, visible in the BSE images. Altogether, 12 analyses from10 zircon grains were made using LA-MC-ICPMS. Two of the analyses were omitted due to slightly higher $^{207}Pb/^{206}Pb$ errors. The ten remaining analyses define a concordia age of 1893 ± 5 Ma with MSWD of concordance 0.095 (Fig. 3b).

4.1.3. Partiokolkka (A2390), 1892 ± 7 Ma

This sample represents the Lammuste lithodeme quartz diorite, country rock of the previous sample (A2389) and belongs to the Nyröpohja intrusion. The zircon grains are subhedral to anhedral, ca. 300 μm long and 100–150 μm wide. They display abundant narrow cracks and lack other significant internal structures. In total 26 analyses were made from 24 zircons with LA-SC-ICPMS. Two of the analyses were omitted due to large discordance. All concordant analyses define a concordia age of 1892 ± 7 Ma with MSWD 0.49 of concordance (Fig. 3c).

4.1.4. Pylvänälä (A2392), 1893 ± 7 Ma

This hornblende tonalite with granular texture, deformation induced foliation, and mafic microgranular enclaves (MME) represents the type locality of the Kangasniemi lithodeme. The zircon crystals display weak oscillatory zoning in BSE images. They are euhedral, 400 μm long, and have width/length ratio of ca. ¼. The grains also contain unidentified inclusions ca. 10 μm in diameter. Both these inclusions and dark areas were avoided in analyses. A total of 33 analyses were made from 20 zircon grains with LA-SC-ICPMS. Nine of the analyses were omitted due to high common lead content. The remaining 24 analyses are not concordant, but upper interception of 1893 ± 7 Ma with MSWD = 0.59 (Fig. 3d) can be calculated using lower interception anchored to 0 Ma.

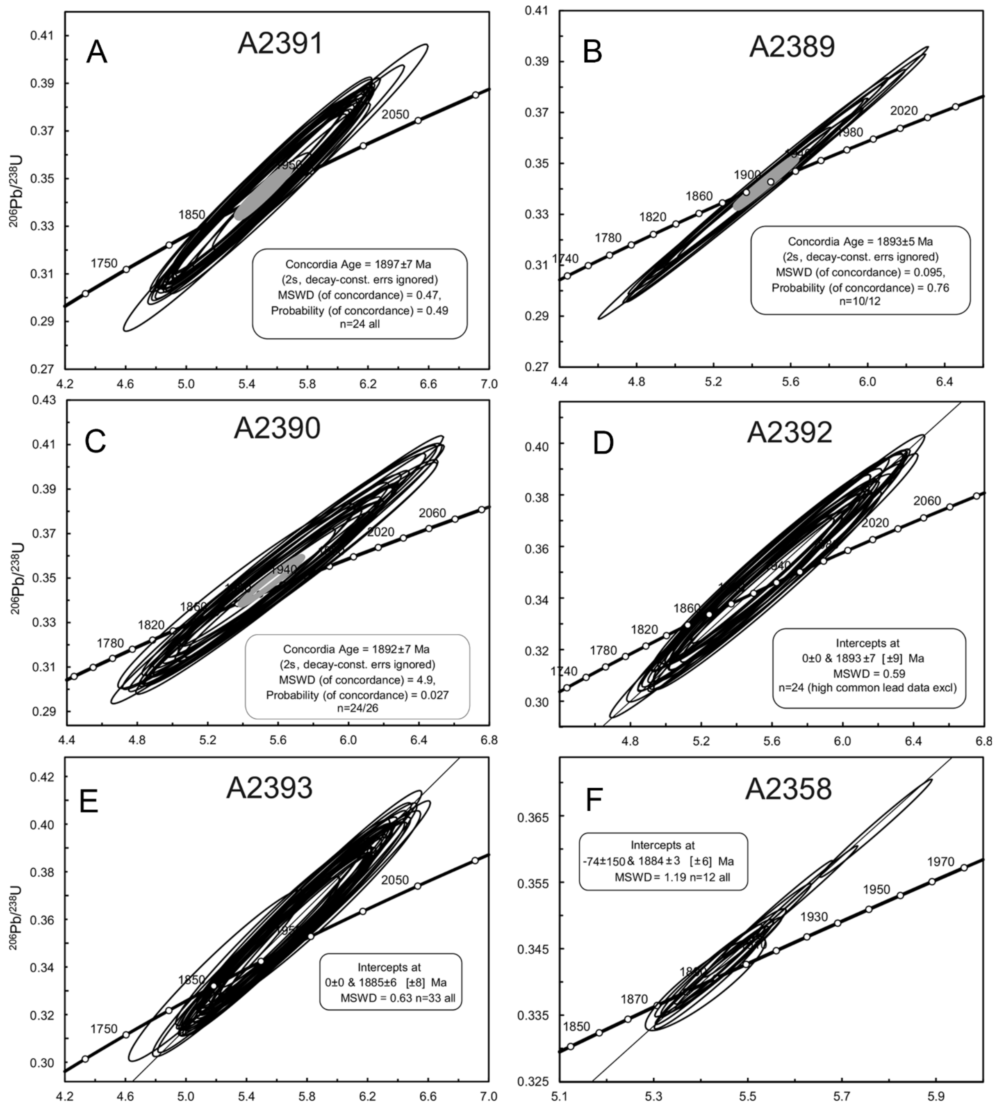

Fig. 3. Concordia diagrams showing zircon U–Pb isotope results for the samples: (A) A2391 Kainulaisenkylä, (B) A2389 Jauhovakka, (C) 2390 Partiokolkka, (D) A2392 Pylvänälä, (E) A2393 Ruuhimäki, (F) A2358 Vaajakoski 3, (G) A2381 Jylhänperä, (H) A2359 Vaajakoski 4, (I) A2441 Viininperä with individual $^{207}Pb/^{206}Pb$ ages with error bars, (J) A2356 Vaajakoski 1, (K) A2361 Simuna, (L) A1610 Riitalampi, (M) A2357 Vaajakoski 2, (N) A2380 Soimavuori, (O) A2425 Oittila, (P) A2382 Kelkkamäki, (Q) A2394 Hiiteri, (R) A2360 Vaajakoski 5.

We regard this to be the best estimate of the crystallization age for this sample.

4.1.5. Ruuhimäki (A2393), 1885 ± 6 Ma

This dark grey, intensively deformed biotite granodiorite belonging to the Muurame lithodeme has a banded appearance due to ca. 10 cm wide leucogranite veins. The zircons are euhedral and display weak oscillatory zoning, some dark areas were observed as rims or near cracks. The maximum length of the zircon grains is 300 µm and width 150 µm. A total of 34 analyses were made with LA-SC-ICPMS. One of the analyses was omitted due to high reverse discordance. With the lower interception fixed to 0 Ma, the discordia line has an upper intercept of 1885 ± 6 Ma with low MSWD = 0.63 (Fig. 3e) which we regard as the best estimate for the crystallization age of the rock.

4.1.6. Vaajakoski 3 (A2358), 1884 ± 3 Ma

Sample A2358 is from a small- and even-grained quartz diorite dike cross-cutting the Vaajakoski granodiorite (A2356), which is the main rock of the outcrop. Both rock types belong to the Vaajakoski lithodeme. Also samples A2357, A2359 and A2360 are from the same outcrop (Fig. 4; Supplementary material 4). The zircon grains are mostly anhedral (likely due to cracking during crushing the sample) to subhedral, crushed fragments with poorly developed zoning, or no zoning at all. Irregular metamictic domains and cracks are common, but inclusions are rare. Out of the 12 spots analyzed with SIMS, 4 are reversely discordant. The BSE images show no morphological differences between the zircons; however, the reversely discordant points have very high U concentrations (2121–8207 ppm), probably causing the discordance. The upper intercept of the discordia line at 1884 ± 3 Ma, calculated from all the analyses, is interpreted to be the crystallization age of the quartz diorite (Fig. 3f). Therefore, the quartz diorite and the hosting granodiorite are coeval within error limits and part of the same magmatic mingling system.

4.1.7. Jylhänperä (A2381), 1882 ± 4 Ma

Sample A2381 is a deformed K-feldspar porphyric granodiorite from the Hiekkapohja area, and represents the Muurame lithodeme of the Jyväskylä suite. The region displays a clear concentration of

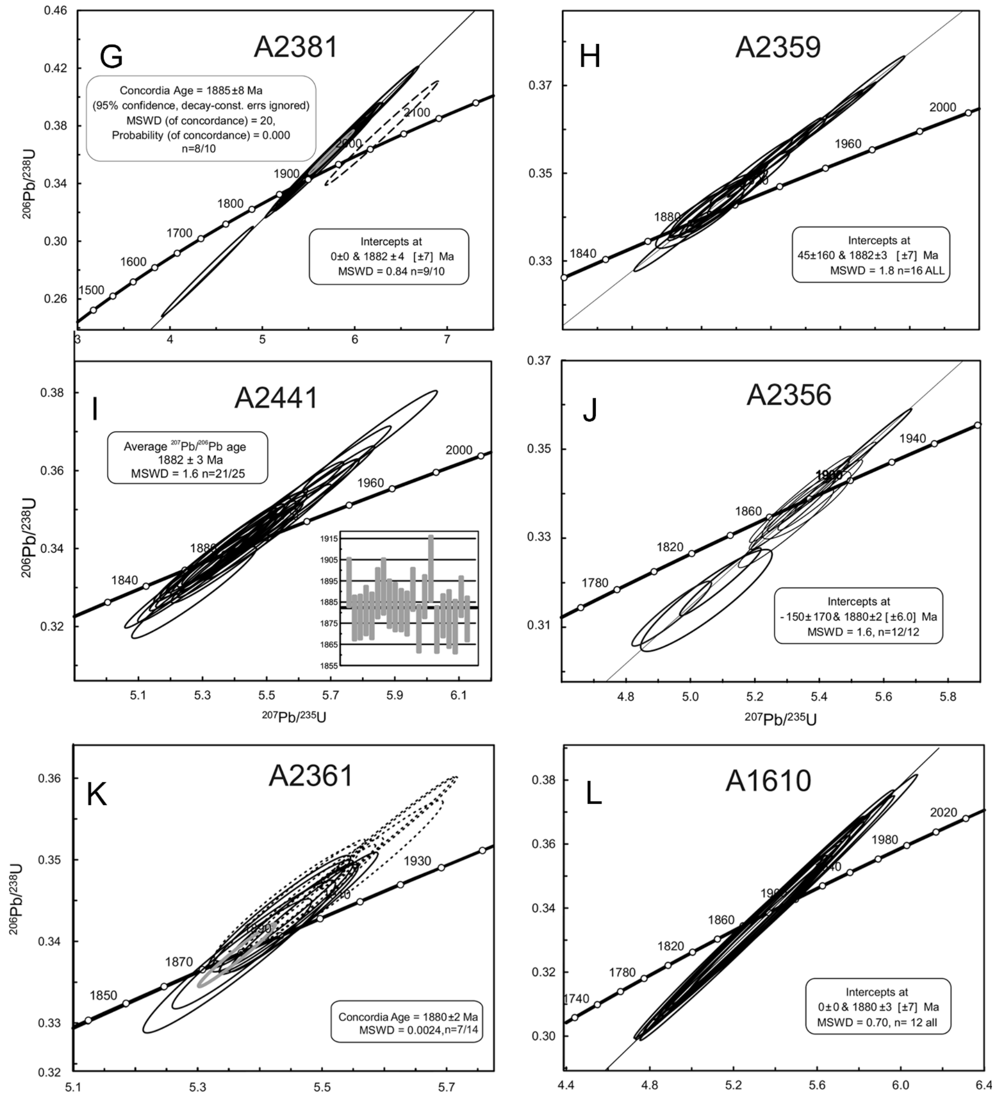

Fig. 3. (*continued*).

mineralization signs (Heilimo et al., 2022). The euhedral to subhedral zircon grains show weak oscillatory zoning, and are ca 300 μm long and 50–100 μm wide. Approximately half of the zircons have darker ca. 10 μm wide altered rims or partial rims, which were avoided when selecting locations for the spot analyses. A total of ten analyses were performed with LA-MC-ICPMS, of which eight are concordant, clustering at around 1880 Ma, one is discordant, and one concordant grain is interpreted as inherited with a clearly older ^{207}Pb/^{206}Pb age of 2053 ± 69 Ma (Fig. 3g). If the lower interception is constrained to 0 Ma an upper interception age of 1882 ± 4 Ma with small MSWD 0.84 can be calculated from nine analyses. We consider this to be the best estimate of the emplacement age for this granodiorite. Alternatively, a concordia age of 1884 ± 8 Ma with high MSWD of concordance 20 can be calculated using the eight concordant analyses.

4.1.8. Vaajakoski 4 (A2359), 1882 ± 3 Ma

Sample A2359 is from a ca. 30 cm wide leucogranite dyke belonging to the Muurame lithodeme. The dyke crosscuts both the leucogranite represented by sample A2356 and the quartz diorite dyke represented by sample A2358 (Supplementary material 4). The obtained zircon grains are euhedral and ca 250 μm long with a length/width ratio of 2.5/1. Weak magmatic zoning is typical and metamict domains common, with only few unaltered cores. A total of 16 analyses were made with SIMS, eight of these are reversely discordant (Fig. 3h). Among the analyzed 16 points, the U concentrations range from 554 ppm to 7818 ppm (avg. 2935 ppm), with highest values in the reversely discordant 8 analyze points. As no reasonable concordia age was yielded, we interpret the upper intercept of the discordia line at 1882 ± 3 Ma with MSWD 1.8, and the lower intercept of 45 ± 160 Ma as the best estimate of crystallization age for this sample (Fig. 3h). Within error limits, the leucogranodiorite dyke and the outcrop's main rock type, Vaajakoski Lithodeme granodiorite, are of same age, but may be slightly older than the granitoid dikes (A2360) crosscutting both of the rock types.

4.1.9. Viininperä (A2441), 1882 ± 3 Ma

This quartz monzonite sample from the northern margin of the Viininperä intrusion (Virtanen and Heilimo, 2018) belongs to the Saarijärvi suite. Zircon crystals from the sample are transparent to pale brown, mainly prismatic, and most of them have bipyramidal crystal faces. The length to width ratios of the 100–400 μm long zircon grains vary between 2 and 5. Most of the grains show oscillatory zoning, but some are homogeneous. No core-rim structures were identified in the BSE images. A total of 25 spots from 22 zircons were measured using LA-SC-ICPMS. Four of the analyses were discarded due to high elevated common lead content. The remaining results are concordant but scattered, which prevents calculation of concordia age. Therefore, we regard the weighted average of the ^{207}Pb/^{206}Pb ages, 1882 ± 3 Ma with mean square of MSWD of 1.6, as the best estimate for the crystallization age of

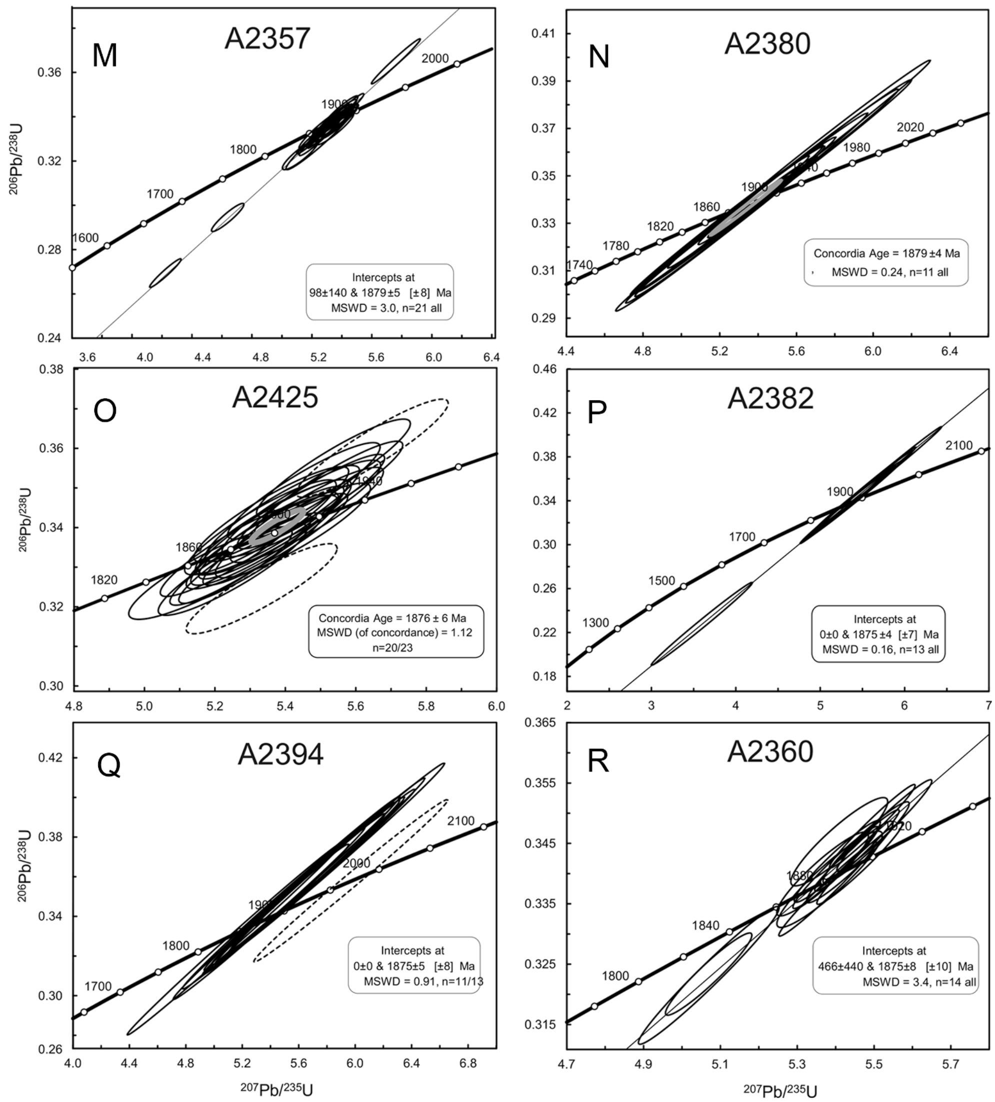

Fig. 3. (*continued*).

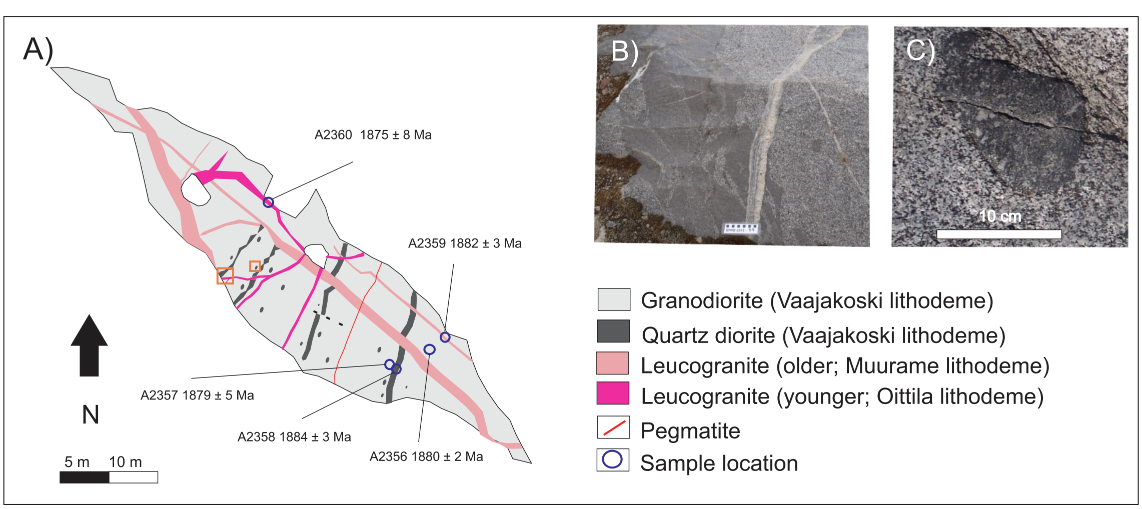

Fig. 4. (A) Sketch of the Vaajakoski key outcrop with quartz diorite (Vaajakoski lithodeme, samples A2356 and A2357), *syn*-plutonic crosscutting diorite dykes and enclaves of the same lithodeme (sample A2358). Two different cross-cutting generations of leucogranite dyke networks (samples A2359 and A2360) belonging to the Muurame and Oittila lithodemes, respectively. (B) Contact between a synplutonic quartz diorite dyke and leucogranite dykes with biotite schlierens. (C) Rounded diorite magmatic mafic enclave with captured plagioclase xenocrystals evidencing interaction between the magmatic mafic enclave and the host rock (more details in Supplementary material 4).

the Viininperä sample (Fig. 3i).

4.1.10. Vaajakoski 1 (A2356), 1880 ± 2 Ma

Sample A2356 is a foliated amphibole-bearing granodiorite and a typical representative of the Vaajakoski lithodeme. It is the main rock type of the outcrop from which also samples A2357–A2360 were collected (Supplementary material 4). Zircons are zoned and mostly euhedral (prismatic 100–350 μm long, aspect ratios 2–4). A total of 12 spots from nine zircons were analyzed with SIMS. The spots form a discordia line intercepting the concordia at -150 ± 70 and 1880 ± 2 Ma MSWD = 1.6. We regard the upper intercept as the emplacement age (Fig. 3j).

4.1.11. Simuna (A2361), 1880 ± 2 Ma

Sample A2361 is a pegmatitic orthopyroxene norite of the Istruala lithodeme from the 3x3 km Simuna intrusion consisting of variable pyroxene-bearing dioritic rocks. The separated zircons are large (100–400 μm, aspect ratios ~4) and crushed to sharp-edged fragments during separation. Faint oscillatory zoning or metamictization is observed in some of the grains. All of the 14 points analyzed with SIMS form a tight cluster ($^{207}Pb/^{206}Pb$ ages 1888–1873 Ma), but do not define a concordia age (Fig. 3k). This is due to reverse discordance of 7 spots, most likely caused by their high U (1230–4465 ppm). As BSE images do not reveal any significant morphological differences between the zircons with variable discordancy, we interpret 1880 ± 2 Ma, the weighted average of all $^{207}Pb/^{206}Pb$ ages, to be the crystallization age.

4.1.12. Riitalampi (A1610), 1880 ± 3 Ma

Sample A1610 is a K-feldspar porphyritic quartz monzonite from the Riitalampi intrusion (Virtanen and Heilimo, 2018) belonging to the Saarijärvi suite. The obtained zircon grains are ca. 200 μm long, euhedral, prismatic bipyramids. Their width/length ratio is ¼, and darker metamict areas are present in some crystals near cracks. The sample was analyzed with LA-MC-ICPMS and provided concordant analyses (Fig. 3l). All 12 analyses yield an upper intercept age of 1880 ± 3 Ma (MSWD = 0.70) when the lower interception is constrained to zero. We consider it to be the best estimate of the crystallization age for this sample.

4.1.13. Vaajakoski 2 (A2357), 1879 ± 5 Ma

Sample A2357 is a similar amphibole granodiorite as the sample A2356 originating from the same outcrop. It was collected 10 cm away from a cross-cutting quartz diorite dike (A2358) to study possible mingling effects (Fig. 4; Supplementary material 4). The prismatic, mostly euhedral zircons are zoned, 100–350 μm long, and have aspect ratios from 2 to 4. Most of the grains contain several inclusions, and some have metamict cores. The dataset, consisting of 21 spots analyzed with the SIMS, contain several discordant results, probably due to Pb loss. One reversely discordant point has anomalously high U concentration (3743 ppm), which may have caused the discordance. The upper intercept of the discordia line at 1879 ± 5 Ma (Fig. 3m) is interpreted as the age of the granodiorite, overlapping with the results from the sample A2356 collected from the same outcrop further away from the diorite dyke. However, three of the youngest $^{207}Pb/^{206}Pb$ ages (1865–1868 Ma) are concordant.

4.1.14. Soimavuori (A2380), 1879 ± 4 Ma

This sample is from a small- even-grained gray granite belonging to the Oittila suite. This intrusion, 1–1.5 km across, cross-cuts the Hiekkapohja porphyritic K-feldspar granodiorite (Heilimo et al., 2022) of the Muurame lithodeme. The zircon population is homogeneous, grains display euhedral bipyramidic and prismatic forms with weak magmatic zoning. The length of the zircons varies from 100 μm to 500 μm. Some of the grains contain rounded inclusions of up to 30 μm in diameter. All 11 analyses made with LA-MC-ICPMS define a concordia age of 1879 ± 4 Ma with low MSWD 0.24, which we interpret as the crystallization age of this sample (Fig. 3n).

4.1.15. Oittila (A2425), 1876 ± 6 Ma

Sample A2425 is an even-grained, unoriented granite from the Oittila intrusion. The zircons are euhedral, from 300 μm to 500 μm long, and typically 100 μm wide. On the boundaries and adjacent to narrow cracks somewhat darker areas can be observed. A total of 23 analyses were made with LA-SC-ICPMS, one of which was excluded due to high common Pb, three were omitted due to weak reverse discordance and one due to older $^{207}Pb/^{206}Pb$ age of 1944 ± 13 Ma considered as inherited. The remaining 18 analyses define a concordia age of 1876 ± 6 Ma with MSWD = 1.12, which we consider as the best estimate of the crystallization age (Fig. 3o).

4.1.16. Kelkkamäki (A2382), 1875 ± 4 Ma

Sample A2382 is an even-grained granite from the Kelkkamäki intrusion belonging to the Oittila suite. The zircon population is homogeneous, crystals are typically euhedral, bipyramidic, 300 μm long and 80 μm wide. A weak oscillatory zoning can be observed as well darker metamict areas parallel to the zoning. Out of 13 analyses with LA-MC-ICPMS one was discordant. If the lower interception is anchored to 0 Ma an upper intercept of 1875 ± 4 Ma with low MSWD = 0.16 can be calculated using all analyses (Fig. 3p). We regard this as the best estimation of the crystallization age.

4.1.17. Hiiteri (A2394), 1875 ± 5 Ma

The Hiiteri sample was collected from a pegmatitic part of a homogeneous diorite intrusion belonging to the Istruala lithodeme. Most of the zircon grains are anhedral or subanhedral, and metamictic dark areas near cracks are common. A total of 13 analyses from 10 zircon grains were performed with LA-MC-ICPMS. Most of the analyses are concordant and cluster close to each other (Fig. 3q). One analysis was excluded from the interpretation due to low U and Pb concentrations. Another spot yielded clearly older 1970 ± 9 Ma $^{207}Pb/^{206}Pb$ age, which we consider inherited. The remaining analyses provide an upper interception age of 1875 ± 5 Ma if the lower interception is constrained to 0 Ma. This fit with low MSWD = 0.91 is considered as the best estimation for the emplacement age of the Hiiteri diorite.

4.1.18. Vaajakoski 5 (A2360), 1875 ± 8 Ma

The sample A2360 is from a narrow leucogranite belonging to the Oittila suite, and it was collected from the same outcrop as samples A2356–A2359 (Fig. 8; Supplementary material 4). The zircons are rounded, euhedral to subhedral (aspect ratios 1–3, length 100–200 μm). Many of them contain inclusions and have strongly metamict rims. Some of the euhedral zircon grains display oscillatory zoning. Out of the 11 analyzed points, three are moderately discordant and two are reversely discordant. The reverse discordance may be due to high U concentrations (1442–1877 ppm) and relatively high U/Th ratio (0.33–0.51) of these spots. The upper intercept of the discordia line is 1875 ± 8 Ma with MSWD = 3.4 (Fig. 3r). This interception is the best estimate of the dyke's crystallization age.

4.2. Whole-rock Sm-Nd results

The 18 samples dated with U-Pb method were also analyzed for whole-rock Sm–Nd isotopes (Table 2; Figs. 5, 6) to evaluate crustal residence times. The dataset contains also two previously analyzed samples (Huhma 1986, Rämö et al., 2001). The three Lammuste lithodeme samples have positive initial ε_{Nd} values varying between 2.0 and 2.5 with depleted mantle model ages ($T_{(DM)}$) from 1980 to 2050 Ma. The one sample from Kangasniemi lithodeme has initial ε_{Nd} + 1.6 and $T_{(DM)}$ of 2040 Ma. The seven samples of the Jyväskylä suite show older $T_{(DM)}$ than the Lammuste suite, varying between 2010 and 2250 with ε_{Nd} ranging from -0.9 to + 0.7. The Lehesvuori sample that was dated earlier forms an outlier with $T_{(DM)}$ of 2420 Ma. The bimodal Saarijärvi suite's

Table 2
Available whole rock Sm-Nd data from study area.

Sample	Unit/location	Rock type	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	± 0.4%	$^{143}Nd/^{144}Nd$	2se	T (Ma)	ε_{Nd}	$T_{(Nd)}DM$	Method	References
A545	Jyväskylä/Lehesvuori	Granite	7.82	32.91	0.1436	0.0000	0.511934	0.000034	1889	-0.9	2421	TIMS	Huhma (1986)
A1610	Saarijärvi/Riitajärvi	Monzodiorite (quartz-)	6.11	31.40	0.1176	0.0005	0.511744	0.000020	1879	1.6	2055	ICP-MS	This study
A2356	Vaajakoski / Vaajakoski 1	Granodiorite (hbl-)	4.42	23.66	0.1129	0.0005	0.511573	0.000010	1880	-0.6	2219	TIMS	This study
A2357	Vaajakoski /Vaajakoski 2	Granodiorite (hbl-)	4.39	23.64	0.1122	0.0004	0.511618	0.000012	1879	0.4	2135	ICP-MS	This study
A2358	Vaajakoski /Vaajakoski 3	Diorite (hbl-)	5.81	28.77	0.1220	0.0005	0.511735	0.000012	1884	0.4	2173	ICP-MS	This study
A2359	Muurame/Vaajakoski 4	Granite (leuco-)	9.51	75.57	0.0761	0.0003	0.511127	0.000012	1880	-0.4	2117	ICP-MS	This study
A2360	Oittila/Vaajakoski 5	Granite (leuco-)	3.56	20.77	0.1037	0.0004	0.511527	0.000012	1880	0.7	2096	ICP-MS	This study
A2361	Istruala/Simuna	Norite (apatite-)	6.86	27.28	0.1520	0.0006	0.512076	0.000012	1875	-0.3	2396	ICP-MS	This study
A2380	Oittila/Soimavuori	Granodiorite	6.29	39.82	0.0954	0.0000	0.511427	0.000010	1879	0.8	2077	TIMS	This study
A2381	Muurame/Jylhänperä	Granodiorite	3.54	19.91	0.1075	0.0004	0.511572	0.000012	1882	0.7	2107	ICP-MS	This study
A2382	Oittila/Kelkkamäki	Granite	4.31	24.83	0.1049	0.0004	0.511589	0.000012	1875	1.6	2031	ICP-MS	This study
A2383	Muurame/Suolikko	Granodiorite	7.04	36.03	0.1181	0.0005	0.511630	0.000006	1881	-0.7	2249	ICP-MS	This study
A2389	Makkola/Jauhovakka	Dyke (intermediate)	2.30	17.09	0.0813	0.0003	0.511325	0.000012	1894	2.4	1972	ICP-MS	This study
A2390	Lammuste/Partiokolkka	Quartz diorite	3.63	20.97	0.1046	0.0004	0.511622	0.000012	1892	2.5	1980	ICP-MS	This study
A2391	Lammuste/Kainulaisenkylä	Diorite (Hbl-)	4.73	23.04	0.1240	0.0005	0.511834	0.000012	1897	2.0	2050	ICP-MS	This study
A2392	Kangasniemi/Pylvänälä	Quartz diorite	4.26	24.88	0.1035	0.0004	0.511564	0.000008	1893	1.6	2039	ICP-MS	This study
A2393	Muurame/Ruuhimäki	Granodiorite gneiss	3.51	18.46	0.1148	0.0005	0.511645	0.000006	1885	0.4	2149	ICP-MS	This study
A2425	Oittila/Oittila intrusion	Granite	4.88	28.53	0.1033	0.0004	0.511587	0.000007	1876	1.9	2004	ICP-MS	This study
Puula 1	Saarijärvi/Puula	Granite (biot, hbl-)	13.41	81.26	0.09978	0.0004	0.51142	0.00001	1875	-0.5	2170	TIMS	Rämö et al. (2001)
126-BEA-96	Istruala/Kälä	gabro	15.34	72.04	0.1286	0.0004	0.511775	0.000008	1875	-1.3	2290	TIMS	Rämö et al. (2001)
A545	Jyväskylä/Lehesvuori	Granite	7.53	41.64	0.1053	0.0000	0.511569	0.000005	1883.4	1.2	2072.1895	TIMS	Huhma (1986)

ICP-MS denotes Inductively coupled plasma mass spectrometry.
TIMS denotes thermal ionization mass spectrometry.
$^{143}Nd/^{144}Nd$ ratio is normalized to $^{146}Nd/^{144}Nd = 0.7219$.

mafic member, Istruala, gives ε_{Nd} -1.3 and relatively old $T_{(DM)}$ 2400 Ma, differing significantly from the rest of the results. The Puula lithodeme, however, yields higher ε_{Nd} (-0.5–+1.6) than Istruala lithodeme with $T_{(DM)}$ 2170–2060 Ma. The Oittila suite does not differ from the other suites with initial ε_{Nd} values -0.4–+1.9 and $T_{(DM)}$ 2120–2000 Ma. In general, all analyzed samples follow the typical Svecofennia array (Fig. 6) established by Huhma (1986) and Huhma et al. (2011) without significant contribution from Archean Karelia crust (eg. Huhma et al., 2012; Käpyaho et al., 2006; Mikkola et al., 2011).

4.3. *Zircon Lu-Hf results*

We analyzed Lu–Hf isotope ratios of zircons from seven lithodemes of the study area. The data are available in the Supplementary material 3 and Fig. 7. Maximum variation of the time-corrected $^{176}Hf/^{177}Hf$ values of zircons from individual sample is 11ε units, which exceeds the 2σ error limits. Thus, the variation must be caused by heterogeneity in the source or contamination en route to emplacement. The overall range of initial $^{176}Hf/^{177}Hf$ in our samples is between 0.28137 and 0.28185; ($\varepsilon_{Hf} \approx$ -8.0 to + 9.1), and there is no significant variation between initial values of different geological units. Our Lu-Hf data are equal within error limits with results from the southern parts of the Svecofennian Province. The data show that evolution of the studied rocks is significantly different from the evolution of Archean components in the Fennoscandia. However, Paleoproterozoic inheritance in the CFGC source cannot be ruled out and is suggested by variation larger than error limits from individual samples.

5. Discussion

5.1. *Crustal growth in the CFGC*

The new geochronological and isotopic results from this study imply a differentiation from the mantle and crustal growth for the CFGC during the Svecofennian orogeny. The studied plutonic rocks are ca. 1900–1875 Ma old (Fig. 8) and pertain to the main phase of the CFGC that has intruded to the surrounding paragneisses with maximum deposition ages from 1.92 to 1.90 Ga and bimodal zircon populations with peaks at ~2.7 Ga and 2.00–1.92 Ga (Huhma et al., 1991; Claesson et al., 1993; Mikkola et al., 2018a). The observed time span of the study area CFGC plutonic rocks, ca. 25 Ma, is relatively short. However, it should be noted that the error limits of the geochronological data leave an uncertainty of ca. 10 Ma to the formation period between the oldest and youngest CFGC rocks. The whole-rock Nd and zircon Hf data yield comparable results (Figs. 6 and 7). Based on the new and published data (Nikkilä et al., 2016; Lahtinen et al., 2016), Nd isotope results confirm the interpretations that a major Archean lower crustal block is absent beneath the Svecofennian in Finland (Huhma, 1986).

It should be noted, however, that a small population of inherited Archean/Paleoproterozoic zircons with ε_{Hf} of -5 and U-Pb ages between 2.25 and 1.95 Ga has been identified from the southern part of the Svecofennian domain (Kara et al., 2018). The radiogenic isotope signatures in the studied rocks of the CFGC also point towards a relatively short crustal residence time (ε_{Nd} -1.3–+2.5), similar to the other parts of the CFGC. The short crustal residence time is additionally evidenced by the Hf isotope data ($\varepsilon_{Hf} \approx$ -8.0−+9.1). Discussion on pre-CFGC components entails models including the Keitele "microcontinent" (Lahtinen et al., 2005; Nironen, 2017), which is based on mainly Sm-Nd characteristics of the CFGC and has been proposed to be ca. 2.1–2.0 Ga in accordance with the detrital zircons of the paragneisses (Lahtinen et al., 2002; Mikkola et al., 2018b). The chemical and isotopic characteristics could be attributed to an island arc or a small, older crustal area with slightly longer evolutionary history capable of generating a sufficiently evolved isotopic signature. It is worth mentioning that zircons of plutonic rocks have relatively homogenous population (U-Pb and Lu-Hf; Fig. 7), this might point to homogenous assimilate, not to

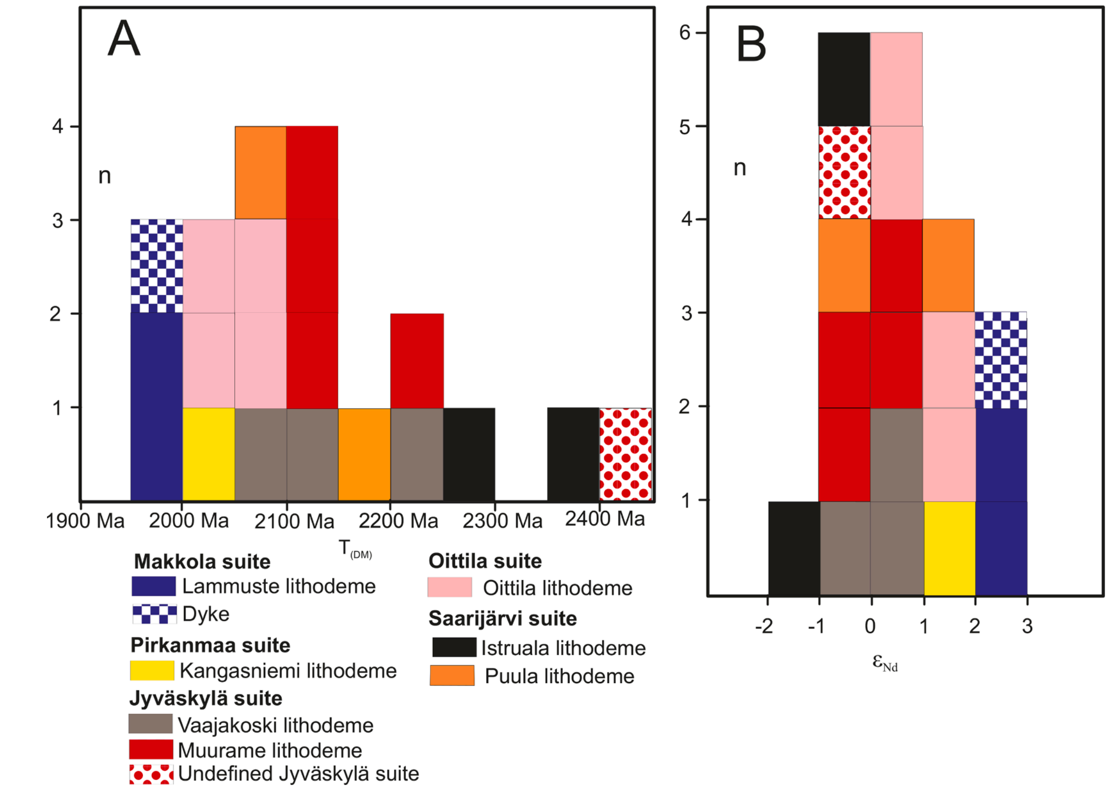

Fig. 5. (A) Cumulative probability of the $T_{(DM)}$ of the studied plutonic rocks. (B) Cumulative probability of initial ε_{Nd} of plutonic rocks 2σ error for ε_{Nd} = 0.5. DM values are denoted depleted mantle (DePaolo, 1981).

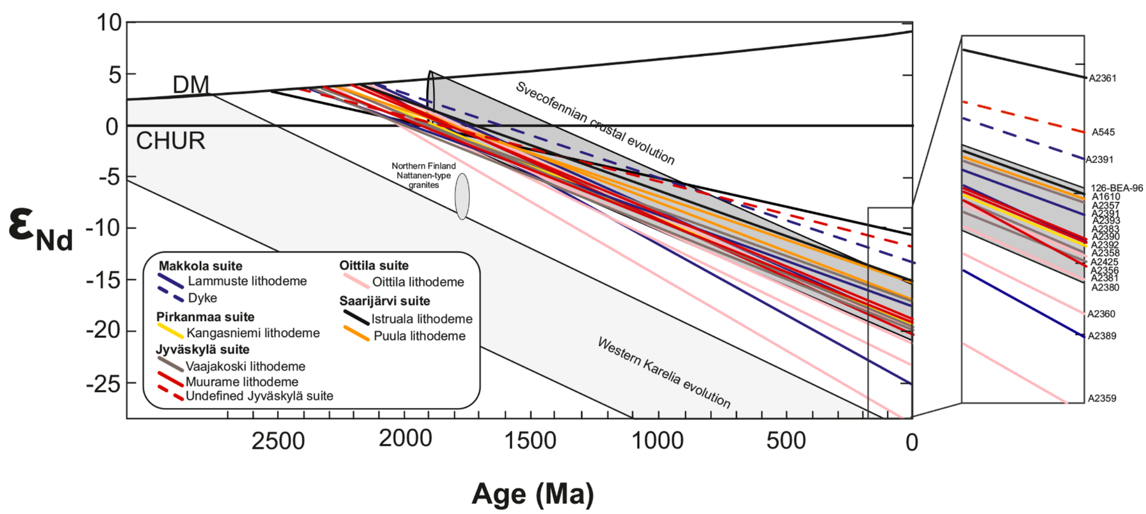

Fig. 6. ε_{Nd} vs. age diagram for the Central Finland Granitoid Complex (CFGC) data. Reference data from Huhma (1986), Huhma et al. (2011), Käpyaho et al. (2006), Mikkola et al. (2011), Halla (2005) and Heilimo et al. (2013). Depleted mantle based on DePaolo (1981). Chondritic uniform reservoir (CHUR) based on DePaolo and Wasserburg (1976).

geochronologically heterogenous detrital zircons populations with multiple age peaks. This would support existence of the proposed ca. 2.1–2.0 Ga old segment of continental crust referred to as Keitele "microcontinent" (Lahtinen and Huhma, 1997). Additionally, the lower initial ε_{Nd} values of the mantle-derived Istruala lithodeme in comparison with other suites, dominated by crustal sources, suggest that some of the Sm-Nd characteristics could in fact result from sediment material recycled though mantle, or assimilation of paragneisses during the magmas route in the crust as the area lacks sufficiently old igneous rocks.

Typically large batholiths, such as the CFGC, are emplaced at the brittle–ductile transition zone in the continental crust at depths of 12–15 km (eg. Vigneresse, 1995) via multiple magma pulses from variable source depths (Petford et al., 2000; Michel et al., 2008). Majority of the units studied here (Lammuste, Kangasniemi, Vaajakoski and Muurame lithodemes, Oittila suite) are consistent with this model and form a compositional continuum among each other (Heilimo et al., 2018). The bimodal Saarijärvi suite sets apart due to its emplacement being related to local transtensional or short-lived extensional settings (Virtanen and Heilimo, 2018). The CFGC emplacement represents incremental growth during the Svecofennian orogeny. Additionally, the emplacement depths

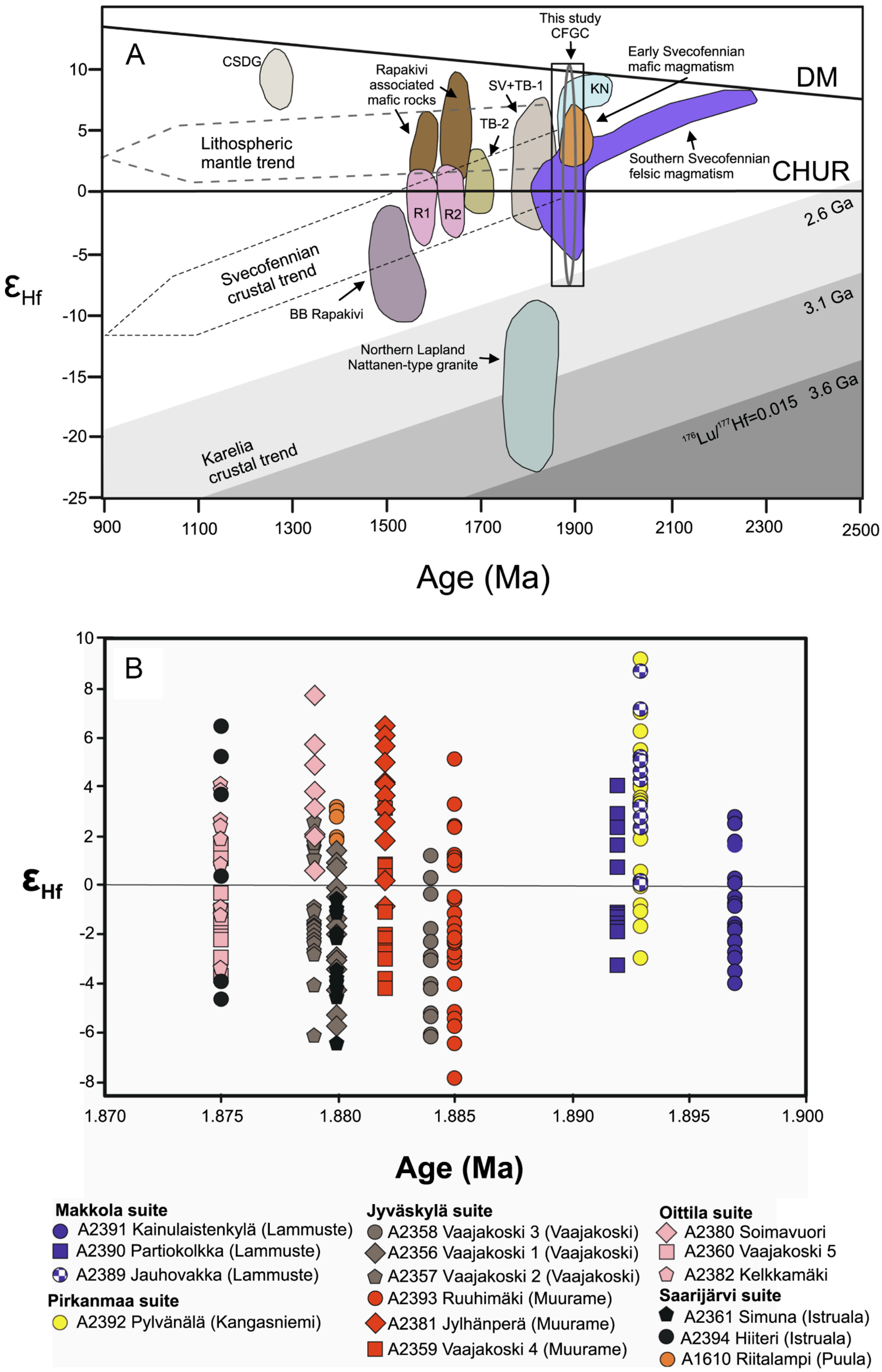

Fig. 7. A) ε_{Hf} vs. age (Ma) diagram for the new data from Central Finland Granitoid Complex (CFGC) and relevant reference data. The depleted mantle curve is modified from that of Griffin et al. (2000), and CHUR curve and contours after Bouvier et al. (2008). The Hf evolution trend for Paleoproterozoic Fennoscandian lithospheric mantle (ε_{Hf}=+4.5 ± 2.5 and $^{176}Lu/^{177}Hf \approx 0.0315$) drawn after Andersen et al. (2009), modified by Andersson et al. (2011); The Hf evolution trend for the Svecofennian crust ε_{Hf}=+2 ± 3 and $^{176}Lu/^{177}Hf \approx 0.015$ (Andersen et al., 2009) Upper limit of Fennoscandian Archean crust (Andersen et al., 2009); Archean granitoids in Fennoscandia (Patchett et al., 1981; Lauri et al., 2011; Heilimo et al., 2013); Knaften arc (KN; Guitreau et al., 2014); (SV; Andersen et al., 2009; Andersson et al., 2011; Kara et al., 2018); Syn to late Svecofennian granitoids and Transscandinavian Igneous Belt generation 1 (SV + TIB-1; Patchett et al., 1981; Vervoort and Patchett, 1996; Andersen et al., 2009; Andersson et al., 2011; Johansson et al., 2015; Kara et al., 2018, 2020; 2021; Kurhila et al., 2010); Northern Lapland Nattanen type granites (Heilimo et al., 2014); Transscandinavian Igneous Belt generation 2 (TIB-2; Andersen et al., 2009); Rapakivi granites from South-East Finland (R1), South-West Finland (R2) and associated mafic rocks (Heinonen et al., 2010); Rapakivi granites from Bothian Basin (BB), Sweden (Andersson et al., 2011); Central Scandinavian Dolerite Group (CSDG; Patchett et al., 1981; Söderlund et al., 2006). B) Close up of the new Hf in zircon data as ε_{Hf} vs. age (Ma) diagram.

of the granitoids vary temporally in the northern part of the CFGC (Nikkilä et al., 2016). Below, we will discuss the source and nature of each unit from study area in more detail (Elliott, 2003).

We interpret that the Lammuste and Kangasniemi lithodemes (ca. 1895 Ma) were generated via melting of a similar, relatively juvenile crustal source in an arc environment. The Lammuste lithodeme is dominated by quartz diorites and quartz monzonites, whereas Kangasniemi lithodeme consists mainly of granodiorites and tonalites. In addition to typical calc-alkaline compositions with fractionated REE patterns and negative Nb and Ti-anomalies (Heilimo et al., 2018), our interpretation is evidenced by similar Nd and Hf isotopic compositions (Figs. 6 and 7). Although overlapping within error margins with the other plutonic rocks the initial ε_{Nd} values are higher than for other units (+1.6–+2.4) which could reflect a relatively juvenile source. Melting of the lower crust can promote the vertical differentiation of the crust by making the lower crust more mafic and middle–and upper crust more felsic (e.g., Brown, 2020).

The Muurame and Vaajakoski lithodemes of the Jyväskylä suite were emplaced at 1885–1880 Ma. Compositionally, the Jyväskylä suite displays maturing calc-alkaline arc characteristics with stronger

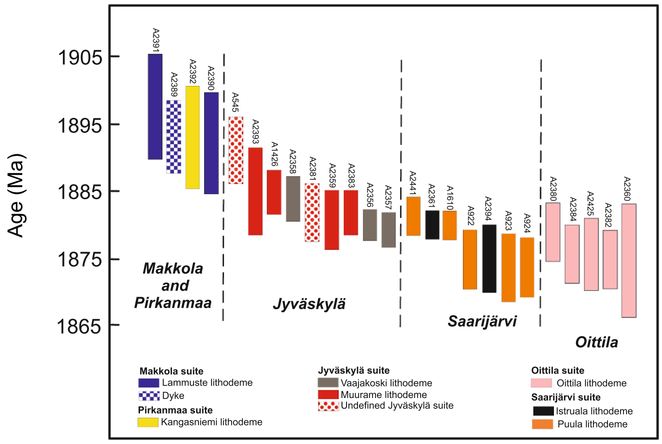

Fig. 8. Summary of available zircon and monazite U-Pb ages (Ma) with error limits from the study area. See Table 1 for references.

enrichment in LREE and increasingly negative Nb and Ti-anomalies without compositional gaps with the marginally older lithodemes (Heilimo et al., 2018). The contacts between the Jyväskylä suite's lithodemes are gradual, and local mingling textures indicating coeval emplacement can be observed. The Lu-Hf and Sm-Nd results are similar, initial ε values being -0.7–+0.7 and +1.6–+2.4, respectively. Compared to the older lithodemes these are lower but overlap within error (Figs. 6 and 7). This indicates a slightly stronger middle crustal contribution, supporting a maturing arc scenario. These granitoids were likely emplaced at the upper-middle crustal level as a part of continuous differentiation of the upper crust towards more felsic compositions as interpreted also by Nikkilä et al. (2016).

The occurrence of leucocratic granodiorites and granites of the Oittila suite (ca. 1875 Ma) as both abundant dykes and small intrusions cutting other units has been interpreted to be the result of low-degree partial melting of pre-existing felsic crust or prolonged magma evolution via extreme fractionation of Muurame lithodeme type magmas (Heilimo et al., 2018). The separation is clearer in the field, the granitic dykes have often been emplaced in brittle conditions, but occasional ductile emplacement is observable (Heilimo et al., 2018). Obtained Lu-Hf and Sm-Nd results are similar (Figs. 6 and 7) to the Jyväskylä suite. Thus, they demonstrate continuous evolution from isotopically homogeneous source in a maturing arc system. In current erosion level the CFGC lacks signs of migmatisation, therefore low degree partial melting of pre-existing granitoids is an unlikely explanation for petrogenesis of the Oittila suite.

Granitoids of the bimodal Saarijärvi suite (Puula lithodeme, 1880–1875 Ma) display A-type characteristics and differ clearly from those of the Jyväskylä suite based on for example higher K_2O, Al_2O_3, Ba and Zr concentrations (Elliott, 2003; Virtanen and Heilimo, 2018). The ε_{Nd} values of the Puula lithodeme -0.5–+1.6 are similar to those of the Jyväskylä suite -0.7–+0.7 (Table 2). However, the mafic Istruala lithodeme stands out with its distinctly lower ε_{Nd} values -1.3– -0.3. This is also observable as lower ε_{Hf} values of the Istruala lithodeme compared to the Puula lithodeme (Fig. 7). The negative ε_{Nd} and ε_{Hf} values of the Istruala lithodeme can be explained by derivation from mantle melts, that assimilated paragneisses with less radiogenic Nd and Hf The Puula lithodeme has higher proportion of lower crustal sources resulting in higher ε_{Nd} values. Temporally the Saarijärvi suite overlaps with the Jyväskylä suite, although the Saarijärvi suite is clearly less deformed and younger based on field relationships (Virtanen and Heilimo, 2018). According to Nikkilä et al. (2016), a possible shift from compression to extension occurred during this time in the CFGC allowing magma ascent though crustal scale shear zones. Alternatively, the overall setting could have still been compressive, and magma ascent could have happened along locally transtensional faults (Nironen 2017, Mikkola et al., 2018a). The less deformed appearance of the Saarijärvi suite could be linked to a shallower emplacement.

5.2. Roles of mafic and felsic magmatism in the formation of the CFGC

Plutonic rocks from the CFGC contain an abundance of different kinds of enclaves (e.g. Nironen, 2005; this study) that highlight the role of mixing/mingling processes between mafic and felsic magma in its formation. In general, enclaves found in granitoid rocks can be classified to four major groups: (1) magmatic enclaves caused by magma mixing; (2) restite enclaves of unmelted source rocks; (3) enclaves of fragmented cumulate material; and (4) wall-rock xenoliths (e.g. Barbarin, 2005; Didier and Barbarin, 1991; Elburg, 1996). Several authors evaluate the mafic microgranular enclaves (MMEs), part of group 1, to be important evidence for the genesis and evolution of granitoid rocks (Didier, 1973; Didier and Barbarin, 1991; Vernon, 1983) in terms of mixing, mingling and hybridization processes between coeval magmas. The majority of the observed enclaves in our study area are group 1 MMEs and synplutonic dyke mixing textures (Fig. 4). All the granitoid units, except the Oittila suite, which represents the last stage of magmatism in the study area, include a clear, but minor mafic component. However, examples of wall-rocks xenoliths (group 4) have been identified in the field at in all of the here studied units (Mikkola et al., 2016; Heilimo et al., 2018; Virtanen and Heilimo, 2018). Based on the abundance of observed group 1 enclaves, and compositional continuums (ibid.) the interaction between coeval mafic and felsic magmas was a significant process during the peak of CFGC formation at multiple depths from deep crust to emplacement depth. The Saarijärvi suite represents similar hybridization and mingling textures as documented by Virtanen and Heilimo (2018).

The isotopic signatures of the mafic and felsic components of the CFGC overlap (Figs. 5–7). This observation can be interpreted in several ways; (1) the granitoids represent lower degree melts and the more mafic diorite member higher degree melts of same or similar mafic source. Or (2) mafic juvenile magma fractionates and interacts with the lower crust forming more granitic melts that propagate through the crust forming the felsic intrusion. Part of the juvenile more mafic magma rises (eg. plumbing system) without significant interaction with existing crust resulting in the observed mafic and felsic components. (3) As for the Saarijärvi suite, the Istruala (mafic component) has partially melted pre-existing older crust forming the felsic Puula lithodeme and sometimes the lithodemes are mingled together (e.g. Virtanen and Heilimo, 2018).

5.2.1. Least-squares approximation of magma mingling

In addition to isotopic data, the interaction between mafic and felsic component can be constrained using whole-rock and mineral compositions. Naturally, the field observations and petrography remain as essential evidence for the interaction and hybridization of magmas with different compositions. Here we combine petrographic evidence with whole-rock and mineral chemical data to explicitly show that the mafic magma must have intruded a partially solidified felsic body. This confirms that these mafic and felsic magmas were coeval and propagated at least partly through the same lithospheric structures. As mentioned earlier multiple lithodemes in study area show mixing and mingling textures (Mikkola et al., 2016; Virtanen and Heilimo, 2018; Fig. 9). We studied a key outcrop of the Vaajakoski lithodeme using geochemical modelling to demonstrate the interaction between synplutonic mafic and felsic magmas forming the CFGC (see Fig. 4; Supplementary material 4 for a detailed description). The radiogenic isotopic compositions (Nd, Hf) and obtained ages of the mafic and felsic members overlap (Figs. 5–7). In general, the input of more mafic magma into the hosting granodiorite (Vaajakoski lithodeme) started when the intrusion was only partly crystalline (MME forming stage), and it continued until the intrusion was nearly solid (synplutonic dyke forming stage). The MMEs contain 3–5 mm size plagioclase xenocrysts, that were captured from the

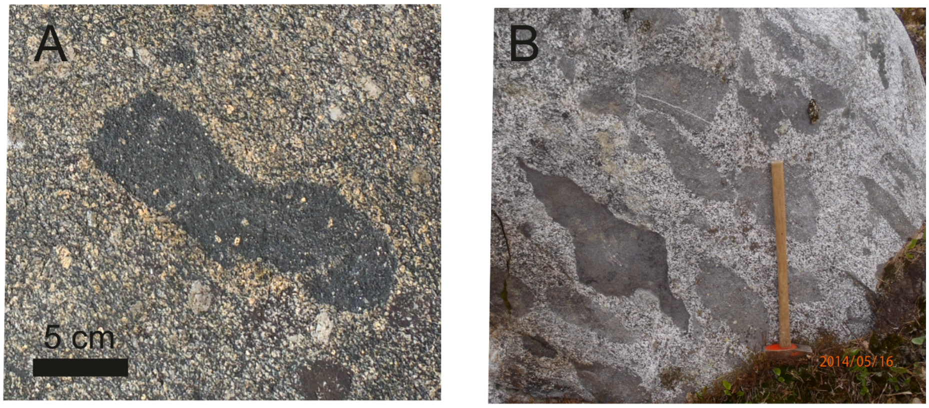

Fig. 9. Examples of mingling textures from Central Finland Granitoid Complex. (A) Granodiorite of the Kangasniemi lithodeme hosting a rounded diorite enclave belonging to the Lammuste lithodeme (outcrop PIM$-2014–76; E = 436795, N = 6910427). Note the capture of coarser grained feldspar crystals by the mafic magma, indicating that the two magmas interacted with each other. (B) Porphyritic granodiorite (Muurame lithodeme) hosting variably angular diorite enclaves (Vaaja-koski lithodeme) indicating that in addition to magma mingling post-crystallization deformation has in places further fragmented the mafic magmatic enclaves (outcrop EPHE-2014–9; E = 436795, N = 6910427). The coordinates are in ETRS-TM35FIN system.

host granodiorite and provide evidence for hybridization. We have estimated the degree of hybridization using least-squares approximation with MAGFRAC program (Morris, 1984) that is based iteration approach. The xenocryst-free synplutonic dyke was chosen as the parental magma of the MME, and MME was chosen to represent the product of the mingling process. Several combinations of the measured major mineral compositions were mixed with the whole-rock composition of the source rock to produce the composition of the MME (Supplementary material 5). Based on this iteration, the best fit was produced by mixing 51.0 % of diorite dyke, with 23.3 % of plagioclase, 9.2 % of quartz, 8.8 % of biotite, and 3.6 % of hornblende from the host rock (Supplementary material 5). This model has good correlation $r^2 = 0.022$. Chemical equilibration between the dykes/MMEs and their host rock highlight a major transport of MgO, FeO, and CaO away from the MME, as well as an introduction of SiO_2, and Na_2O into the MMEs. The mingling model demonstrates that some of the major minerals, plagioclase, quartz, biotite, and hornblende were likely captured by the mafic magma during ascent or emplacement. This is supported by observations at both, microscope and outcrop scales, and in the case of plagioclase, the xenocrysts are well evidenced.

5.3. Implications for the Paleoproterozoic crustal growth in Fennoscandia (Finland)

The crustal growth curve from Finland records three major episodes at 2.8–2.7 Ga, 1.9–1.8 Ga, and ca. ~1.6 Ga (Fig. 9). Two of these episodes have counterparts in the proposed supercontinent record (e.g. Condie and Aster, 2010; Fig. 10). The period at 2.8–2.6 Ga is linked to the Archean supercontinent assembly (possibly Superia/Kenorland) inferred by e.g. Bleeker (2003). The Svecofennian period 1.9–1.8 Ga that is partially related to assembly Columbia supercontinent (2.1–1.8 Ga). The Svecofennian orogeny occurred at 2.0–1.7 Ga as a part active margin the Great Proterozoic Accretionary Orogen was active for at least 900 My between 2 and 1 Ga (e.g. Condie, 2013). The same active margin, based paleocontinent reconstructions, contained at least Laurentia, Greenland, likely Amazonia together with Baltica (Pisarevsky et al., 2014). According to Condie (2014) Svecofennian orogeny as a whole display positive initial ε_{Nd} values (and ε_{Hf} values), which is relatively rare on the global scale. This points to limited amount of recycling of the of the older crust as well as to "fast" segregation of the crust form mantle, just like results of this study from CFGC. Most orogens contain significant volumes of reworked older crust as showed with mixed $\varepsilon_{Nd,\ Hf}$ values (Condie, 2014).

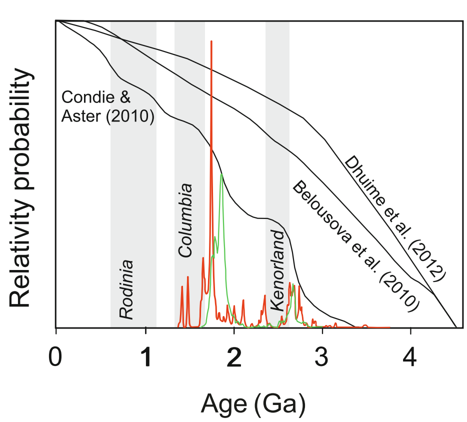

Fig. 10. Cumulative distribution of magmatic U-Pb and Sm-Nd ages (red line) as well as detrital U-Pb ages from Finland (Huhma et al., 2011). Also shown are some of the proposed global crustal growth curves (Dhuime et al., 2012; Belousova et al., 2010; Condie and Aster, 2010) with the of proposed stable supercontinent periods with gray. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6. Conclusions

1. The mainly calc-alkaline CFGC plutonic rocks have been emplaced between 1.90 and 1.87 Ga. The timespan represents relatively fast crustal growth in the core nuclei of the Svecofennian orogeny.
2. The radiogenic isotope fingerprints from plutonic rocks of the CFGC point towards a source with a relatively short crustal residence time without significant contribution of Archean crustal components. However, the assimilation with Paleoproterozoic ca. 2.1–2.0 Ga component is plausible based on the isotope signature.
3. The compositionally variable magmatism from the CFGC has been partially simultaneous as evidenced by synplutonic dykes and mafic magmatic enclaves as mixing and mingling textures. These evidence significant hybrid reactions between temporal magma pulses during the emplacement and crystallization of the magma.
4. Svecofennian rocks and the CFGC have been on the margin of Great Proterozoic Accretionary Orogen at 1.9 Ga when supercontinent Columbia started formation.

CRediT authorship contribution statement

Esa Heilimo: Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft. **Perttu Mikkola:** Conceptualization, Data curation, Investigation, Validation, Writing – review & editing. **Marjaana Ahven:** Investigation, Validation, Writing – review & editing. **Hannu Huhma:** Investigation, Validation, Writing – review & editing. **Yann Lahaye:** Investigation, Validation, Writing – review & editing. **Ville J. Virtanen:** Investigation, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data are provided in Appendixes

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.precamres.2023.107125.

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